# Effect of Transcutaneous Vagus Nerve Stimulation on Sports Performance

by

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ABSTRACT

Vagus nerve stimulation (VNS) has shown benefits beyond its original therapeutic application, though there is a lack of research into these benefits in healthy and athletic populations. To address this gap in the VNS literature, the present study addresses the feasibility and possible efficacy of transcutaneous VNS (tVNS) in improving performance and various biometrics during two athletic tasks: golf tee shots and baseball pitching. Performance, cortical dynamics, anxiety measures, muscle excitation, and heart rate characteristics were assessed before and after stimulation using electroencephalography (EEG), the State-Trait Anxiety Inventory (STAI), and electrocardiography (ECG) during the baseball and golf tasks as well as electromyography (EMG) for muscle excitation in the golf participants. Golfers exhibited increased perceived quality of each repetition (independent from outcome) and an improvement in state and trait anxiety after stimulation. Golfers in the active stimulation group also showed a greater reduction in right upper trapezius muscle excitation when compared to the sham stimulation group. Baseball pitchers exhibited an increase in perceived quality of each repetition (independent from outcome) after active stimulation but not an improvement of state and trait anxiety. No significant effects of stimulation Priming, stimulation Type, or the Priming×Type interaction were seen in heart rate, EEG, or performance in the golf or baseball tasks. The present study supports the feasibility of tVNS in sports and athletic tasks and suggests the need for future research to investigate further into the effects of tVNS on the performance, psychologic, and physiologic attributes of athletes during competition.

ACKNOWLEDGMENTS

I was very fortunate to be presented with this opportunity to complete such a novel and interesting experiment in a lab full of very talented people. A few individuals that played a large role in helping complete this project are Dr. William 'Jaime' Tyler, Dr. Sarah Wyckoff, and Nick Hool. Dr. Tyler receives a considerable amount of unsolicited emails from students who after meeting him and taking his course would like to be a part of his lab, myself included. He put faith in me with very limited knowledge of my background and the kind of student I was to finish a project pushing forward novel neuromodulation applications. Dr. Wyckoff was exceptionally helpful in helping design this study, submit ethics approval requests, collect data, analyze data, and prepare my defense documents. I could not have completed this project without the hard work and help from her. Nick Hool deserves substantial credit for developing the stimulation device used in this investigation as well as his help with data collection and data organization. Lastly, an acknowledgment of the rest of the individuals in the Tyler lab and the School of Biological and Health Systems Engineering that helped me complete my education thus far and finish my master's thesis project.

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## Introduction

While the importance of developing neuromodulation techniques to provide therapy for drug-resistant pathologies should not be overlooked, using neuromodulation to improve the performance of healthy populations would have a broad impact on society. Vagus nerve stimulation (VNS) is a form of neuromodulation that has been shown to be safe and effective for treating drug-resistant epilepsy (George, Sonnen, Upton, Salinsky, & Ristanovic, 1995; Handforth et al., 1998). It has also shown benefits in treatment-resistant depression samples (Aaronson et al., 2013; Albert et al., 2015; Rush et al., 2005). Although VNS is only approved by the United States Food and Drug Administration for treating drug-resistant depression and epilepsy, there are ongoing investigations of additional applications for VNS including enhancing stroke rehabilitation when paired concurrently with traditional rehabilitation exercises (Childs, DeLeon, Nickel, & Kroener, 2017; Khodaparast et al., 2014; Meyers et al., 2018), enhancing conditioned fear extinction when paired with traditional fear extinction exercises (Noble et al., 2017), and increasing activity and expression of various neurotransmitter systems (Ben-Menachem et al., 1995; Dorr & Debonnel, 2005; Marrosu et al., 2003). Despite evidence of invasive VNS being a safe and effective therapy, it requires surgery and implantation of a signal generator and electrode which involves risk factors (Revesz, Rydenhag, & Ben-Menachem, 2016) which may not be ethical for use in healthy individuals. However, Transcutaneous Vagus Nerve Stimulation (tVNS) is a non-invasive technique that stimulates the auricular branch of the vagus nerve through the skin to achieve similar results as invasive VNS in epilepsy populations (Bauer et al., 2015). There is also evidence suggesting that it can improve working memory and other cognitive function

(Hoffmann et al., 2018; Sun et al., 2017). Within the wide-ranging literature of possible applications for VNS and tVNS, there are no published studies investigating their use in athletic populations. To maximize the impact of VNS as a successful therapy and training tool, there is a need to experiment with healthy and athletic samples to extend any functional benefits to broader populations than treatment resistant depression and epilepsy patients.

