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Tuna robotics: hydrodynamics of rapid linear accelerations

Robin Thandiackal, Carl H. White, Hilary Bart-Smith and George V. Lauder

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Review timeline

Original submission:	30 October 2020
Revised submission:	18 January 2021
Final acceptance:	27 January 2021

Note: Reports are unedited and appear as submitted by the referee. The review history appears in chronological order.

Review History

RSPB-2020-2726.R0 (Original submission)

Review form: Reviewer 1

Recommendation
Accept with minor revision (please list in comments)

Scientific importance: Is the manuscript an original and important contribution to its field?
Excellent

General interest: Is the paper of sufficient general interest?
Excellent

Quality of the paper: Is the overall quality of the paper suitable?
Excellent

Is the length of the paper justified?
Yes

Should the paper be seen by a specialist statistical reviewer?
No

Do you have any concerns about statistical analyses in this paper? If so, please specify them explicitly in your report.
No

It is a condition of publication that authors make their supporting data, code and materials available - either as supplementary material or hosted in an external repository. Please rate, if applicable, the supporting data on the following criteria.

Is it accessible?
Yes

Is it clear?
Yes

Is it adequate?
Yes

Do you have any ethical concerns with this paper?
No

Comments to the Author
This manuscript examines the hydrodynamics during accelerated swimming from rest in the robotic Tunabot Flex. It reveals where and when forces arise along the body throughout multiple swim cycles and relates these observations to mechanical power. I think the analysis excellent that is very well conducted. I do not have any criticisms of the experiments or the analysis. I do think this could be a much stronger contribution if the authors more thoroughly examine how the hydrodynamic forces along the body relate to swimming kinematics and work. I give an example below of what I mean. But this can be done by showing velocity and acceleration through time and by refocusing the Discussion (see below).
I would enthusiastically recommend this manuscript for publication after the suggested revisions.

Detailed comments:
Methods
Could not access mp4
Results
As you mention in the Introduction, fish generally increase acceleration by increasing amplitude, but your do it only by increasing frequency. What do you see as the implications of this and any idea how your tail tip velocities and frequencies compare to real fish/tuna?
Fig. 5 – It would be very informative and useful to have velocity and acceleration vs. time plotted along with the other parameters in the figure.
Time times in fig. 5 do not seem to correspond to the time stamps in fig. 4.

Discussion
The discussion spends a lot of time comparing these results to lamprey and other studies. I understand that the lamprey study is one of the few that has examined acceleration from rest but lamprey swim using very different kinematics and propulsive mode. This is a really nice data analysis and the strength of the analysis is having simultaneous measurements of pressure and force (from hydrodynamics), swimming kinematics (vel and accel) and work measurements (mechanical power). It think this paper would be greatly improved and be a much more valuable contribution with a more thoughtful analysis of how the hydrodynamic forces along the body relate to the swimming kinematics and measured work. For example, I find it surprising and interesting that peak axial forces arise from forces not on the caudal fin but from forces along the body in front of the peduncle (that is at least my interpretation of Fig. 5). But what forces coincide with peak accelerations and velocities (this data is not shown)?

Review form: Reviewer 2

Recommendation
Major revision is needed (please make suggestions in comments)

Scientific importance: Is the manuscript an original and important contribution to its field?
Marginal

General interest: Is the paper of sufficient general interest?
Good

Quality of the paper: Is the overall quality of the paper suitable?
Marginal

Is the length of the paper justified?
Yes

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No

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Decision letter (RSPB-2020-2726.R0)

16-Dec-2020

Dear Mr Thandiackal:

Your manuscript has now been peer reviewed and the reviews have been assessed by an Associate Editor. The reviewers' comments (not including confidential comments to the Editor) and the comments from the Associate Editor are included at the end of this email for your reference. As you will see, the reviewers and the Editors have raised some concerns with your manuscript and we would like to invite you to revise your manuscript to address them.

We do not allow multiple rounds of revision so we urge you to make every effort to fully address all of the comments at this stage. If deemed necessary by the Associate Editor, your manuscript will be sent back to one or more of the original reviewers for assessment. If the original reviewers are not available we may invite new reviewers. Please note that we cannot guarantee eventual acceptance of your manuscript at this stage.

To submit your revision please log into http://mc.manuscriptcentral.com/prsb and enter your Author Centre, where you will find your manuscript title listed under "Manuscripts with Decisions." Under "Actions", click on "Create a Revision". Your manuscript number has been appended to denote a revision.

When submitting your revision please upload a file under "Response to Referees" - in the "File Upload" section. This should document, point by point, how you have responded to the reviewers' and Editors' comments, and the adjustments you have made to the manuscript. We require a copy of the manuscript with revisions made since the previous version marked as 'tracked changes' to be included in the 'response to referees' document.

Your main manuscript should be submitted as a text file (doc, txt, rtf or tex), not a PDF. Your figures should be submitted as separate files and not included within the main manuscript file.

