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14. ABSTRACT

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RPPR Final Report
as of 12-May-2020

Agency Code:

Proposal Number: 73559EGCF

Agreement Number: W911NF-18-1-0423

INVESTIGATOR(S):

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Report Date: 31-Oct-2019

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Final Report for Period Beginning 01-Aug-2018 and Ending 31-Jul-2019

Title: Mechanisms and principles of extreme energy flow in organismal and synthetic movement

Begin Performance Period: 01-Aug-2018

End Performance Period: 31-Jul-2019

Report Term: 0-Other

Submitted By: Sheila Patek

Email: snp2@duke.edu

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Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees:

STEM Participants:

Major Goals: Examine the conceptual foundation of impulsive movement, probe the current technical barriers to key measurements and analyses, and establish 5-10 year vision for this field. Involve an interdisciplinary, international and career-spanning group of scientists and engineers.

Accomplishments: See attached PDF.

Training Opportunities: Nine graduate students and eight early career faculty participated and presented in the workshop. Workshop participants also included a substantial proportion of underrepresented groups in science and engineering.

Results Dissemination: Nearly forty individuals participated in the workshop and many of them continued on to write symposium articles on this topic in the journal issue that accompanied the symposium (not sponsored by this workshop grant).

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: Co PD/PI

Participant: E. A. Azizi

Person Months Worked: 1.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)

RPPR Final Report
as of 12-May-2020

Participant: Suzanne Cox
Person Months Worked: 1.00
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Funding Support:

Participant Type: PD/PI
Participant: S. N. Patek
Person Months Worked: 2.00
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Funding Support:

Participant Type: Graduate Student (research assistant)

Participant: Sathvik Divi
Person Months Worked: 6.00
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Funding Support:

Participant Type: Faculty
Participant: Mark Ilton
Person Months Worked: 1.00
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Funding Support:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)

Participant: Sarah Longo
Person Months Worked: 1.00
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Funding Support:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)

Participant: Jeff Olberding
Person Months Worked: 1.00
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Funding Support:

RPPR Final Report
as of 12-May-2020

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)

Participant: Ryan St. Pierre

Person Months Worked: 1.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Participant Type: Faculty

Participant: Gregory Sutton

Person Months Worked: 1.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

WORKSHOP: Playing with power: Mechanisms and principles of extreme energy flow in organismal and synthetic movement

This workshop (Fig. 1) brought together our MURI team research effort and associated recent Science paper to the broader scientific and engineering communities. The world of extremely small, high acceleration systems that can be used repeatedly and repeatably remains iconic in biology and out of reach in synthetic systems. Through the MURI team effort, we have established a broad conceptual, mathematical and experimental framework that is enabling a community-wide, multidisciplinary effort to measure, characterize and synthesize these systems in a coherent and forward-looking way. However, in order to do this, we need to engage the community to train, discuss and plan this effort. This workshop brought together 30 multidisciplinary researchers to learn about the conceptual framework and establish a general plan to push forward a visionary and coherent approach to studying these systems. The workshop was held on the day preceding the largest comparative biomechanics conference (Society for Integrative and Comparative Biology) that already attracts a large number of interdisciplinary researchers. It also tied in directly to a scheduled symposium that addressed power amplification in a range of biological systems.

MURI WORKSHOP - JANUARY 3, 2019, TAMPA, FL



"This was an excellent workshop and I learned a lot from attending. It was really great to get engineers and biologists together because it was useful to hear how the two fields approach similar topics and to help foster new collaborations."

Figure 1. Hands-on workshop and presentations with 30 participants plus 9 MURI team presenters, January 3, 2019, Tampa, FL. The workshop included the following sessions:

- (1) Dr. Sarah Longo, Duke University: *History and current use of the term power amplification.*
- (2) Prof. Sheila Patek, Duke: *Overview of spring actuation, latch mediation.*
- (3) Prof. Mark Ilton, Harvey Mudd; Dr. Jeff Olberding, UC Irvine: *Transition between spring v. motor launching, relevance of size for material behavior and elastic behavior, tunable space of outputs.*
- (4) Dr. Suzanne Cox, Penn State; Sathvik Divi, Carnegie Mellon; Dr. Ryan St. Pierre, Carnegie Mellon: *Scaling and integrated tuning through physical models.*
- (5) Prof. Mark Ilton, Harvey Mudd; Prof. Manny Azizi, UC Irvine: *Advances in studying biological materials for springs.*
- (6) Sathvik Divi, Carnegie Mellon; Dr. Ryan St. Pierre, Carnegie Mellon: *How to measure latch mediation, identify likely latches based on morphology, assess latch quality, and test hypotheses through modeling.*
- (7) Dr. Greg Sutton, Bristol: *Trap jaw ants as a case study for finding and quantifying springs.*

SICB 2019 Workshop

Principles and analysis of small, high acceleration systems in biology and synthetic systems

January 3, 1-5 pm, Tampa Convention Center, Room 18

Small, high acceleration systems that can be used repeatedly and repeatedly are iconic in biology and still largely out of reach in synthetic systems. This workshop will bring together multidisciplinary, multi-stage researchers to learn, debate and plan a visionary and coherent approach to studying these systems. We will examine the conceptual foundation of small, fast movement and probe the current technical barriers to key measurements and analyses.

Workshop schedule:

1:00 - 1:30 pm Cross-disciplinary connections and common language

LEARNING OUTCOME: Meet colleagues and establish a common set of features, definitions and performance parameters of small, high acceleration systems in biology and engineering.

SMALL GROUP WORK (15 min): In groups of three, each participant has 2 minutes to show slides of their focal systems or systems that they find particularly fascinating in biology or engineering. State the performance parameter (i.e., the parameter that best expresses what their system is doing or is used for) and the units.

FULL GROUP DISCUSSION (15 min): Diversity of and definitions for small, fast systems based on small group definitions.

1:30-2:00 pm The power of a classic paradigm

LEARNING OUTCOME: Understand how the “power amplification” paradigm has defined the study of small, fast *biological* systems and how this contrasts and possibly constrains interdisciplinary conceptualization beyond biology.

PRESENTATION (10 min - **Dr. Sarah Longo, Duke University**): History and current use of the term power amplification.

SMALL GROUP WORK (10 min): *Focal questions: Are we limited by this current paradigm (power amplification)? If you use a different term other than “power amplification” for this set of phenomena, what is it and why?*

FULL GROUP DISCUSSION (10 min)

2:00-3:00 pm Latch-mediated spring actuation

LEARNING OUTCOME: Explore a new paradigm of studying small, fast systems from the perspective of spring actuation and latch mediation.

PRESENTATION (10 min - **Prof. Sheila Patek, Duke**): Overview of spring actuation, latch mediation.

PRESENTATION (15 min - **Prof. Mark Ilton, Harvey Mudd; Dr. Jeff Olberding, UC Irvine**): Transition between spring v. motor launching, relevance of size for material behavior and elastic behavior, tunable space of outputs.

HANDS-ON CHALLENGE (35 min - **Dr. Suzanne Cox, Penn State; Sathvik Divi, Carnegie Mellon; Dr. Ryan St. Pierre, Carnegie Mellon**): Scaling and integrated tuning through physical models. Hands on challenge of assumptions: 1) Stiffer springs always store more energy, 2) Latches are ideal, 3) Energy in = energy out.

3:00-3:20 pm

BREAK

3:20 - 4:20 pm Analysis of small, fast systems

LEARNING OUTCOME: Gain practical knowledge of techniques for studying systems from the perspective of spring actuation and latch mediation.

PRESENTATION (15 min - **Prof. Mark Ilton, Harvey Mudd; Prof. Manny Azizi, UC Irvine**): Advances in studying biological materials for springs.

PRESENTATION (15 min, **Sathvik Divi, Carnegie Mellon; Dr. Ryan St. Pierre, Carnegie Mellon**): How to measure latch mediation, identify likely latches based on morphology, assess latch quality, and test hypotheses through modeling.

PRESENTATION (15 min - **Dr. Greg Sutton, Bristol; Prof. Sheila Patek, Duke**): Trap jaw ants as a case study for finding and quantifying the springs.

