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Behavioral responses of sub-adult Atlantic Sturgeon (Acipenser oxyrinchus oxyrinchus) to electromagnetic and magnetic fields under laboratory conditions

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by

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Abstract

BEHAVIORAL RESPONSES OF SUB-ADULT ATLANTIC STUREGON (*ACIPENSER OXYRINCHUS OXYRINCHUS*) TO ELECTROMAGNETIC AND MAGENETIC FIELDS UNDER LABORATORY CONDITIONS

By Andrew McIntyre III

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Environmental Studies at Virginia Commonwealth University

Virginia Commonwealth University, 2017

Major Director: Greg Garman, Director, VCU Rice Rivers Center

Electromagnetic fields (EMF) produced by high voltage (HV), submarine transmission cables leading from offshore wind energy generation facilities could affect foraging or migratory behaviors of electro-receptive fishes, including endangered Atlantic Sturgeon. However, no published studies have quantitatively evaluated the possible behavioral effects of EMF exposure on sturgeon during residence in coastal waters. This study evaluated behavioral responses by sub-adult Atlantic Sturgeon to electromagnetic and magnetic fields under controlled laboratory conditions. Fabricated EMF generators were used to emulate a range of field EMF conditions that migratory fishes could encounter in proximity to submarine HV sources. Sensor arrays and digital video recorders synoptically quantified EMF conditions and fish behaviors during experimental trials. This thesis will describe the unique, experimental EMF generator/sensor array, present results of the behavior study, and suggest implications of the findings for Atlantic Sturgeon management and conservation. 45 trials were conducted over the course of the study. Study fish were subjected to 3 different field strengths (5µT, 100 µT, 1000 µT), generated using both AC and DC current. Time spent in generated field area, number of passes through the field area, and swimming speed were used to quantify behavioral changes in test subjects. From the data collected and analyzed there was no evidence indicating a change in fish behavior due to the influence of field strengths, field orientations, or field types used during the study.

Introduction

Background

The environmental impacts associated with the use of fossil fuels has created a demand for sustainable, clean energy. Energy technologies based on wind, water, solar, geothermal gradients, and tidal dynamics offer an opportunity to reduce reliance on fossil fuels, but each of these alternative energy approaches must be evaluated for possible negative environmental consequences prior to widespread implementation (Pachauri and Reisinger 2014)

Between 2010 and 2015, European Union nations have invested substantially in offshore wind power to meet growing energy needs (Hernández et al. 2017). The United States, in the last decade, has more than doubled land-based wind energy generation, but until recently has been slow to develop potential offshore wind energy areas (EIA 2017). Offshore wind energy has numerous advantages, over land based wind power generation, that make it an attractive renewable energy source. Offshore seafloors are owned by federal and state government so the construction of wind turbines in these areas does not encroach on private property (Gilman et al. 2016). The initial cost of construction and maintenance for offshore turbines exceeds land-based turbines, but because of topographic differences, average offshore winds speeds tend to be greater and more uniform then those on land (Levitt et al. 2011). Because potential energy generation is based on wind speed, offshore wind turbines are frequently more efficient than land based turbines (Wiser et al. 2015). Another benefit of offshore locations for wind energy production is that the most densely populated areas of the United States are located in coastal regions and with these large populations comes high demands for electricity. Within coastal areas there is limited space for land-based wind electricity generation, but offshore wind sites would be conveniently located to serve coastal areas and a growing demand for electricity (Gilman et al. 2016).

The Atlantic Outer Continental Shelf (OCS) has the potential to support offshore wind infrastructure because of the gradual slope of the area and shallow waters that extend far offshore (Pratt 1968). However, more data on localized wind patterns and marine topography are needed to assess the economic feasibility of offshore wind projects on the OCS (Gilman et al. 2016). To date, the Bureau of Ocean Energy Management (BOEM) has issued commercial leases for the development of offshore wind in the waters off the coasts of Rhode Island, Massachusetts, New Jersey, Maryland, Virginia (Smith et al. 2015).

Plans to construct experimental offshore wind turbines in the Virginia Wind Energy Area (WEA) near Virginia Beach, Virginia were postponed in 2016 (Pietryk 2017). Had this project reached completion, the Virginia WEA would have been the first offshore, wind-powered electric generation facility in the United States Proposals for similar projects elsewhere (e.g. Block Island Wind Farm, Deepwater One South Fork Wind Farm) suggest that—eventually—offshore wind power will be a new energy resource in the US, and could be a step toward reducing carbon emissions; however, turbines and associated infrastructure may pose new and poorly understood threats to marine living resources (Boehlert et al. 2010).

There are numerous potential impacts to marine species linked to the development of offshore wind capacity. Possible threats to marine species include habitat modification, collision risks, noise pollution, and electromagnetic fields (EMF) (Inger et al. 2009). The initial construction of turbine infrastructure can damage benthic communities, and change the marine landscape. Changes to seafloor topography and artificial structure in marine environments can alter the movements of invertebrates, marine mammals, birds, and fish species. New turbine support structures built on previously bare seafloors will act as fish aggregation devices similar to artificial reefs (Langhamer and Wilhelmsson 2009). Increased aggregations of fish species in turn will draw marine mammals and seabirds. Mooring cables and other structures used to support turbines may increase the risk of entanglement for both fish species, and marine mammals (Boehlert et al. 2010). Noise pollution generated from the construction and operation of offshore wind turbines is also a serious concern for marine mammals and fish species because these marine species use their acoustic senses for orientation, communication, and reproduction (Thomsen et al. 2006). One of the least understood effects caused by the operation of offshore wind generation sites relates to anthropogenic EMF.