When revising your manuscript you should also ensure that it adheres to our editorial policies (https://royalsociety.org/journals/ethics-policies/). You should pay particular attention to the following:

Research ethics:
If your study contains research on humans please ensure that you detail in the methods section whether you obtained ethical approval from your local research ethics committee and gained informed consent to participate from each of the participants.

Use of animals and field studies:
If your study uses animals please include details in the methods section of any approval and licences given to carry out the study and include full details of how animal welfare standards were ensured. Field studies should be conducted in accordance with local legislation; please include details of the appropriate permission and licences that you obtained to carry out the field work.

Data accessibility and data citation:
It is a condition of publication that you make available the data and research materials supporting the results in the article. Please see our Data Sharing Policies (https://royalsociety.org/journals/authors/author-guidelines/#data). Datasets should be deposited in an appropriate publicly available repository and details of the associated accession number, link or DOI to the datasets must be included in the Data Accessibility section of the article (https://royalsociety.org/journals/ethics-policies/data-sharing-mining/). Reference(s) to datasets should also be included in the reference list of the article with DOIs (where available).

In order to ensure effective and robust dissemination and appropriate credit to authors the dataset(s) used should also be fully cited and listed in the references.

If you wish to submit your data to Dryad (http://datadryad.org/) and have not already done so you can submit your data via this link http://datadryad.org/submit?journalID=RSPB&manu=(Document not available), which will take you to your unique entry in the Dryad repository.

If you have already submitted your data to dryad you can make any necessary revisions to your dataset by following the above link.

For more information please see our open data policy http://royalsocietypublishing.org/data-sharing.

Electronic supplementary material:
All supplementary materials accompanying an accepted article will be treated as in their final form. They will be published alongside the paper on the journal website and posted on the online figshare repository. Files on figshare will be made available approximately one week before the accompanying article so that the supplementary material can be attributed a unique DOI. Please try to submit all supplementary material as a single file.

Online supplementary material will also carry the title and description provided during submission, so please ensure these are accurate and informative. Note that the Royal Society will not edit or typeset supplementary material and it will be hosted as provided. Please ensure that the supplementary material includes the paper details (authors, title, journal name, article DOI). Your article DOI will be 10.1098/rspb.[paper ID in form xxxx.xxxx e.g. 10.1098/rspb.2016.0049].

Please submit a copy of your revised paper within three weeks. If we do not hear from you within this time your manuscript will be rejected. If you are unable to meet this deadline please let us know as soon as possible, as we may be able to grant a short extension.

Thank you for submitting your manuscript to Proceedings B; we look forward to receiving your revision. If you have any questions at all, please do not hesitate to get in touch.

Best wishes,
Dr Locke Rowe
mailto: proceedingsb@royalsociety.org

Associate Editor
Board Member: 1
Comments to Author:
Dear Dr Thandiackal,
We have received three reviews, two of which are clearly supportive of the manuscript and one somewhat less so. Please address all the points raised by each reviewer as fully as possible, paying particular attention to justifying the methodological and statistical approaches that underpin the conclusions (as per Reviewer 2; points 2 and 3).
I look forward to reading your response.
Kind regards.

Reviewer(s)' Comments to Author:

Referee: 1

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Author's Response to Decision Letter for (RSPB-2020-2726.R0)

See Appendix A.

Decision letter (RSPB-2020-2726.R1)

27-Jan-2021

Dear Mr Thandiackal

I am pleased to inform you that your manuscript entitled "Tuna robotics: hydrodynamics of rapid linear accelerations" has been accepted for publication in Proceedings B.

You can expect to receive a proof of your article from our Production office in due course, please check your spam filter if you do not receive it. PLEASE NOTE: you will be given the exact page length of your paper which may be different from the estimation from Editorial and you may be asked to reduce your paper if it goes over the 10 page limit.

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figshare repository. Files on figshare will be made available approximately one week before the accompanying article so that the supplementary material can be attributed a unique DOI.

Thank you for your fine contribution. On behalf of the Editors of the Proceedings B, we look forward to your continued contributions to the Journal.

Sincerely,
Dr Locke Rowe
Editor, Proceedings B
mailto: proceedingsb@royalsociety.org

Associate Editor:
Board Member
Comments to Author:
(There are no comments.)

Appendix A

Responses to referees

We would like to express our gratitude to the referees for their helpful comments on our manuscript. We appreciate the positive reactions and constructive suggestions for improvement. We have conducted new analyses to better understand the contribution of the tail on the Tunabot, revised the manuscript in line with the referee's suggestions to focus more on thunniform locomotion and on the contribution of the body and peduncle area to thrust during acceleration, and added a new supplemental figure. The rewritten abstract for the paper reflects this change in emphasis also. We hope that this revised manuscript proves acceptable.

Below we describe in detail the specific changes we have made to address the referees' concerns through our revisions (comments in black, our responses in blue).