DISCUSSION (15 min, whole-group discussion): *What can you suggest for solving these technical problems? What issues are inherent to your systems that we haven't thought about yet?*

4:20 - 5:00pm Return to cross-disciplinary connections and common language

LEARNING OUTCOME: Revise and discuss the common set of features and definitions of small, high acceleration systems in biology and engineering.

SMALL GROUP WORK (20 min): Each small group revises their common definition of fast, small systems in biology and engineering that links their system.

FULL GROUP DISCUSSION AND WRAP UP (20 min)

Workshop Leaders

	Title	Department	Institution	Website
Manny Azizi	Associate Professor	Ecology & Evolutionary Biology	University of CA Irvine	http://azizi.bio.uci.edu/
Suzanne Cox	Postdoctoral Associate	Kinesiology	Penn State	https://sites.psu.edu/zanne/science/
Sathvik Divi	PhD Student	Mechanical Engineering	Carnegie Mellon	https://www.meche.engineering.cmu.edu/faculty/bergbreiter.html
Mark Ilton	Assistant Professor	Physics	Harvey Mudd College	https://physics.hmc.edu/faculty/ilton/
Sarah Longo	Postdoctoral Associate	Biology	Duke University	https://pateklab.biology.duke.edu/users/sarahlongo
Jeff Olberding	Postdoctoral Associate	Ecology & Evolutionary Biology	University of CA Irvine	http://jpolberding.wixsite.com/jpolberding
Sheila Patek	Associate Professor	Biology	Duke University	www.thepateklab.org
Ryan St. Pierre	Postdoctoral Associate	Mechanical Engineering	Carnegie Mellon	https://www.meche.engineering.cmu.edu/faculty/bergbreiter.html
Greg Sutton	Royal Society University Research Fellow	Biological Sciences	University of Bristol	http://www.bristol.ac.uk/biology/people/gregory-p-sutton/overview.html

Participants

Participant	Title	Department	Institution	Website
Chris Anderson	Assistant Professor	Biology	University of South Dakota	http://www.chamaeleonidae.com
Philip Anderson	Assistant Professor	Animal Biology, PEEC	University of Illinois Urbana-Champaign	http://www.philipslanderson.com/
Henry Astley	Assistant Professor	Biology & Polymer Science	University of Akron	http://gozips.uakron.edu/~hastley/
Saad Bhamla	Assistant Professor	Chemical & Biomolecular Engineering	Georgia Tech	https://www.bhamla.gatech.edu/
Elio Challita	BioE Student	Chemical & Biomolecular Engineering	Georgia Tech	http://bioengineering.gatech.edu/people/elio-challita
Kaijung Chi	Professor	Physics	National Chung Hsing University, Taiwan	http://lifes.nchu.edu.tw/en_teacher02.asp?url=132&cno=2&tno=43
Steve Deban	Associate Professor	Integrative Biology	University of South Florida	https://sites.google.com/view/debanlab/
Alex Duman	PhD Student	Ecology & Evolutionary Biology	University of CA Irvine	https://alexduman.weebly.com/
Joan Edwards	Professor	Biology	Williams College, Williamstown, MA	https://biology.williams.edu/profile/jedwards/

Jeff Gau	PhD Candidate	Bioengineering	Georgia Tech	http://www.bioengineering.gatech.edu/people/jeffrey-gau
Josh Gibson	PhD Student	Entomology	University of Illinois Urbana-Champaign	https://www.life.illinois.edu/suarez/josh.html
Roi Holzman	Professor	Zoology	Tel Aviv University	https://en-lifesci.tau.ac.il/profile/holzman
John Hutchinson	Professor	Comparative Biomedical Sciences	The Royal Veterinary College	https://www.rvc.ac.uk/about/our-people/john-hutchinson
Sandy Kawano	Assistant Professor	Biological Sciences	California State University	http://sandykawano.weebly.com
Liz Mendoza	PhD Student	Ecology & Evolutionary Biology	University of CA Irvine	http://meel097.wixsite.com/elizabethmendoza
Urike Muller	Professor	Biology	Fresno State University	http://zimmer.csufresno.edu/~umuller/FBDS/FBDS-home/FBDS-home-welcome.html
Kiisa Nishikawa	Regents' Professor	Biological Sciences	Northern Arizona University	https://in.nau.edu/nishikawa-lab/
Mary Kate O'Donnell	PhD Candidate	Integrative Biology	University of South Florida	https://marykateodonnell.wordpress.com/
Rich Palmer	Professor	Biological Sciences	University of Alberta	https://www.ualberta.ca/science/about-us/contact-us/faculty-directory/rpalmer