Magnetic and electromagnetic (M/EM) fields are produced by high voltage (HV) transmission cables leading from offshore wind turbines. Cetaceans, sea turtles, marine invertebrates, and some fish species are examples of taxa known to be responsive to magnetic and electric fields (Kirshvink 1997). Research regarding the response of many marine species to anthropogenic electromagnetic fields is unknown. Anthropogenic M/EM fields could alter behaviors of electro-sensitive fishes including elasmobranchs, eel, and sturgeons (Gill et al. 2014); migratory species may be particularly affected during periods of travel between offshore and nearshore habitats wind energy generation occurs. High voltage transmission cables leading from offshore wind farms may be buried or placed directly on the sea floor. Magnetic or electromagnetic fields generated by HV benthic or buried transmission cables vary greatly in strength depending on cable shielding, burial depth, distance from cable, strength of electric current, and current type (Woodruff et al. 2012). Values of M/EM fields from HV marine transmission cables can range widely from a few microTesla (μT) to 8 milliTesla (mT) depending on the type of HV cable (Woodruff et al. 2012, Cada et al. 2011). Due to the broad range of field strengths that may be generated from submarine transmission cables and the potential impacts that anthropogenic EMF could have on marine fish species, it is imperative that the risks posed by submarine transmission cables are understood before the offshore wind generation industry expands in the United States.

Atlantic Sturgeon Life History

The Atlantic Sturgeon (*Acipenser oxyrinchus oxyrinchus*) ranges from the St. John River, New Brunswick to the St. Johns River, Florida, may live for up to 60 y, and reach lengths > 4 m (Bain 1997). The species is both anadromous and iteroparous and adults return to natal, coastal rivers to spawn (Bain 1997; Jenkins and Burkhead 1994). Heavy commercial harvest, habitat loss, and pollution during the late 19th and early 20th centuries caused serious declines in Atlantic Sturgeon populations throughout its range (Boreman 1997; Murdy et al. 1977). In response Virginia declared a moratorium on recreational and commercial fishing of Atlantic Sturgeon in 1974, and the Atlantic States Marine Fisheries Commission (ASMFC) enacted a moratorium on Atlantic Sturgeon fishing across the entire Atlantic Coast in 1998 (ASMFC 1998). Five genetically distinct population segments (DPSs) of Atlantic Sturgeon are recognized within the United States, and all but the Gulf of Maine population are federally listed as endangered (King et al. 2001). Recent research indicates that Atlantic Sturgeon in the Chesapeake Bay DPS spawn in the freshwater reaches of the James, Rappahannock, and York river systems (Balazik et al 2012). In order to spawn adult Atlantic Sturgeon must return from open ocean habitat and enter coastal bays and rivers before heading upstream. During this phase of their migration, fish might be exposed to EMF from HV voltage transmission cables leading to offshore WEAs.

Sensory Capabilities

Research concerning how EMF-sensitive fish species respond to different ranges of EMF is still evolving, so it is unclear how many species may respond to M/EM fields produced by HV transmission cables (Gill et al. 2014). EMF-receptive fishes are classified into two categories: magneto-receptive and electro-receptive. Magneto-receptive includes primarily teleost fishes, including Elasmobranchii, Chondrostei, Siluroidei, Mormyriformes, and Gymnotoidei (Teeter et al. 1980). Electro-receptive taxa are capable of sensing magnetic fields, but also have ampullary electroreceptors that allow them to detect low frequency electric fields (Bullock 1973). These sensory organs are associated with the lateral line sensory system (Teeter et al. 1980).

Atlantic Sturgeon, ampullary receptor pores are found along the snout and gill covers. The pore openings each have short canals, at the base of which lie ampulla. The canals and ampulla are filled with a gel like material. The ampulla contain microvilli clusters that transmit stimuli to receptor cells located at the base of the ampulla. The ampullary organs detect the potential electrical difference between pore openings and the membrane of receptor cells (Teeter et al. 1980). These sensory organs in sturgeon are very similar in structure to ampullae of lorenzini structures in elasmobranchs, except that sturgeons have shorter receptor canals than elasmobranchs (Hofman 2011). The functional roles of field sensing organs include environmental orientation and navigation, as well as detection of weak bio-electric fields from prey species (Basov 1999, Miller 2004). There are no published studies addressing the possible effects of EMF exposure from offshore HV transmission lines on Atlantic Sturgeon behavior (Tricas and Gill 2011).