Responses to Referee 1:
This manuscript examines the hydrodynamics during accelerated swimming from rest in the robotic Tunabot Flex. It reveals where and when forces arise along the body throughout multiple swim cycles and relates these observations to mechanical power. I think the analysis excellent that is very well conducted. I do not have any criticisms of the experiments or the analysis. I do think this could be a much stronger contribution if the authors more thoroughly examine how the hydrodynamic forces along the body relate to swimming kinematics and work. I give an example below of what I mean. But this can be done by showing velocity and acceleration through time and by refocusing the Discussion (see below).
I would enthusiastically recommend this manuscript for publication after the suggested revisions.
We highly appreciate this positive feedback of our study and thank the referee for their helpful suggestions. In brief, we agree with the reviewer and have modified the manuscript accordingly to focus on the body and peduncle area and how forces are distributed along the body. Please find our more detailed response below.

As you mention in the Introduction, fish generally increase acceleration by increasing amplitude, but you do it only by increasing frequency. What do you see as the implications of this and any idea how your tail tip velocities and frequencies compare to real fish/tuna?
We thank the referee for pointing this out. This comment led us to clarify and better justify why we investigate accelerations by increasing tail beat frequency in the introduction.
It is true that fish show higher tail beat amplitudes during acceleration compared to steady swimming (Akanyeti et al. 2017; Wise, Schwalbe, and Tytell 2018). However, as Akanyeti et al. (2017) mention and show (in their supplementary material Table S3), acceleration increases with both tail beat amplitude and tail beat frequency. They also show that tail beat frequency has a much stronger effect on acceleration. So in summary, when fish accelerate they do so at a higher tail beat amplitude compared to steady swimming but they largely modulate the acceleration itself by the tail beat frequency.

In our study we deliberately used a robotic platform with a design that ensures a constant tail best amplitude with increasing frequency. This platform, the Tunabot Flex (White, Lauder, and Bart-Smith 2020) has hard-stop limits on side to side motion which ensures a constant amplitude as frequency changes. Our goal was to focus on the effect of frequency on acceleration in a controlled manner, and not to confound the results with uncontrolled changes in amplitude. Many fish robots display a decrease in tail beat amplitude when the frequency is increased as they are not able to generate sufficient lateral forces at higher frequencies, and indeed this was true of our original Tunabot platform (Zhu et al. 2019), which we elected not to use for that reason in this project.

Finally, similarities (midline kinematics, stride length and Strouhal number) between the Tunabot Flex platform and yellowfin tuna are reported in White et al. 2021 paper in press (but available on the BB web site now).

Fig. 5 – It would be very informative and useful to have velocity and acceleration vs. time plotted along with the other parameters in the figure.

Time stamps in fig. 5 do not seem to correspond to the time stamps in fig. 4.

Thanks for this suggestion. We have added a visualization of the velocity over time to Fig. 5. and also to the corresponding supplementary figures. The forward speed subplot now shows the filtered center of mass (COM) forward speed as well as the linearly increasing speed stemming from our model of constant acceleration.

It is correct that the time instances in Fig. 5 do not correspond to Fig. 4. Here our idea was to focus on more of the spatial aspects in the flow field in Fig. 4 (at a limited number of time instances) and to provide a higher time resolution in Fig. 5.

The discussion spends a lot of time comparing these results to lamprey and other studies. I understand that the lamprey study is one of the few that has examined acceleration from rest but lamprey swim using very different kinematics and propulsive mode. This is a really nice data analysis and the strength of the analysis is having simultaneous measurements of pressure and force (from hydrodynamics), swimming kinematics (vel and accel) and work measurements (mechanical power). I think this paper would be greatly improved and be a much more valuable contribution with a more thoughtful analysis of how the hydrodynamic forces along the body relate to the swimming kinematics and measured work. For example, I find it surprising and interesting that peak axial forces arise from forces not on the caudal fin but from forces along the body in front of the peduncle (that is at least my interpretation of Fig. 5). But what forces coincide with peak accelerations and velocities (this data is not shown)?

We thank the referee for their positive feedback on our data analysis. We have rewritten large parts of the discussion according to your comments which were in agreement with the other referees, and with our own re-reading of the manuscript. Our original idea was to discuss in some detail the only published paper on acceleration from rest (which happens to be in an anguilliform swimmer), but we agree that it is a better use of the limited space given length limitations for Proceedings papers to refocus the discussion on the tunabot and hydrodynamic forces. Specifically, we reduced the discussion of the comparison to lamprey and focused more on the contribution of thrust forces from the posterior main body before the peduncle. You will also notice that we removed the tail fin from our analysis. The corresponding reasons are listed in the response to the 2nd comment from referee 2.