Chris Richards	Research Fellow	Paleorobotics	Royal Veterinary College, London, UK	https://www.rvc.ac.uk/about/our-people/christopher-richards
Thomas Roberts	Professor	Ecology & Evolutionary Biology	Brown University	https://www.brown.edu/research/labs/roberts_lab/
Mike Rosario	Assistant Professor	Biology	West Chester University	http://rosariolab.com
Greg Sawicki	Professor	Mechanical Engineering, Biological Sciences	Georgia Tech	http://www.me.gatech.edu/faculty/sawicki
Janneke Schwaner	PhD Student	Biological Sciences	University of Idaho	http://www.webpages.uidaho.edu/McGowanLab/People.htm
Dominic Vella	Professor	Applied Mathematics	University of Oxford, Oxford, UK	http://people.maths.ox.ac.uk/vella/
Aimy Wissa	Assistant Professor	Mechanical Science & Engineering	University of Illinois Urbana-Champaign	http://bamlab.mechse.illinois.edu/
Hannah Wood	Research Entomologist	Entomology	NMNH Smithsonian Institute	https://qrius.si.edu/expert/hannah-wood
Justin Jorge	PhD Student	Biological Sciences	Duke University	https://pateklab.biology.duke.edu/labmembers

MURI Workshop Followup Questionnaire
February 21st 2019, 1:20 pm EST

Q1 - What is your career stage?

What is your career stage?

full professor

Pre-tenure faculty

Assistant Professor

Assistant Professor

Research scientist - permanent position

Assistant Professor

Graduate Student

Graduate student

professor

Professor

Q2 - What aspects of the workshop content did you find to be novel?

What aspects of the workshop content did you find to be novel?

I would say the historical context of the term 'power amplification'. Overall I appreciated the effective presentations, but am familiar with the topic.

Investigation of properties of the elastic structures themselves

New paradigm for thinking about impulsive systems and the importance of the latch.