Study Objectives

This study sought to quantify behavioral responses by sub-adult Atlantic Sturgeon to generated M/EM fields under controlled (laboratory) conditions, based on the following study objectives. First, the study evaluated proposals (Pietryk 2017) for placing HV transmission cables from proposed wind turbines in the vicinity of known or suspected Atlantic Sturgeon migration corridors near Virginia Beach, Virginia. Using these data, we attempted to emulate the EMF conditions that migratory fishes might encounter near proposed submarine HV sources originating from the Virginia WEA. The second objective was to design, build, and test an EMF generator capable of producing a range of fields comparable to fields that might be experienced by Atlantic Sturgeon under natural conditions and in the vicinity of HV cables. The field generating system was coupled with a magnetometer sensor array to assess field strengths during experimental trials. The third study objective was to expose experimental animals to generated EMFs and measure a suite of simple behaviors under control and test conditions. Results of this study will help managers and policy-makers further evaluate the possible ecological effects of offshore wind energy projects on living marine resources, including the endangered Atlantic Sturgeon.

Methods

Experimental Subjects and Holding Facilities

Sub-adult Atlantic Sturgeon of Canadian origin (age-3; 40 cm, mean FL) were obtained from the University of Maryland’s Horn Point Research Facility and were acclimated at the Virginia Commonwealth University Aquatics Facility (1000 W. Cary Street, Richmond, VA) for a minimum of two weeks before testing. All captive sturgeon were maintained and used in strict accordance with VCU IACUC (AD520115) protocols. A subcutaneous passive integrated transponder (PIT) tag uniquely identified each fish. Up to 20 sturgeon were held in a 600-g circular fiberglass tank supplied with an artificial current. Single, randomly chosen animals were transferred to the experimental flume, a 250-g circular fiberglass tank for control and experimental trials, after which fish were returned to the holding tank. Salinity in both tanks was held at 5 ppt (artificial seawater) and the holding facility maintained a 12:12 hour photoperiod with artificial lighting; water temperature in both tanks was maintained at 18-20° C. Water quality (e.g. ammonium and nitrate) in the aquarium facilities was monitored 3x weekly and maintained at optimal conditions through partial water changes. Fish were fed a commercial diet (Ziegler Finfish Silver) at a maintenance ration of approximately 3% bw/d.

Electromagnetic Field Generating and Monitoring Equipment

High-precision current generators were purchased from a commercial source (ValueTronics) and connected to a coil of 20-gauge magnetic wire wrapped around a rectangular wood frame. The frame was mounted to a circular wood table that allowed researchers to rotate the coil and control field orientation. The coil and frame system was mounted beneath the experimental tank leaving 2.5 cm of space from the coil frame to the tank bottom (Figure 1).

The EMF generator system used was capable of producing fields comparable to those produced by offshore underwater transmission cables. To determine appropriate (M/EM) field strengths used in experimental trials, we evaluated published wind farm proposals (Pietryk 2017) for placing HV transmission cables from offshore wind turbines. Published data on cable type, depth of burial, and the characteristics of the M/EM fields likely to be generated by proposed HV cables were used to emulate experimentally the EMF conditions that migratory fishes might encounter in the field (Guidi and Fosso 2012; Green 2007; Kirby et al. 2002).

Project collaborators from Virginia Commonwealth University Engineering partnered on the construction of a magnetometer array to measure and record magnetic field values during experimental trials. The array consisted of six, triple-axis digital magnetometer sensors orientated across the base of the experimental tank, allowing the magnetic field to be measured in multiple directions and to be calculated via the magnetic/EM equation relationship (Figure 2). The two sensors were connected to extension wires attached to a commercial microcontroller (Arduino MEGA 2560). In order to record and quantify fish movements in the area of the experimental tank subjected to generated M/EM fields, a high definition Panasonic camcorder was mounted above the experimental tank using a Joby flexible mounting system.

Experimental Protocol

Experimental animals were selected at random from a pool of twelve individual sturgeons for the direct current (DC) trials and nine sturgeons for the alternating current (AC) trials. Study animals were transferred from the holding tank to the experimental tank 24 h prior to conducting study trials. All trials were conducted in the evening hours between 5 pm and 9 pm, during which no personnel access to the facility was allowed. Following acclimation to the experimental tank, fish behavior was recorded for 1 h in the absence of any generated fields to record baseline (control) behavior. Study subjects were then subjected to a preselected EMF trial for an additional 1 h, during which selected swimming behaviors were recorded. Hence, each experimental trial involved recording the behaviors of a single fish during a 2-h period. After each trial period the study animal’s PIT tag number was recorded and the subject was returned to the holding tank.

Magnetic and Electromagnetic Field Trials

A total of 45 trials were conducted during the study using a range of field types, strengths, and orientations. Thirty trials used generated DC fields: 15 were conducted using 0° field orientation (field generated perpendicular to tank area) and 15 were conducted using 90° field orientation (field generated perpendicular to tank area). Different field orientations were used to simulate fish in the wild passing directly over, or parallel to, HV submarine cables. Three M/EM field strengths were generated during DC trials: 5μT, 100μT, and 1000μT (five replicates each). Fifteen AC trials (also five replicates) were conducted using 0° field orientation and the same field strengths as the DC trials. For all trials, the M/EM field strengths were measured with magnetometers (described above). The region of the experimental tank with measured field strengths ≥ 50% of the target field strength was deemed 'affected' and marked with tape prior to each trial for later visual reference (Figures 3, 4). All other areas of the circular experimental tank were determined to be unaffected by the generated field.