Responses to Referee 2:

1. This manuscript (RSPB-2020-2726) presents hydrodynamics and energetics of a tuna-inspired robot in linear acceleration. The tuna-like robot is definitely one of the most remarkable achievements in fish swimming mechanics and robotics. However, since the tuna-like robot design has already been reported previously (White et al., 2020, and Zhu et al., 2019), in this manuscript typed as "Research Article", the tuna-like robot system could not be considered as an original contribution for this manuscript, while the original contribution is the experimental analysis based on the robot system. After reading the manuscript, my impression is, the current manuscript is not yet delivering clear take-home messages based on the quantitative analyses-There are analyses of acceleration, flow pattern, force and power, but these results only receive basic description in the numbers. As I explained above, the tuna-like robot system could not be considered as an original contribution for this manuscript, thus the original quantitative analyses are expected to be more comprehensively interpreted. Take-home messages such as: what kind of acceleration mechanism or feature revealed by the quantitative analyses, what is different from previous experimental or numerical analyses, and what can inspire the future robotic designs, ought to be specified to show sufficient significance for publication in the Proceedings B.
We agree with the referee that the design of the Tunabot Flex *per se* is not the main contribution of this manuscript. Details of the design are given in the White et al. 2021 paper (in press, and available from the Bioinspiration and Biomimetics journal web site), and they differ significantly from the Zhu et al. (2019) version in which tail beat amplitude varied in a somewhat uncontrolled manner with increasing tail beat frequency. We specifically chose the Tunabot Flex as our experimental platform because of its design that ensures that tail beat amplitude stays constant as acceleration increases.

We would like to emphasize that we believe that this manuscript represents a significant new contribution for two key reasons. First, we use a robotic platform to study a fish swimming behavior that has received only very limited attention to date and is very difficult to study in live animals. Second, we present a new approach to the problem of studying accelerating fishes with the ability to quantify kinematics, fluid flow, power consumption, and also to use a validated surface pressure algorithm to estimate the power output into the fluid. We are not aware of any previous study that is able to quantify all these components of organismal movement through a fluid environment.

In response to this suggestion, we have refocused the Discussion section and emphasized the following take-home messages:

- During acceleration of a thunniform swimmer the posterior part of the main body generates considerable amounts of thrust. This highlights that whereas thunniform swimmers are considered to use lift-based propulsion mainly using their tail fin during steady swimming, accelerations from rest are supported by forces generated by accelerating the adjacent fluid. We believe that this is an important new result. This is also consistent with previous computational studies that show that anguilliform swimmers relying on a undulatory pump mechanism outperform carangiform swimmers relying on lift-based propulsion at lower speeds (Iman Borazjani and Sotiropoulos 2009; I. Borazjani and Sotiropoulos 2010). Here we show that the *same* swimmer can use two different mechanisms.

- Whereas in carangiform swimmers during steady-state swimming the anterior part of the body can generate thrust, we only observe drag in our robot model during acceleration. Given that carangiform and thunniform swimming dynamics are generally comparable, this indicates that thrust is produced differently along the body for acceleration and steady-state swimming in thunniform swimmers.

2. My biggest concern on the methodology is the calculation of the force on the robot body. The pressure field obtained by PIV is 2D. According to the methodology introduced in Thandiackal and Lauder, 2020, the surface force was calculated based on the assumption that pressure is equally distributed along the depth of the body, and thus that forces could be obtained by multiplying the computed pressure at the mid-section of the body with corresponding surface area slices perpendicular to the midline. Here, I doubt if this assumption is valid. Because (1) from head to tail peduncle, the tuna cross-section is relatively round, while assuming pressure as equally distributed along the depth of the body requires high ratio of height to width; (2) according to the study of Borazjani and Daghooghi, 2013, since the tuna is using lift-base thrust mechanism, the leading edge provide essential thrust, while in the 2D PIV, the no leading edge is measured, (3) last but most important, as shown in Fig. 2B, the PIV measures the surface pressure until the end of "fork length " but as the main thruster of the tuna, the lunate tail corresponds to no surface area in PIV and is out of the pressure analysis.

We thank the referee for pointing out this important issue. We have refocused our analysis now on the main body (from head to peduncle joint) of the tunabot and removed the force estimations at the tail fin. In a new analysis stimulated by this comment, we separately analyzed the lunate tail fin and its imposed dynamics (see supplementary material where we added the new results). For this purpose, we quantified the flow field around the tail fin obtained using PIV at the quarter span (as opposed to the half span through the midbody). As expected and pointed out by the referee, we found a strong leading edge vortex that contributes to significant thrust at the tail that is not captured in our previous PIV at the half span through the midbody. With this insight, we decided to exclude the force computation for the tail fin from our analysis. We acknowledge that the force computations for the main body rely on the assumptions mentioned by the referee and highlight this more strongly in the manuscript now.

As an aside, the point raised by the referee is an important one that we have actually considered previously in our paper that validated the Dabiri pressure algorithm approach (Lucas, Dabiri, and Lauder 2017). In that paper, Figure 1 shows two simple fish body shapes that we tested under conditions using our flapping foil robotic system where we can measure the forces generated during swimming directly, and compare with those estimated using the pressure algorithm. Figure 1 in that paper compares a rectangular body shape with no tail to a shape with a tail where analyses at the mid body region would be expected to miss 3D effects of flow around the tail region. We concluded then that "During the 3D tests, the agreement between the measured force and torque values from the flapping-foil system and the predictions based on the pressure fields was, in the majority of cases, exceptional." So, at least for the two shapes considered in that paper, the 3D effects of tail shapes was minimal on overall force production. However, for high-frequency motion of the lunate tunabot tail where strong leading edge vortices form, we might expect a larger tail contribution even during acceleration from rest where development of the LEV can take time and delay the contribution to thrust.