In this study, we investigated the feasibility and efficacy of using tVNS to improve the performance of golfers and baseball pitchers using preliminary experiments with baseball and golf tasks. A full golf experiment was completed, while limited data was collected in the baseball experiment due to time and season constraints inhibiting the completion of the experiment. These experiments included an electrical nerve stimulation protocol in between two sets of tasks to determine differences in performance and other biometrics.

Evaluating the performance of golfers was executed at a TopGolf driving range which uses a tracking system for determining how close the ball's endpoint is to the target pin. In golf, it is advantageous to hit the ball as close to the pin as possible to minimize the number of shots necessary to hit the ball into the hole. Since reducing the number of shots taken to hit the ball into the hole equates to better performance, this measure using TopGolf ball-tracking system is used as the primary measure of performance in golfers.

To evaluate the participants' pitching performance in the baseball experiment, ball speed and accuracy were measured for each pitch. Although there is a lack of scientific, peer-reviewed literature about the effects of pitch speed and pitch accuracy (command) on pitcher success, it is understood that increasing levels of both are related to level of competition and success. The sequence in which pitches are thrown throughout an at-bat can be manipulated

by the pitcher and is indicative of the pitcher's ability to achieve a desirable outcome. Desired outcomes are dependent on the situation and state of the game, but always involve an attempt to avoid solid contact between the pitched ball and the hitter's swing; so theoretically, changing pitch type (speed and trajectory), pitch speed, and location of the pitch will minimize the hitter's ability to predict where to swing to make solid contact with the ball. Therefore, the pitcher's ability to achieve a desired outcome may be dependent on how well they can accurately command the ball and how fast they can throw it. We chose to test only four-seam fastballs, a very common pitch with minimal movement and historically high speed, for the purpose of simplicity and keeping the total number of pitches thrown by the participants to a minimum.

In addition to pitching and golfing performance measures, we collected electroencephalography (EEG) data, perceived quality of each repetition or "feel", heart rate (HR) and electrocardiograph (ECG) data including heart rate variability (HRV), and state-trait anxiety data as measured by the State-Trait Anxiety Inventory (STAI) as well as electromyographs (EMG) of the left and right upper trapezius during a resting state in the golf experiment. tVNS has been shown to modulate heart rate characteristics including heart rate and heart rate variability (Balasubramanian, Harikumar, Nagaraj, & Pati, 2017; De Couck et al., 2016; Selty, Vaughn, Quint, Robertson, & Messenheimer, 1998). The STAI was included as a response variable due to the modulatory effect of tVNS on anxiety as shown in the previously mentioned literature. Anxiety is an important measure in many athletic tasks not limited to baseball and golf, but due to the large amount of fine motor skill and mental focus involved in these sports, varying levels of state-trait anxiety could have significant

impacts on the athlete's performance level. Further, even in sports that require less fine motor skill and mental demand than baseball such as swimming (Burton, 1988), anxiety has been shown to affect performance which supports the importance of collecting subjective anxiety data in baseball experiments using the STAI. EMG was used as a measure of muscle excitation to determine if upper trapezius muscle activation was affected by stimulation between golf shots.

Many of the studied applications for VNS involve pairing stimulation concurrently with traditional training methods. However, due to the various injury risks in overhead throwing athletes (Lin, Wong, & Kazam, 2018; Wong, Lin, Ayyala, & Kazam, 2016), the participants in the baseball experiment were not required to execute a training session of pitches in the study to minimize overuse-related injury risk. To compensate for the lack of concurrently executed physical training with stimulation, we incorporated the use of motor imagery training. Motor imagery is a subset of predictive control that involves mentally rehearsing a task and has shown to predict motor performance (Sirigu et al., 1995) and share similar central neural structures as physically executed actions (Decety, 1996). In theory, the interaction of motor imagery training and tVNS could improve the pitcher's ability to throw a four-seam fastball at higher speeds and with higher accuracy. Motor imagery was not included in the golf experiment.