Analysis of Video Footage

Approximately 60 hours of digital imagery were reviewed and analyzed to compute three simple metrics of fish behavior within the experimental field: time (in seconds) spent within the designated field area, number of passes through the designated field area, and mean swimming speed (m/s) within the designated field area. For each trial, measurements from videography were made separately for one 'control' hour (field off) and for one 'experimental hour' (field on). For each combination of field type (AC *versus* DC), orientation (90° *versus* 0°), and maximum field strength (5μT, 100μT, or 1000μT), mean values for each behavior metric (n=5 replicates) were calculated. Hypothesis testing (control *versus* experimental means; $\alpha = 0.05$)

was conducted using a non-parametric Wilcoxon Singed-Rank Test. All statistical calculations were computed using **R** statistical software.

Results

The data collected was used to produce three histograms that compare control and experimental tests for behavioral metrics and the relevant combinations of generated field attributes. The histograms compare time spent in field area, number of passes, and swimming speed for all trials between control and test groups (Figures 5, 6, and 7). The time experimental subjects spent in the tank generated field area for all tests ranged between 106 - 301 seconds per, 1 h period. The number of passes through the generated field area made by experimental subjects for all tests ranged between 25 – 64, per 1 h period. The average swimming speed of experimental subjects through the generated field area for all tests ranged between 8.1 – 14.8 cm/s, per 1 h period. Only three comparisons resulted in differences greater than one standard error between control and experimental pairs (Fig. 3a, 100μT; Fig. 4b, 5μT; Fig. 5c, 5μT). Results of hypothesis testing for all trials and all behavioral metrics are summarized with p-values (Table 1). These analyses did not demonstrate any clear patterns in the data among field strengths, field orientations, or field types. Based on these results the initial hypothesis that selected field strengths and types used during the study would have an effect on sturgeon behavior was rejected.

Discussion

This is the first study to experimentally evaluate the effects of M/EM fields from submarine HV cables on Atlantic Sturgeon behavior. Results of the study suggest that, the types and ranges of M/EM fields to which Atlantic Sturgeon were exposed in the laboratory did not result in biologically relevant changes to simple behaviors in sub-adult individuals. Fields used in this study were chosen to emulate conditions to which wild sturgeon might be exposed in the immediate vicinity of benthic HV transmission cables from coastal wind turbines. Hence, these results are not consistent with the hypothesis that localized M/EM fields from anthropogenic sources—specifically benthic HV cables—in coastal ocean habitats may negatively impact migrating or foraging wild Atlantic Sturgeon. However, conclusions from this laboratory study should be qualified by limitations in the study design. For example, only one age cohort (sub-adults) of Atlantic Sturgeon was available for the study and fish were exposed individually (cp. as groups) to experimental fields. In addition, the transferability of laboratory-based M/EM field exposures and subsequent behavioral responses to real-world conditions, including higher ocean salinities and a range of water temperatures, is unknown.

Future studies would be improved by more precise, real-time measurements of field area in the experimental tank, improvements to the magnetometer-based sensor array, the use of multiple, synchronized cameras, and the application of digital image processing and recognition software. Sturgeons and other taxonomic groups of marine and anadromous fishes that possess electromagnetic sensory organs may have a threshold field strength—not achieved by the current study—that will evoke behavioral or physiological responses.

Research on whether anthropogenic electric fields and EMF can produce a noticeable behavioral change in sturgeon species is both sparse at times conflicting. A Russian publication by Basov (1999) found that low frequency electric fields could evoke both a feeding and escape response in Sterlet and Russian sturgeon, while a study conducted by Bevelhimer et al. (2015) suggested that there was not an ecologically relevant response from Pallid sturgeon when exposed to EMF of similar frequency and strength to those produced by HV transmission cables. While the responses of different sturgeon species to EMF is still being studied there is comparatively a much larger body of research concerning elasmobranch responses to magnetic and electric fields (Collins and Whitehead 2004, Bullock 1973, Kalmijn 1982). Some species of elasmobranchs can be deterred by, attracted by, and habituated to electro/magneto stimuli, and in one study juvenile Lemon sharks displayed a decreased sensitivity after prolonged exposure to external magnetic fields (O'Connell et al. 2011). As stated earlier Atlantic sturgeon possess similar electro-sensory organs as elasmobranchs. So it is not unreasonable to hypothesize that similar behaviors can be induced in Atlantic sturgeon with specific M/EM fields.

Even if anthropogenic M/EM fields from offshore wind energy facilities do not directly influence Atlantic Sturgeon behavior, other factors associated with offshore wind production could pose risks to Atlantic Sturgeon and other benthic marine and anadromous fishes. In a recent study by Love et al. (2016), fish assemblage structure and density over energized *versus* un-energized benthic, HV transmission cables were not significantly different, but estimates of density for some fish species were higher in the vicinity of both cables, compared to adjacent, natural benthic habitat. Based on these findings changes to benthic habitat caused by installation of submarine cables may have a greater effect on marine fish behavior and movement than anthropogenic EMF. The United States has been slow to develop its offshore wind resources and this could present a unique opportunity for ecologists to document and minimize future impacts from wind energy before harm to marine species occurs.