Break-out sessions with demonstrations

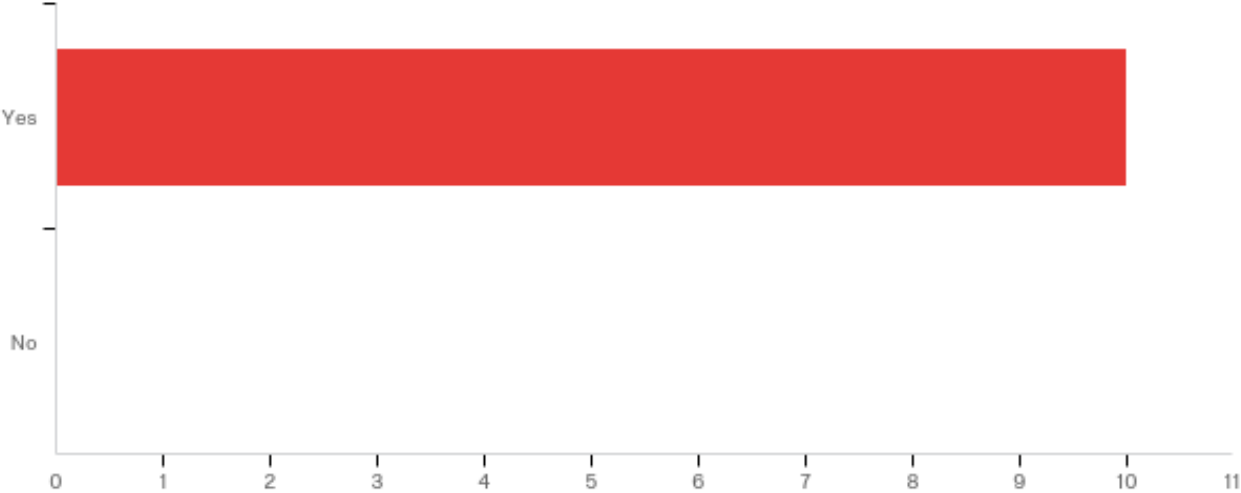
Playing with different models

Particularly the collaborative discussions were valuable

Hands-on demonstrations

The small-group 'speed-dating' exchanges

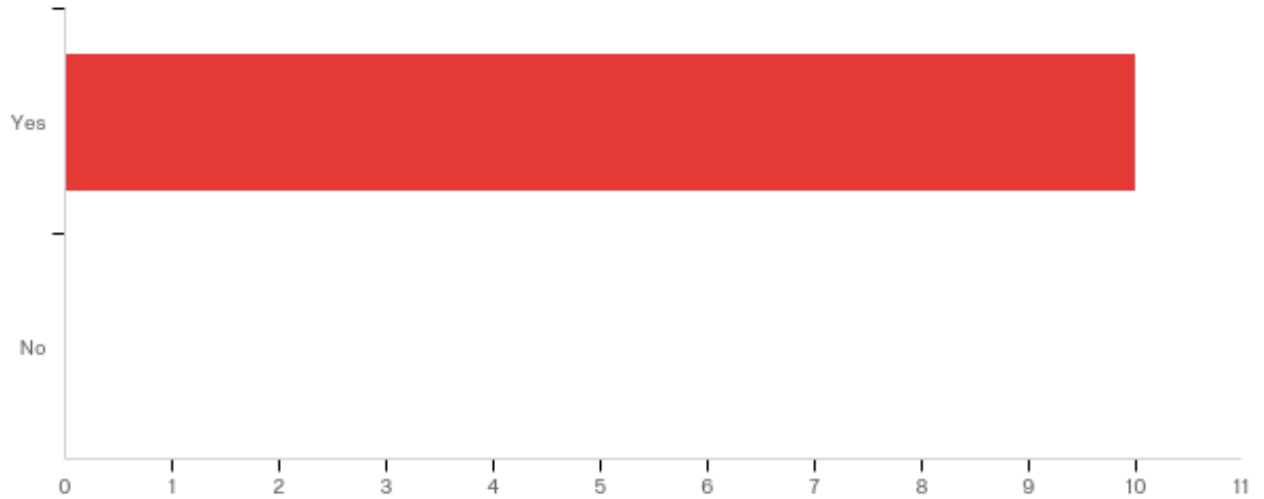
Q3 - Did you interact with scientists you had not previously met?



#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	Did you interact with scientists you had not previously met?	1.00	1.00	1.00	0.00	0.00	10

#	Answer	%	Count
1	Yes	100.00%	10
2	No	0.00%	0
	Total	100%	10

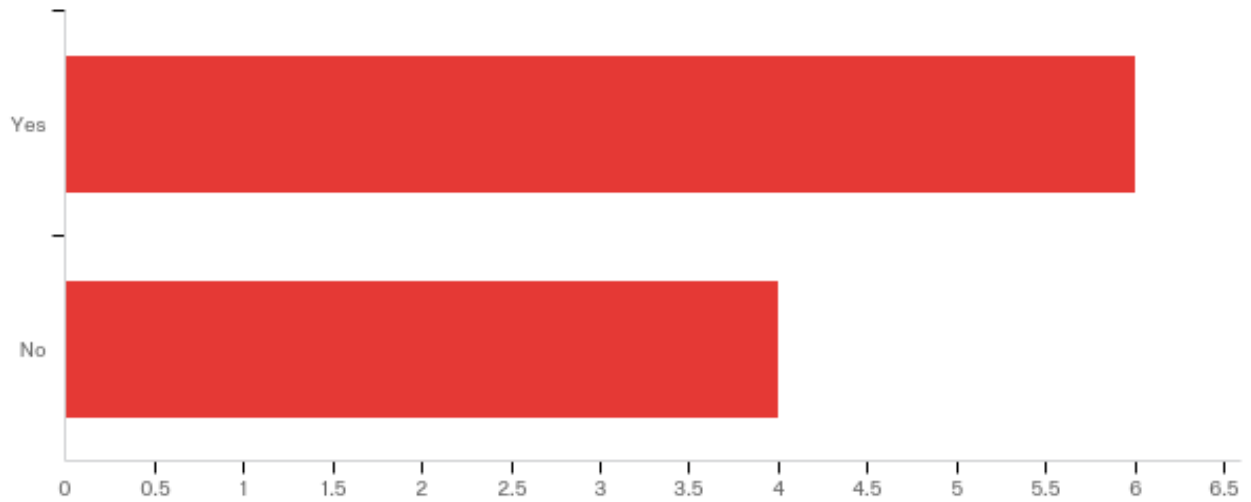
Q4 - Did you interact with scientists outside your field you had not previously met?