As a result of thinking about this some more, we plan to do future post-Covid experiments to specifically address the development and contribution of the LEV to acceleration from rest by visualizing flow on the tail in a very zoomed-in view, but have refocused this manuscript around the body flows and thrust and drag forces where our data are consistent and show interesting patterns.

3. I have a concern on the statistical analyses in the paper. According to Table 1, as the duty-cycle increases, it appears that the degree of data dispersion also increases. At duty-cycle = 45%, between the two measurements, the difference of two acceleration results (0.91 plus–minus 0.14) has a 30% range. Based on this degree of data dispersion, I think size of samples are insufficient. At duty-cycle = 90%, the data dispersion may be much significant, and a single measurement is definitely insufficient.

We agree with the referee that our sample sizes are small, particularly at the 95% duty cycle. Unfortunately we were not able to replicate at the fastest accelerations (and cannot enter the lab with collaborators now to do more work), but we have limited our conclusions to those which are supported across all the tested accelerations. For example, when we present our conclusions (1) that the head region experiences drag forces and does not display head "suction thrust" and (2) that the body itself (surprisingly) contributes substantially to thrust during acceleration from rest, these statements are true for *all* of the tests conducted without exception, even though our sample sizes for any one acceleration are low.

In addition, we devoted considerable effort in the White et al. (2021) paper on steady swimming in this exact same Tunabot Flex to replicating data each duty cycle tested (which match the ones tested here) and assessing and presenting variation. The variation within tested duty cycles was extremely small compared to the differences in swimming speed, power consumption, and kinematics that we measured among the different duty cycles. As a result, we are confident that the considerable differences we see in acceleration among duty cycles is valid, and examination of Fig. 3A shows just how different the different accelerations were.

4. In the last paragraph of Page 14, Line 305, the author argues that a large areas of negative pressure consistently behind the accelerating robot is discovered. I could not agree that this is a new discovery. To my knowledge, negative pressure behind swimming fish should be normal phenomenon. Strong vorticity is associated with low pressure, and the existence of low pressure is the condition to maintain the vertex structure. Since fish forms vertex street behind, there must be negative pressure behind the fish. In Fig.4, if we compare the positions of the vorticity cores (both clockwise and anticlockwise) in the 4th row with pressure field of the last row, we may notice the negative pressure zones basically overlap the high-vorticity-magnitude zones. If the authors argue the acceleration is a factor for the low pressure zone, more rigorous analysis against pressure field of a steady swimming fish is required.

The referee is absolutely correct. This is not a new discovery and we apologize that the wording indicated this. We certainly know from our past work on flow visualization behind swimming fishes and the extensive literature on this that there will be low-pressure in vortex cores generated by the fish wake. In our revision we still point out the regions of negative pressure because we think that this is an important characteristic of the wake. However, we have rephrased (especially removing the word 'discovered') the explanations referring to the underlying vortices as the main reason for this observation.

5. In Line 379 to 383. The authors argue that the absence of "head suction" during the robot linear accelerations suggests that a change in hydrodynamic function of the head region must occur during the transition from initial acceleration to steady swimming. The basis for this argument seems insufficient, unless the "head suction" is observed in steady swimming of thunniform swimmers. As the author mentioned in Line 379, the kinematics, morphology and head oscillation of anguilliform swimmer is dramatically different from thunniform swimmer, the absence of "head suction" may simply because the thunniform swimmer could not generate it.

We thank the referee for this comment. We have rewritten this section and put less emphasis on the lamprey acceleration. We also now support our argument more strongly by referring to Lucas et al. 2020, where it was shown that the anterior part of the body generates thrust during steady swimming in carangiform swimmers (trout and bluegill). Although our robot emulates a thunniform swimmer, we think that the swimming kinematics are comparable and steadily swimming tuna likely rely on similar mechanisms during steady swimming.

In addition, we have a large ongoing collaborative project on the computational fluid dynamics of thunniform locomotion. One paper on this has appeared recently (Wang et al. 2020). This paper illustrates (with one whole-body figure in the supplemental material) that head oscillation in thunniform swimmers generates "head suction" that contributes to thrust. High-quality kinematics on live swimming tuna are rare, and in the 2019 paper on the original Tunabot (Zhu et al., 2019) and also in the White et al. (2021) paper on the Tunabot Flex we present new data on thunniform swimming kinematics that show clearly that head oscillation occurs during normal rectilinear locomotion and that similar head oscillation occurs in a related species (mackerel). Based on the recent literature on head-suction thrust in swimming fishes, we certainly expect that these patterns of head oscillation would generate head-suction during steady swimming. Thus, we find it particularly interesting that we do not see this here during acceleration from rest.