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Current Type/ Orientation (°)	Field Strength (μ)	p-value Time in Field Area	# of Passes	Speed
DC, 0	5	0.81	1	0.81
	100	0.63	0.81	0.81
	1000	1	0.81	0.44
DC, 90	5	0.63	0.06	0.13
	100	0.86	0.63	0.81
	1000	1	0.42	0.19
AC, 0	5	0.63	0.06	0.13
	100	0.81	0.19	0.63
	1000	0.81	0.63	1

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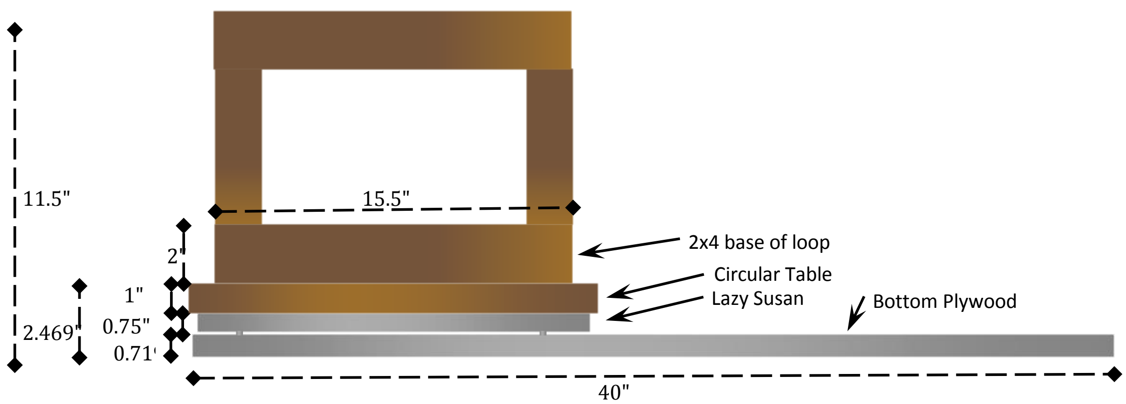
3. Graphical representation of a generated DC field in the experimental tank with cable parallel to path of motion. (B $\vec{}$-field indicated by arrows). Graphic created by C. Deloglos, VCU Engineering. 21

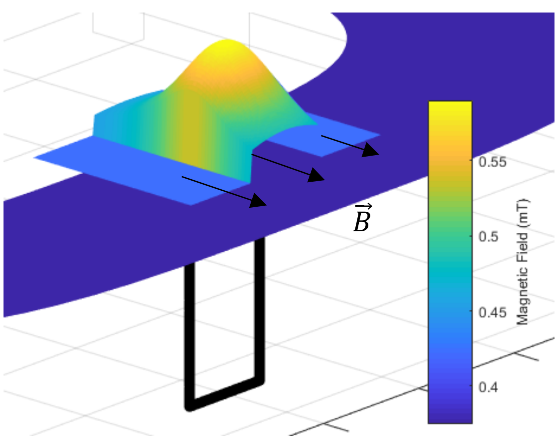
4. Graphical representation of a generated DC field in the experimental tank with cable perpendicular to path of motion. (B $\vec{}$-field indicated by arrows. Graphic created by C. Deloglos, VCU Engineering. 22

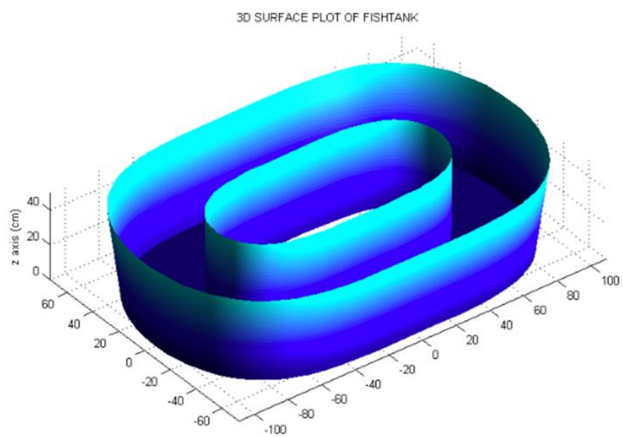
5. Time Spent in Field Area histogram: Observed time spent in M/ EM field area during control and experimental tests. Experimental animals were first exposed to no field for 1 h (control), followed by exposure to one of three field strengths (5 µT, 100 µT, 1000 µT) for 1 h. Each control and test column pair represents five replicates using different individuals, chosen randomly. Bars represent 1 standard error of the mean; a) direct current (DC) with 0° field orientation; b) DC with 90° field orientation; c) alternating current (AC) with 0° field orientation. ………….. 24