In all, the present study was designed to evaluate the feasibility and efficacy of tVNS therapy in sports and whether the benefits seen in epileptic and depression populations could be extended to healthy populations to improve athletic performance. Performance is the main outcome measure and is expected to improve after stimulation and improve greater in the

active stimulation group when compared to the sham stimulation group. EEG power in FP1 and FP2, heart rate, and anxiety are expected in decrease after stimulation, while heart rate variability, feel, and upper trapezius EMG are expected to decrease after stimulation. These changes are expected to be more dramatic in the active stimulation group.

## Methods

The methods for the golf and baseball experiments were very similar and involved identical stimulation protocol allowing them to be described together in the following section.

### Participants

A total of 3 healthy, male, right-handed baseball pitchers ranging from 23 to 25 years of age (mean age 24.25 ± 1.3 years) and 18 male and female golfers (13 male, 5 female) ranging from 19 to 73 years of age (mean age 38.7 ± 18.6 years) were recruited using flyers on the main campus of Arizona State University (ASU), in sports training facilities, on social media, via email, and word-of-mouth. Participants were screened using an online screening survey (RedCap etc. etc.) to ensure the fulfillment of the following inclusion criteria: (a) not currently undergoing treatment or medication for neurological or psychological disorder, including addiction (b) no medical implant (c) no frequent migraines or headaches (d) no history of panic attacks or acute anxiety disorder (e) no frequent fainting or vaso-vagal syncope or neurocardiogenic syncope (f) no Reynaud's disease, Tempomandibular Joint Disorder, or other facial neuropathy (g) no history of concussion or brain injury, significant face/head injury or facial metal plate or screw implants (h) no history of hospitalization for neurological or psychological disorder (i) no recent hospitalization for surgery/illness (j) no

uncorrectable vision or hearing (k) no recent drug or alcohol treatment within the last 3 months (l) no high blood pressure, heart disease, or diabetes diagnosis  The hypotheses of the experiment or the type of stimulation were not disclosed to the participant. The experiment conformed to the ethical standards of ASU and was approved by the ASU Institutional Research Board. This was a between-group study design, so each participant only experienced one type of stimulation (active or sham). In the golf experiment, there were 10 participants assigned to the active stimulation group and 8 participants assigned to the sham stimulation group. Group assignment was not matched, paired, or randomized. For the baseball pitching experiment, due to the small number of participants, all participants were assigned to the active stimulation group. One participant was assigned to the sham stimulation group, but the data was not used for the study due to a performance score which was outside of 2 standard deviations from the mean. The remaining three participants were given active stimulation during the experiment.

**Tasks**

**Golf**

Golf participants were required to perform 20 golf shots towards a target at 150 yards. The target is a traditional pin as would be seen in a standard golf course, but with bins for the ball to land that extend radially outward from the target pin.

**Baseball**

Participants were required to perform 20 game-like fastballs at their maximal comfortable intent towards the center of the 20-inch by 20-inch command trainer target in front of a 7-feet by 7-feet standing net that were grouped into two blocks consisting of 10

pitches each. The horizontal distance to the target (i.e. from the plate where the pitcher's rear foot was planted) was 60.5 feet. A standard mound with a height of 10 inches was used to replicate an in-game environment.

## Performance Measures

### Golf

The score assigned to each of the bins around the 150-yard target is inversely proportional to its radial distance away from the pin, indicating a higher score when the ball ends in a bin closer to the target pin. Each shot was assigned a score between 5 and 10 with 10 corresponding to the shot ending in the closest bin to the pin and 5 corresponding to a shot ending in the furthest bin radially from the pin. If the ball did not end in any of the bins, the shot was assigned a performance score of 0. The scores were averaged to obtain the overall performance score for each block of shots.

### Baseball

To measure pitch velocity, a Stalker Sport II radar device (Applied Concepts, Richardson, Texas) was placed in line of the pitch trajectory behind the pitcher. It was placed behind the pitcher to allow the experimenter to be near the participant which allows one experimenter to collect all measures alone. The pitch velocity score was calculated by dividing the pitch velocity (in miles per hour) by a factor of 10. This scaling factor was used to convert the velocity score to the same order of magnitude as the accuracy score to allow for similar sensitivity to accuracy and speed.

Pitch accuracy was measured by applying a location score to each pitch: a score of 4 for hitting the middle 10-inch by 10-inch square on the 20-inch by 20-inch command trainer

target, 3 for hitting the target outside of the middle square, 2 for hitting the middle half of the 7-feet by 7-feet net behind the target but missing the target, 1 for hitting the outer half of the net, and 0 if the pitch missed the target and net completely or hit the ground before reaching the target. The total performance score for each block of pitches was the sum of all velocity and command scores.