6. The initial power peak (Fig.5 upper panel) is highlighted in the abstract as a main finding. I agree with the authors' explanation in Line 444-446, the initial power peak seems a characteristic of the DC motor. Then, if the initial power peak is a universal feature of the DC motor, rather than a feature caused by fish/robot swimming hydrodynamics, should it be considered as a major finding?
We agree with the referee and have removed the corresponding sentence from the abstract. We do not consider this as a major finding. We also shortened the explanations regarding the power peak in the discussion and focused on the characteristics of the DC motor, as we think this is the main contributor of the initial power peak.

7. According to Fig. 5 and the text (Line 331), a phase shift exists between the electrical power and the mechanical power, which seems interesting and important, but didn't receive further explanation. My explanation is, in undulation, the flexible part of the robot may store elastic potential energy and release with a time delay. Please confirm if this is reasonable.
The referee's comment has stimulated some thinking by the authors! Due to the design of the robot, we do not believe that for the main body segments that elastic potential energy could be stored. However, the design of the caudal peduncle joint includes a single, internal spring that provides a torsional restoring force to the joint which is needed to ensure that the tail moves to a neutral midline position when no fluid forces are exerted on it (for example, during sitting at rest). This also prevents the tail from starting at a non-neutral position during our experiments, and mimics the longitudinal spring-like tendons in live tuna. So we conclude that the referee's suggestion may well be correct for the peduncular joint and now we wonder just how much this contributes to the phase lag. Our mechanical power measurements in the fluid are focused on the body region itself and not the tail but it could still be true that the peduncular springs are influencing flow and resulting in the phase lag. We need to think about this some more, and could do future experiments with different peduncular spring constants to see if we can alter the phase lag to address this question specifically.

8. According to the design shown in Fig. 1. There are gaps at the body joints, regulating the curvature of the body. Is the gap open to water? How much hydrodynamic influence could the gaps result during undulation?
Thanks for this question, and we have conducted some separate zoomed-in views to examine the flow in these "gaps" directly. Also, these flooded gaps and related hydrodynamic influences are, among other factors, investigated in White et al. 2021 by comparing robot configurations with variable number of joints (2 DOF (degree of freedom), 3DOF, 4DOF) holding tail beat amplitude constant. It was shown that e.g. the 3DOF and 4DOF

configurations performed similarly regarding swimming speeds for a given frequency, and that the 2DOF configuration reached considerably lower speeds. Furthermore, when accounting for the cost of transport, the 4DOF configuration significantly outperformed the less flexible configurations. This shows that adding more segments and thus gaps does not reduce performance. In fact, the increased body flexibility from additional segments greatly improved swimming performance.That previous study also provides results for drag measurements to demonstrate how drag force differences between configurations are negligible despite the different number of gaps present.

In addition, from our flow visualization experiments we observed small jets of water directed out of the robot at instances when the gaps were closing. There is also a complementary effect where water gets sucked in immediately after when the gap opens up again. So we believe that there is little net effect on robot performance. In our work here we neglect these events due to their short time span and low magnitude. This is implemented using temporal filtering of the velocity fields. A more detailed analysis of these gap dynamics are planned for the future.

As an aside we investigated using a stretchy lycra-type "skin" over the robot (as in the original Tunabot), but our experience with this showed that it was very hard to control exactly how tightly to stretch the skin and that the skin changed its tension as experiments proceeded. So we elected to not include a skin over the gaps, and in light of the White et al. (2021) results and our flow visualization results we believe that the gaps have minimal effect on acceleration performance. In the appendix of White et al. (2021), we also discuss through a comparison between different tunabots that a flexible skin may actually be detrimental to performance depending on the design execution, which is contrary to the commonly held notion that flexible materials are better and necessary for high-performance, bio-inspired systems.

We incorporated a small section in the text (methods: first paragraph), where we now explicitly mention the dynamics around the gaps and the temporal filtering.

Minor points:

9. Method, first paragraph, Line 108.

"The Tunabot Flex was preceded by the original Tunabot (Zhu et al. 2019)."Could the authors briefly explain the difference or improvement of current robot here?

We have added text to the manuscript to indicate that the "Tunabot Flex improved the mechanical and bio-inspired designs of its predecessor, including variable body flexibility, whilst utilizing the same external dimensions and motor." As noted above, we removed the skin and improved the spring-like behavior of the caudal peduncle, and added the segments to generate body flexibility and greatly improve swimming performance. A complete discussion of differences and improvements between tunabots is provided in the appendix of White et al. (2021). Overall, the Tunabot Flex platform studied here swims steadily nearly twice as fast as the original Tunabot.

10. Fig.1 caption, Line 119.

“The robot consists of three freely-rotating body joints”. “freely” is not accurate since the rotational angles are restricted.

Corrected in the revised manuscript, we removed “freely-rotating”. Thanks.

11. Method, third paragraph, Line 140.

“The flexible power cables suspending the robot within the flow tank did not restrict acceleration from rest.” This sentence is unclear.