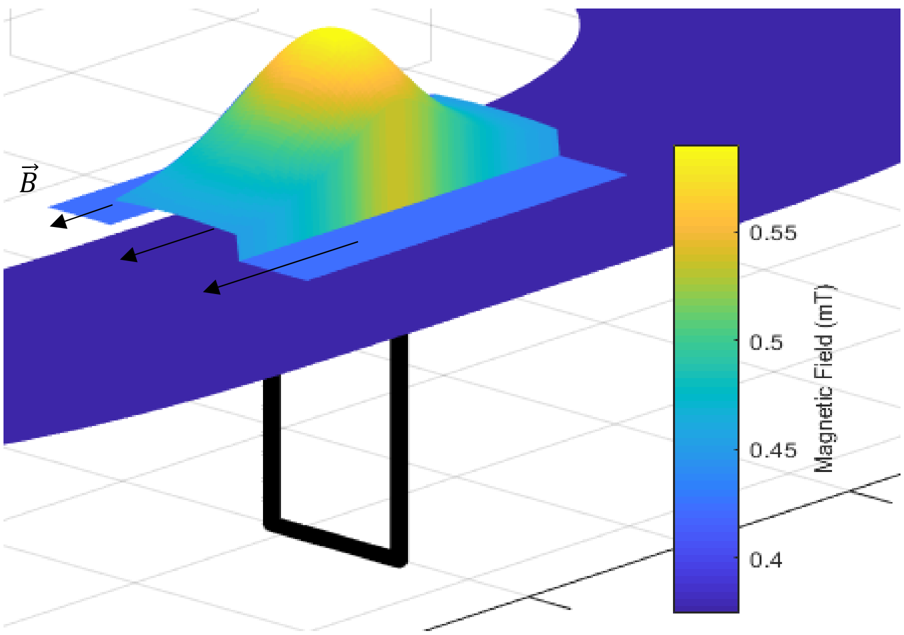
6. Number of Passes Histogram: Observed number of passes through M/ EM field area during control and experimental tests. Experimental animals were first exposed to no field for 1 h (control), followed by exposure to one of three field strengths (5 µT, 100 µT, 1000 µT) for 1 h. Each control and test column pair represents five replicates using different individuals, chosen randomly. Bars represent 1 standard error of the mean; a) direct current (DC) with 0° field orientation; b) DC with 90° field orientation; c) alternating current (AC) with 0° field orientation. 25

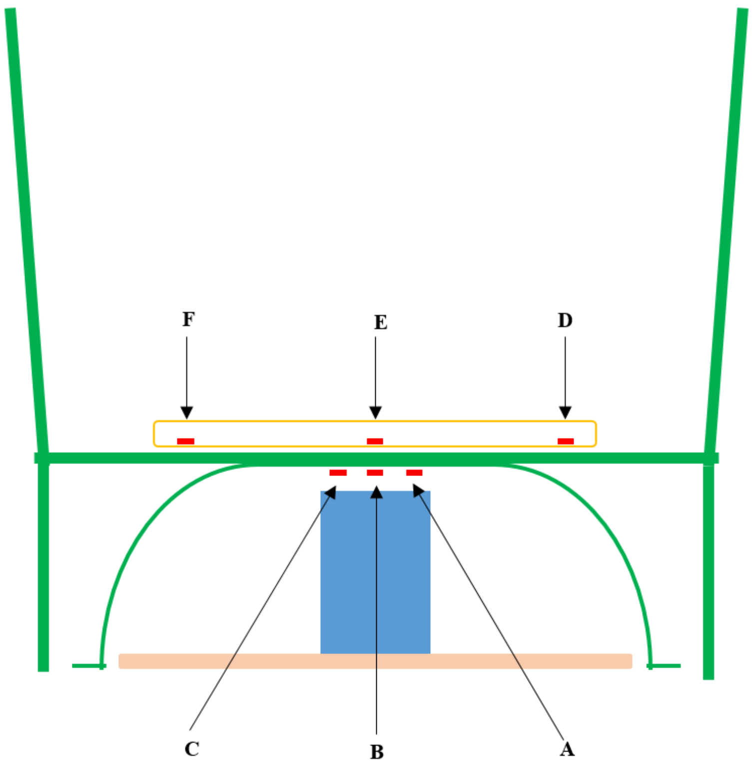
7. Swimming Speed Histogram: Observed swimming speed in centimeters per second through EM field area during control and experimental tests. Experimental animals were first exposed to no field for 1 h (control), followed by exposure to one of three field strengths (5 µT, 100 µT, 1000 µT) for 1 h. Each control and test column pair represents five replicates using different individuals, chosen randomly. Bars represent 1 standard error of the mean; a) direct current (DC) with 0° field orientation; b) DC with 90° field orientation; c) alternating current (AC) with 0° field orientation. ……….. 26