#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	Did you interact with scientists outside your field you had not previously met?	1.00	1.00	1.00	0.00	0.00	10

#	Answer	%	Count
1	Yes	100.00%	10
2	No	0.00%	0
	Total	100%	10

Q5 - Did you find the hands-on demonstrations to be useful?



#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	Did you find the hands-on demonstrations to be useful?	1.00	2.00	1.40	0.49	0.24	10

#	Answer	%	Count
1	Yes	60.00%	6
2	No	40.00%	4
	Total	100%	10

Q6 - Comments about the hands-on demonstrations?

Comments about the hands-on demonstrations?

fun for sure, but we were all decompressing a little at that time.

These were fun. I didn't have a good sense of how long to spend at each and never made it to some of them.

It would have been useful to have more time for the demonstrations or more specific tasks for attendees to complete so they could gain more from the activity

I found these demonstrations useful mainly because of the discussion they produced.

They were interesting and helpful in visualizing some core concepts discussed but seemed a bit disorganized at times.

flow from one activity to another was not well managed

I appreciated the effort people put into making them, but didn't find them very helpful for my interests

Q7 - What did you find to be the most useful or important outcome of the workshop?

What did you find to be the most useful or important outcome of the workshop?

I was pleasantly surprised about the wide support around avoiding the term 'power amplification' to refer to energy storage.

Stimulated new thinking about my own work

New ways of thinking about systems that cut across taxonomy.

Discussion of the challenges and misconceptions, and new lines of inquiry that would be valuable to study

Chatting with others and asking questions about methods with other researchers

Networking, getting caught up with the field and understanding the challenges ahead

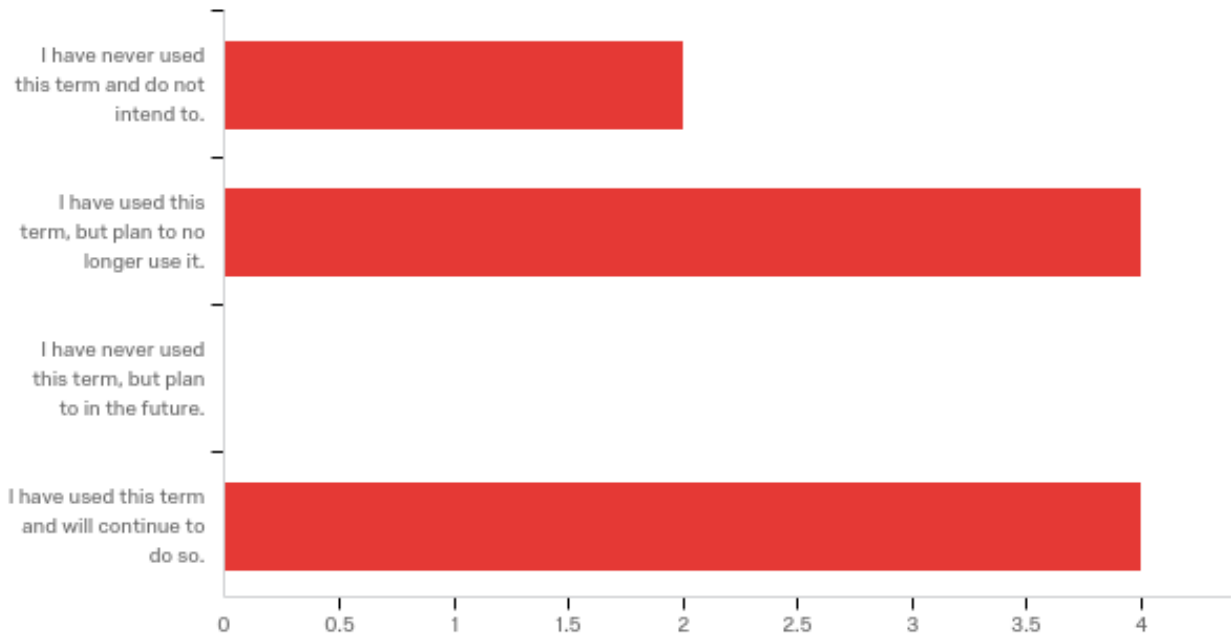
Increased community and networking with scientists working on similar topics and facing similar challenges.