We have clarified this in the revised manuscript. The robot was free to move forward while suspended and the very short time course over which we conducted our acceleration analyses means that very little change in the angle of the supporting cables occurred. We have added more explanations about this in the methods sections “experimental setup” and “particle image velocimetry”.

12. A pair of parentheses seems missing in Eq.1.

Thanks for catching this, corrected in the revised manuscript.

13. As shown in Eq.2, this study assumes a constant acceleration from zero initial speed. Since during forward acceleration, the net thrust (also the acceleration) decreases to zero as the fish is sufficiently accelerated. Please emphasize in the text that the analysis based on this constant acceleration assumption is limited to small time interval from zero initial speed.

Thanks, yes. This is a key point, and we have added text to the manuscript to emphasize this point (in the methods: “Forward direction, acceleration, and lateral displacement”).

14. Please define “initial electrical power peak”and “secondary electrical power peak”.

This is an important point to clarify and we have done this in the revised manuscript.

15. Please provide the definitions of electrical and mechanical powers in the manuscript.

Done in the revised manuscript.

16. Discussion, first paragraph, first sentence. “In order to steadily swim, fish must first accelerate from rest.” This sentence has a logic error, since “from rest” is not a necessary condition.

We have deleted the “from rest” in the revised manuscript.

17. Discussion, first paragraph, third sentence. “Despite this commonplace and necessary fish maneuver, nearly all previous analyses of linear fish acceleration consider accelerations while transitioning between steady swimming speeds as opposed to accelerations from rest.” I could not understand.

Apologies for the confusing sentence! We have edited this sentence and hopefully it is clearer now. We were trying to say that previous studies of fish accelerations consider changes in speed from one steady swimming speed to another. Our study focuses on acceleration from zero velocity, at rest. There is a necessary acceleration when fish start to move.

18. Page 18, second paragraph, line 388. Do "these experiments" mean the experiments in this manuscript? Please clarify.
Thank you. Clarified in the revised manuscript.

19. Please check and unify the format in references, especially the usage of "Pt".
Thank you. Corrected in the revised manuscript.

Responses to Referee 3:

Many of my comments have to do with the methods and the assumptions made there. Some of these may have resulted in conclusions that could be a result of noise from the system rather than the overall mechanics. I think that there should be more focus on what may be system specific quirks rather than broad conclusions about fish swimming overall.
We appreciate that the reviewer is concerned with "noise" in the system, but we believe that our experiments show that the system is extremely robust. The White et al. (2021) paper describes the basics of this platform in detail, and the tests that were done to quantify performance. We made a special effort in this manuscript to draw significant conclusions that hold across all the acceleration magnitudes that we induced, and indeed we were able to obtain highly consistent results. And these results address two points not at all well studied in fish locomotion: acceleration from zero velocity, and how thrust is generated by thunniform swimmers during acceleration behaviors.

Lines 78-81: I suggest list a few conclusions from these other studies using robotic platforms to study acceleration. How is Tunabot Flex different from these previous studies? How will this new system lead to new conclusions?
We thank the referee for these suggestions and included the main conclusions from the listed previous robotic studies on acceleration in the main text. At the same time we added more explanations on how Tunabot Flex is different from these previous platforms focusing on its thunniform shape and what new lines of research questions we can address with this new robot.

Line 126: Proc B is a journal that has a wide readership. It might be useful to quickly define some of your variables here like "duty cycle."
Thanks for this suggestion. We now clearly define "duty cycle" in the text.

Line 139: Is there some evidence that 2-3 tailbeats is enough to reach peak acceleration and then decline? For steady swimming, the standard seems to be 3-5 tailbeats to get a good idea of what is going on. To me, 2-3 sounds like not enough to get the details of a complex behavior such as acceleration. This could be very different since we are looking at a robot and not a live fish, but some explanation or citation describing how 2-3 tailbeats is sufficient would be helpful here.

Thanks for this question. As you also point out, the general dynamics of acceleration from rest involve an increase of acceleration from zero in a first phase and decrease of acceleration towards (close to) zero in a second phase once steady cruising speed is reached. In our study here, we focused on the first phase and therefore analyzed the first 2-3 tail beats because the center of mass (COM) forward speed showed a clear increase during this period. More precisely, we tested the model of constant acceleration for this phase by looking at the linear regression and the corresponding fit. Our results indicate that it is a good model (R^2>0.96) and that therefore acceleration in the first phase can be considered constant.

We adapted the corresponding explanations in the METHODS ("forward direction, acceleration, and lateral displacement") and the first paragraph of the RESULTS and hope that this is more clear now.

Line 141: After looking at the video, I would like a more detailed description about how the authors determined this vertical swinging as insignificant. It is a lot of motion (7mm) over such a short distance (70mm), so I think it needs to be justified a little. We are looking at a different place along the robots' body at each frame of the trial. Is there evidence that the hydrodynamics at +/- 5% of the initial vertical placement are the same? Also, I would keep units the same in the last sentence of this paragraph (0.007m, 0.07m or 7mm, 70mm).