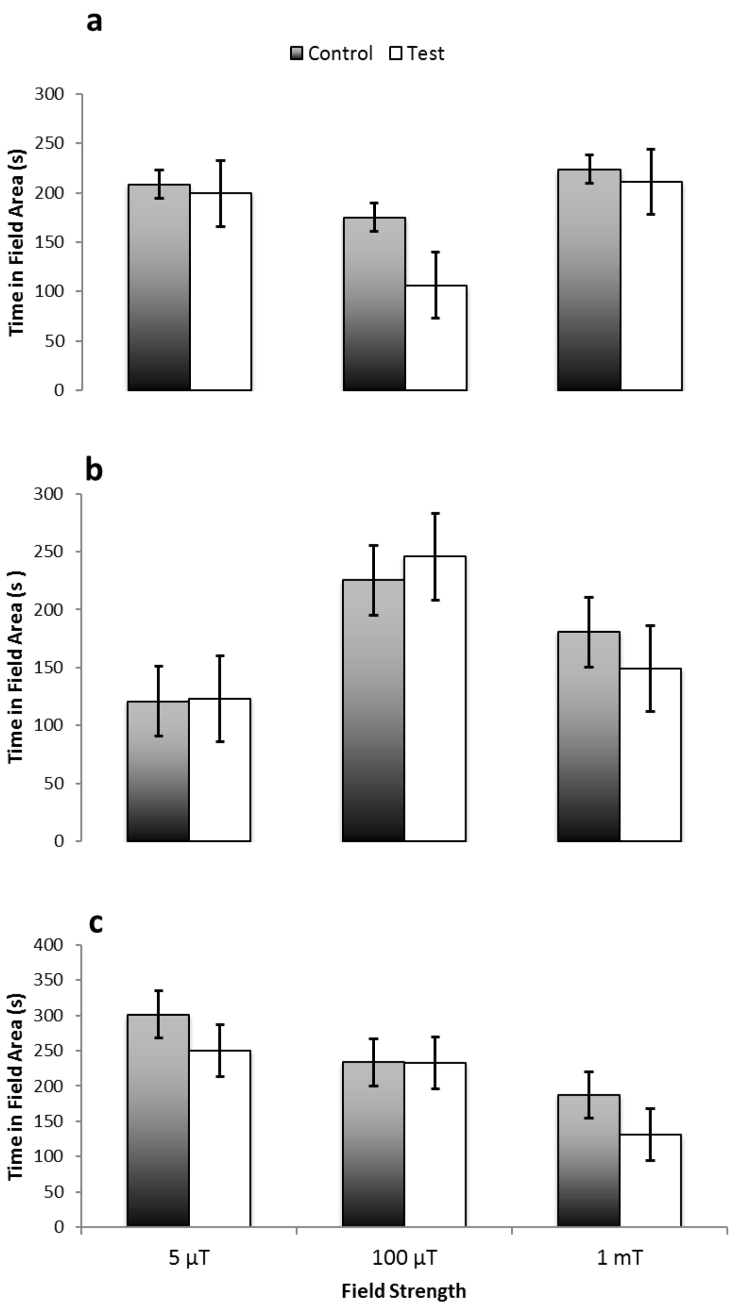

11.5"
15.5"
2"
2x4 base of loop
1"
Circular Table
0.75"
Lazy Susan
Bottom Plywood
2.469"
0.71'
40"

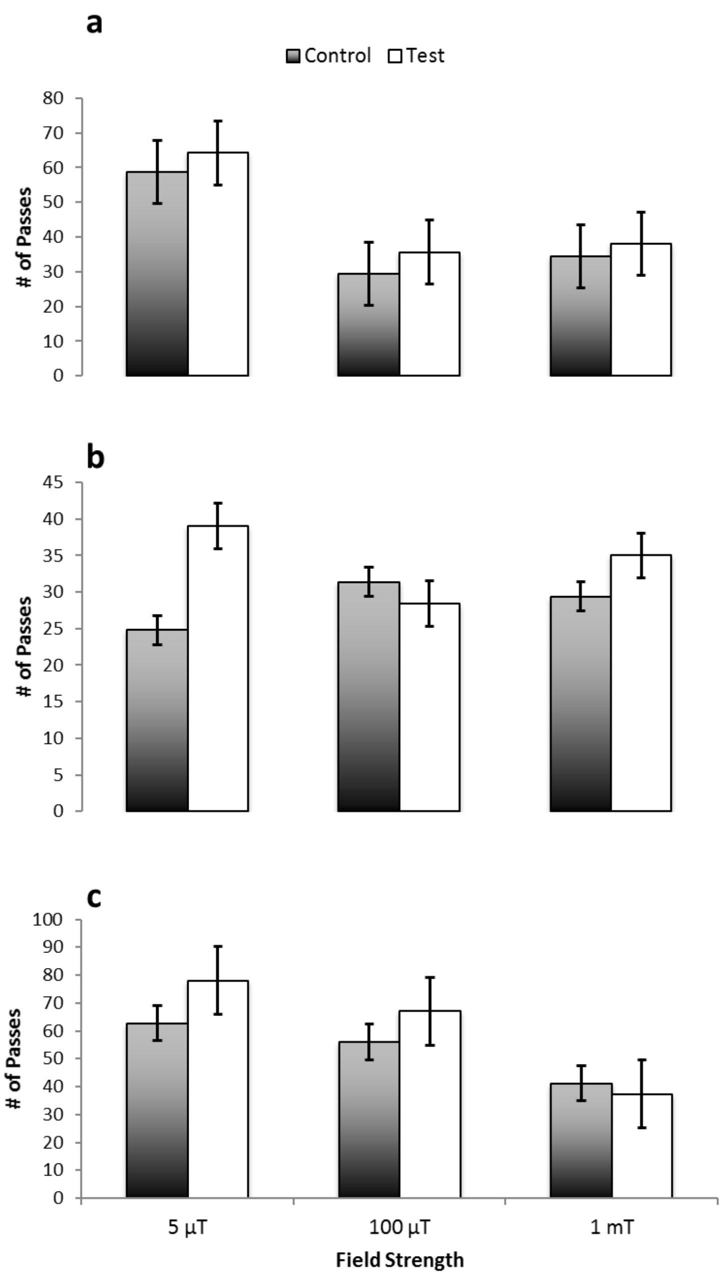

$\vec{B}$
0.55
0.5
0.45
0.4
Magnetic Field (mT)