Definitely the interaction with other people studying "PA" mechanisms! I'm based in an entomology lab that's more ecologically focused so getting to talk to biomechanically minded people is always a pleasure! :)

i got a broad overview of the field

Thought-provoking reflection on the term "power amplification"; and now the conundrum of what to use in its place. Also, interaction with people from the engineering side of things.

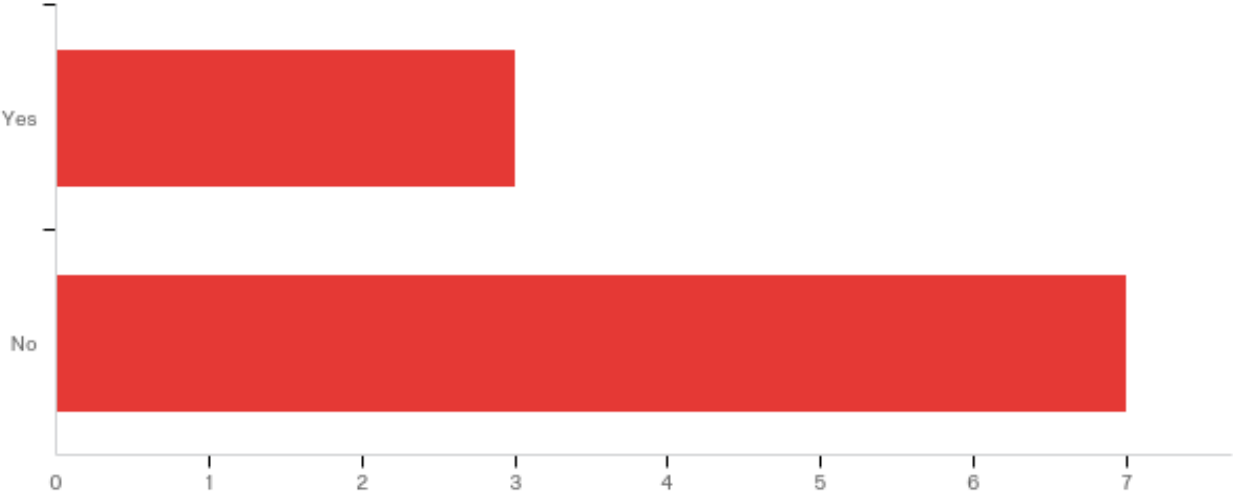
Q8 - Do you use the term "power amplification"?



#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	Do you use the term "power amplification"?	1.00	4.00	2.60	1.20	1.44	10

#	Answer	%	Count
1	I have never used this term and do not intend to.	20.00%	2
2	I have used this term, but plan to no longer use it.	40.00%	4
3	I have never used this term, but plan to in the future.	0.00%	0
4	I have used this term and will continue to do so.	40.00%	4
	Total	100%	10

Q9 - Do you feel there was enough time for discussion during the workshop?



#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	Do you feel there was enough time for discussion during the workshop?	1.00	2.00	1.70	0.46	0.21	10

#	Answer	%	Count
1	Yes	30.00%	3
2	No	70.00%	7
	Total	100%	10

Q10 - Are there any elements of the workshop that you feel could have been improved?

Are there any elements of the workshop that you feel could have been improved?

more time for discussion; less talking at participants; talks were a little too similar and homegenous; the focus was a little narrow on the reading assignment.

Could always use more time for some of the activities, but I feel like that is always the case.

I wish that there had been more time to network with other attendees. The discussions were really helpful so I wonder if it would be useful in future workshops to have people work on a shared Google Docs file to take notes about the discussion, so that it could become a review or opinion paper that could be published.