**Psychologic Measure**

The STAI survey was used to measure state and trait anxiety during the tasks. After both blocks of golf shots or baseball pitches, the participant was asked to complete the STAI in the form of a survey on the RedCap data collection system. Higher scores on the STAI survey represent higher levels of state and trait anxiety. These values were uploaded to the online site where data from all participants is stored together. In addition, the participants were asked to subjectively rate their general "feeling" about the repetition. This was not a measure of how the participant felt about the outcome of the repetition, but if the outcome was removed, how the participant generally felt about its execution.

**Physiologic Measures**

EEG was measured with The Original Muse headset (InteraXon Inc., Toronto ON, Canada). The Muse headset is a consumer-grade EEG device that is lower-cost and more convenient for dynamic tasks than traditional EEG caps due to its wireless and low-profile characteristics. Four sites were measured that were analogous to Fpz as the reference electrode, and Fp1, Fp2, Tp9, and Tp10 as the four channels of EEG. The Muse headset was connected to a mobile device with the Opti Brain application (Opti Brain, Mesa, Arizona) which calculates the average power in each frequency band from each electrode throughout

the entire capture period and separately during the last 1 second of capture. Because the Opti Brain application averages the power of the four sites, separate recordings were made at the beginning of each pitch. This provided EEG data just before the participant began their pitching delivery. Data from Tp9 and Tp10 was omitted due to amount of noise that the two electrodes were subject to. There is not direct contact with the skin, and conductive gel or saline solution were not used to improve the conductivity of the signal, so only the signals from the frontal two electrodes (Fp1 and Fp2) were used for analysis. Validity of the Muse headset for research purposes has been confirmed using raw data streaming to a computer for analysis in third party software (Krigolson, Williams, Norton, Hassall, & Colino, 2017).

The Nexus 10 biofeedback and neurofeedback system was used to collect electrocardiographs in the golf experiment. This data was used for the heart rate and heart rate variability metrics. For the baseball experiment, heart rate and heart rate variability were measured using a Polar H7 heart rate monitor (Polar USA, Bethpage, New York) connected to the Heart Rate Variability Logger mobile application (Marco Altini, Amsterdam) to collect and export data for further analysis. The main metric used to assess heart rate variability in both experiments is the R-R interval, which is calculated in the mobile application connected to the heart rate monitor in the baseball experiment and calculated during post processing in Kubios HRV software for the golf data. For the golf experiment, heart rate and heart rate variability were assessed at resting states before each block of shots; contrarily, it was assessed in four blocks during the baseball experiment: during the first block of testing pitches, during the first five minutes of stimulation, during the second five minutes of stimulation, and during the second block of testing pitches.

EMG was measured using the same Nexus 10 unit connected to two surface electrodes, one on the left upper trapezius and one on the right upper trapezius. These electrodes were placed during resting state physiological measures before the first block of golf shots, with the leads being removed while the golfer completes the task with the electrodes still placed. The leads were then reconnected to the electrodes for the second resting state physiologic measurement period.

**Stimulation**

In both experiments, an auricular VNS device was used to provide electrical current to the auricular branch of the vagus nerve through the skin of the neck just behind the ear via a pin-style electrode wrapped in conductive hydrogel.