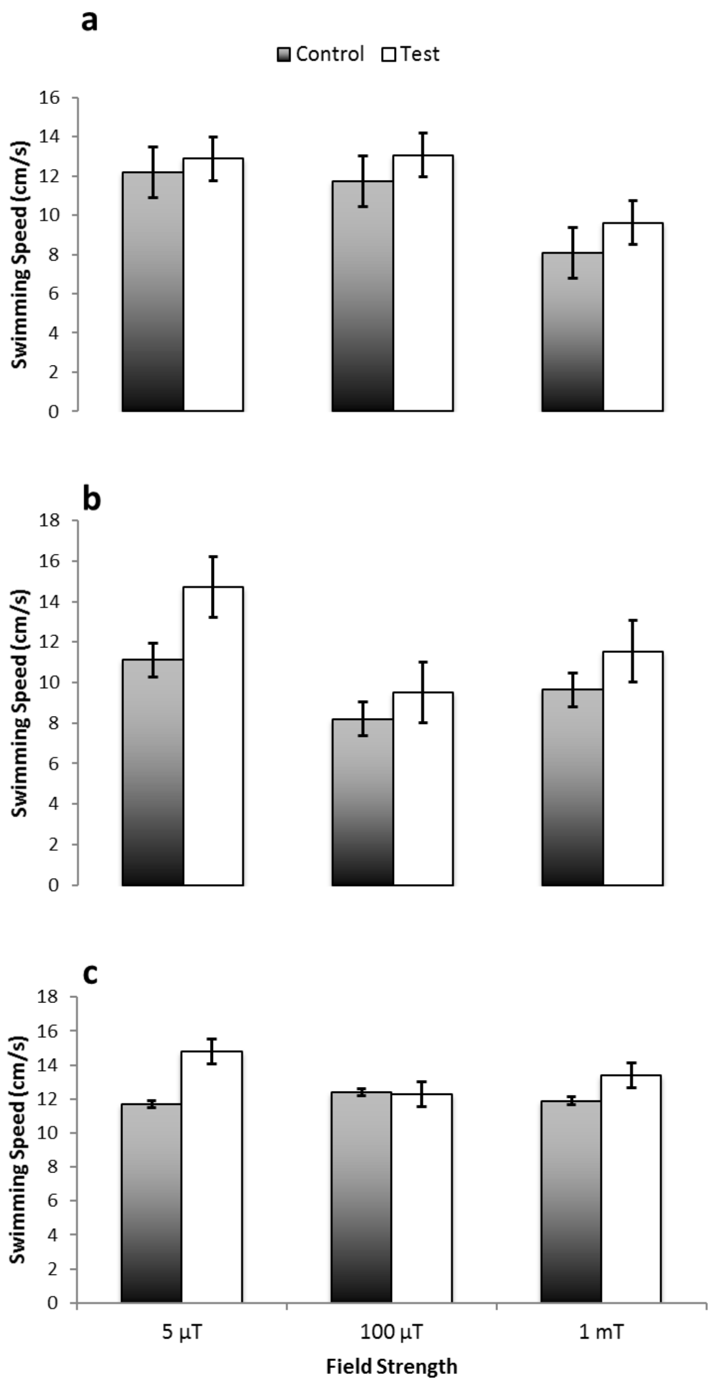

3D SURFACE PLOT OF FISHTANK
z axis (cm)
40
20
0
60
40
20
0
-20
-40
-60
100
80
60
40
20
0
-20
-40
-60
-80
-100


$\vec{B}$
0.55
0.5
0.45
0.4
Magnetic Field (mT)


F
E
D
C
B
A


a
Control
Test
300
250
200
150
100
50
0
Time in Field Area (s)
b
300
250
200
150
100
50
0
Time in Field Area (s)
c
400
350
300
250
200
150
100
50
0
Time in Field Area (s)
5 µT
100 µT
1 mT
Field Strength


a
Control
Test
80
70
60
50
40
30
20
10
0
# of Passes
b
45
40
35
30
25
20
15
10
5
0
# of Passes
c
100
90
80
70
60
50
40
30
20
10
0
# of Passes
5 µT
100 µT
1 mT
Field Strength


a
Control
Test
Swimming Speed (cm/s)
16
14
12
10
8
6
4
2
0
b
18
16
14
12
10
8
6
4
2
0
Swimming Speed (cm/s)
c
18
16
14
12
10
8
6
4
2
0
Swimming Speed (cm/s)
5 µT
100 µT
1 mT
Field Strength