It was great but I wanted to spend more time brainstorming with others

Hands on activities could be slightly more organized or directed; I would have appreciated more time in discussion groups as it was difficult to juggle introductions and tackling the questions presented during the given time frames.

better organization of demos, always more time for discussion

a couple of the presentations to the whole group seemed too long for their content

Q11 - Would you be interested in attending a similar workshop in the future? Please include your name and suggestions for locations.

Would you be interested in attending a similar workshop in the future? Please include your name and suggestions for locations.

Probably.

Yes. Henry Astley, and paired with SICB is good for me.

Yes. Phil Anderson. I am at the University of Illinois, Urbana-Champaign. We are fairly centrally located in the US and have a very large Engineering College that might have useful facilities.

Yes, Hannah Wood

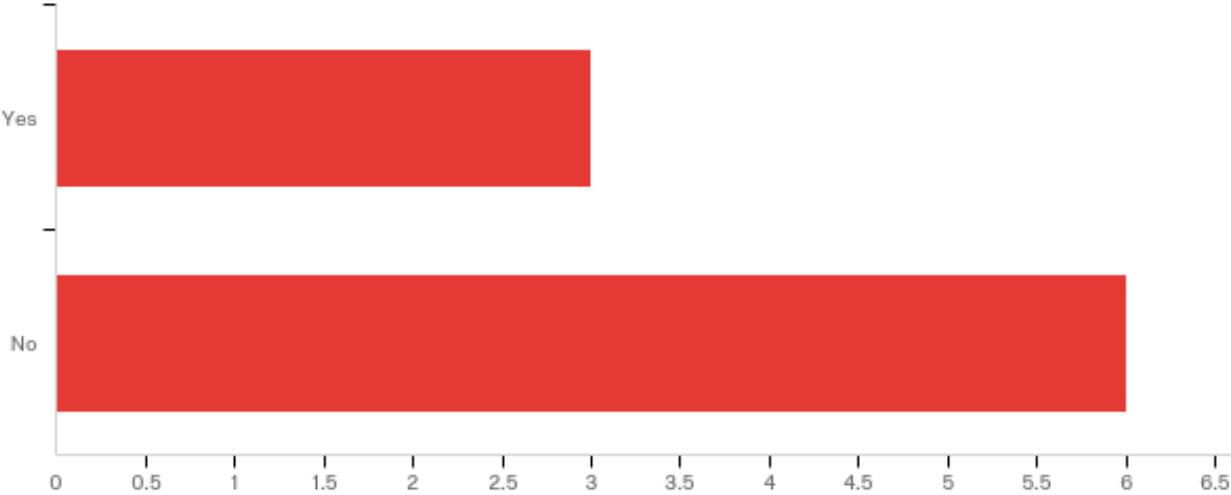
I would love to attend another in Austin or at future SICB's

Absolutely!; Josh C Gibson (UIUC); I'm not particularly picky about locations if travel and lodgings are covered; otherwise whatever is cheaper for me I suppose. Maybe at Duke or another base of operations for the MURI team so we can get a hands-on look at some of the methods and materials you all get to use?

yes - kiisa nishikawa

Rich Palmer; a pre/post-SICB workshop seems like the simplest logistically and economically (easy to add an extra day to a pre-planned trip)

Q12 - Would you be interested in organizing a similar workshop in the future?



#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	Would you be interested in organizing a similar workshop in the future?	1.00	2.00	1.67	0.47	0.22	9

#	Answer	%	Count
1	Yes	33.33%	3
2	No	66.67%	6
	Total	100%	9

Q13 - Any other comments?

Any other comments?

I very much appreciated the purposeful planning of the workshop and many of the conversation prompts. I also enjoyed the way the groups continually got broken up to mix us and get us to talk meaningfully to many people.

This was an excellent workshop and I learned a lot from attending. It was really great to get engineers and biologists together because it was useful to hear how the two fields approach similar topics and to help foster new collaborations. It was also really helpful to have the workshop at the beginning of the meeting, so we had time during the week to continue our discussions with some of the other workshop attendees. Thank you for organizing!