Thank you for this comment. It is important that the mid section of the robot stays in the laser sheet for the first 2-3 tail beats that are analyzed. An elevation of 7mm is within the limits that ensures that the mid section of the robot can be captured in the laser sheet. That this is indeed the case is confirmed by looking at the leftmost column in Fig. 4 (velocity field): The robot outline profile is consistently maintained across the acceleration maneuver. If the robot mid section had been outside the laser sheet we would notice gaps filled with fluid particles starting to appear at the peduncle, keeping in mind that we recorded a ventral view and the robot is lifting up because of the cables.

To make this point more clear, we added this explanation to the text in addition to the quantitative distances which we also adapted to be consistent in units.

Line 203: Are you assuming a constant acceleration for the entire 2-3 tailbeat trial? Or just between each time step? If over the entire trial, do you have evidence that the acceleration is constant? If so, I would suggest citing it here. [I see that you addressed this at line 234. Was this acceleration measured a different way? I am confused about which method you used to confirm your model assumption?]

Thank you for this comment. We agree that our wording and explanations were not clear enough and apologize for the confusion. Please check our response above to your question regarding the reasoning behind the 2-3 tail beats that we used to analyze the acceleration of the Tunabot. In summary, we tested a *model* of constant acceleration and found a good fit

(R^2>0.96), which led us to the conclusion that acceleration can be considered constant in the first phase. We did not *assume* constant acceleration *a priori*, but rather wanted to test whether or not constant acceleration was actually observed by the tunabot accelerations.

We adapted the corresponding explanations in the METHODS ("forward direction, acceleration, and lateral displacement") and the first paragraph of the RESULTS and hope that this is more clear now.

Line 373: I realize that the only other study of acceleration from rest is in the lamprey, but it might be more useful here to compare your kinematics with accelerations between swimming speeds. You can use previous studies on Tuna or Bluegill, as both are more similar morphologically to Tunabot. It might even be useful to get a couple of videos of bluegill accelerating from rest and do a simple kinematic analysis for comparison. Nothing as in depth as what is presented here, just head and tail amplitudes over time would be a good enough comparison for the discussion. The lamprey is just so morphologically different it does not seem like a good comparison.

We thank the referee for this suggestion. Please check our response to comment 5 of referee 2. In summary, we reduced the comparison to lamprey and focused more on a comparison to steadily swimming carangiform swimmers and the observed thrust generation in the anterior part (Lucas, Lauder, and Tytell 2020). The suggestion for future post-CoVid research on bluegill starting from rest is a good one, and we hope to undertake a future study of linear accelerations from rest in several bony fish species of different body types.

Line 381: Does the sentence starting with 'Such "head suction" …" refer to the lamprey or the Tunabot?

Thank you for catching this lack of clarity. We have rephrased parts of this paragraph accordingly.

Line 419: I worry that some of this has to do with the fact that the body is segmented at the tail. Looking at the PIV video in the supplementary data, I can see small jets of particles coming from between each segment when the robot bends its tail. This would have a seemingly large effect on the lateral forces and the pressure field calculations. Was anything done to reduce the noise from these rapidly closing segments? If not, how can you separate your results from the noise? I think there is a need for some discussion about this.

We certainly did think about the effects of the gaps in the robot on our flow visualization data, and we used temporal filtering of the velocity fields to separate our results from the noise (the jets appear only over a short period of time and shortly after water gets sucked back in as the gaps open up again). Please also check our answer to referee 2 for comment 8. We conducted some separate zoomed-in view experiments of flow around the body during steady swimming to examine the flow in these "gaps" directly. Also, the hydrodynamic influence of these gaps was, among other factors, investigated in White et al. 2021 by comparing robot configurations with variable number of joints (2 DOF (degree of freedom), 3DOF, 4DOF). It was shown that the 3DOF and 4DOF configurations performed similarly regarding swimming speeds for a given frequency, and that the 2DOF configuration reached considerably lower speeds. This shows that adding more segments and thus gaps does not reduce performance, and that the effect of the additional segments is highly beneficial to swimming speed, despite the presence of the gaps.

In addition, from our flow visualization experiments we observed small jets of water directed out of the robot at instances when the gaps were closing. However, there is also a complementary effect where water gets sucked in immediately after when the gap opens up again. So we believe that there is little net effect on robot performance. In our work here we neglect these events due to their short time span and low magnitude. This is implemented using temporal filtering of the velocity fields. A more detailed analysis of these gap dynamics are planned for the future.

As an aside we investigated using a stretchy lycra-type “skin” over the robot (as in the original Tunabot), but our experience with this showed that it was very hard to control exactly how tightly to stretch the skin and that the skin changed its tension as experiments proceeded. So we elected to not include a skin over the gaps, and in light of the White et al. (2021) results and our flow visualization results we believe that the gaps have minimal effect on acceleration performance.

We incorporated a small section in the text (methods: first paragraph), where we now explicitly mention the dynamics around the gaps and the temporal filtering.

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