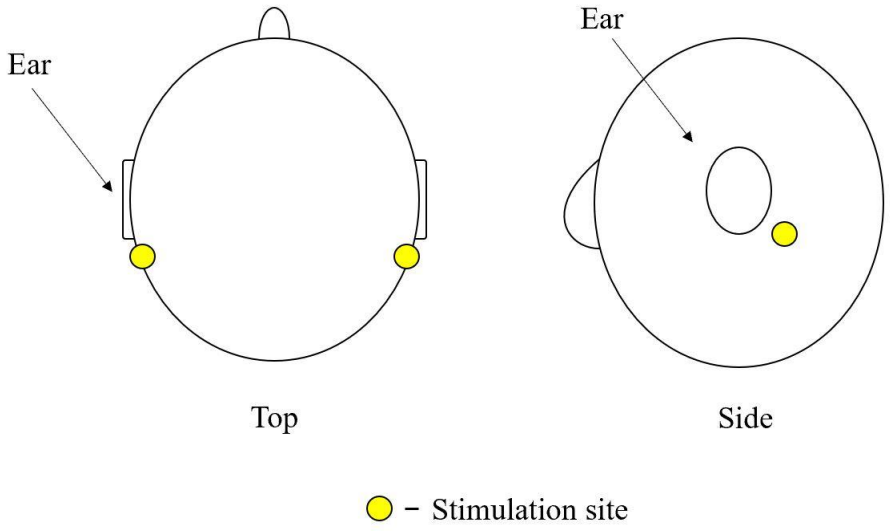


*Figure 1.* Stimulation site for the auricular vagus nerve stimulation device used in the baseball and golf experiments

The stimulation device provided current at 100 hertz with intensities between 0 and 40 milliamps. For the active stimulation group, after the system was placed on the participant

and the stimulation was powered on, the stimulation intensity was incrementally increased by approximately 1.6 milliamps to a point at which the participant could feel the stimulation but was not yet uncomfortable with the intensity. Once the stimulation intensity was chosen and the electrodes were adjusted to the optimal position, the participant sat still with closed eyes for 10 minutes.

For sham stimulation, the system was placed on the participant, powered on, and increased in intensity until the participant could feel any sensation, and the stimulation was turned off. The participants were informed that an intensity just below the threshold of sensation was being tested so it was normal to not feel the electrical current or other sensation from the electrodes.

**Motor Imagery**

In the baseball experiment, the participants were instructed to practice motor imagery which involved executing 10 mental repetitions of the pitching task and the outcome. Because the main outcome measure of interest is the performance of the pitcher, the participants were instructed to focus more heavily on the outcome of their 10 imagined pitches than the mechanics and movement of their delivery. The participants in the sham group were not instructed to perform 10 mental repetitions to represent a negative control for testing the combined effect of tVNS and motor imagery. This process was not included in the golf experiment.

## Procedure

### Golf

After the participants arrived at TopGolf, they were first asked to compete a demographic questionnaire. Upon completion of the demographic questionnaire, physiological measurement devices were placed (EMG and ECG) and 5 minutes of resting state physiological data collection was completed. After the five-minute baseline measure of the participant's ECG and upper trapezius EMG, the EEG headset was placed on the participant and the ECG and EMG electrode leads were removed. The golfers were then allowed 5 warm up shots before the first testing block. 10 testing shots were then completed by the participant with a short pause in between each shot to record and save the experimental data. Upon completion of the first 10 testing shots, the EEG headset was removed, and the participant was required to fill out the STAI survey depicting their state and trait anxiety during the shots. The stimulation protocol was then completed for 10 minutes, followed by the replacement of ECG and EMG electrodes for a second resting state physiologic measurement phase before the second block of testing shots. The second block of testing shots was then completed, followed by a STAI survey depicting the participant's anxiety during the second block of shots. Finally, the participant was required to complete a safety questionnaire to report any adverse effects of the stimulation immediately after the experiment as well as 24-hours after the experiment.

### Baseball

The participants were first asked to complete a demographic questionnaire upon arrival to the data collection site. Each participant was instructed to execute their standard

pre-game warmup routine before physiological measurement devices were placed. After the pre-game warmup routine was completed and the data collection devices (EEG and HR) were placed, the participant was allowed 5 warmup pitches before the testing set of pitches mimicking the in-game pre-inning warmup routine allowed in competitive baseball. Once the 5 warmup pitches were complete, the participant was instructed to complete the task with a short pause in between each pitch to record and save the experimental data. After the 10 pitches were complete, the EEG device was removed and the participant filled out the STAI survey depicting their state-trait anxiety throughout the previous set of pitches. Following completion of the STAI survey, the subject was given stimulation (primed), either sham or active, for 10 minutes. The active stimulation group was instructed to imagine at least 10 pitches including the outcome of the pitch and all of the sensations involved. Following the 10 minutes of stimulation, the EEG device was replaced, and the participant completed another 5 in-game pre-inning warmup pitches. The second block of 10 pitches was then completed while all experimental data was collected. After the second block of 10 pitches, the EEG and HR device were removed and the subject was asked to complete a second STAI, followed by a safety questionnaire to gather information about their experience throughout the experiment immediately upon completion and 24-hours after the experiment. The experimental procedure can be seen in Figure 2.

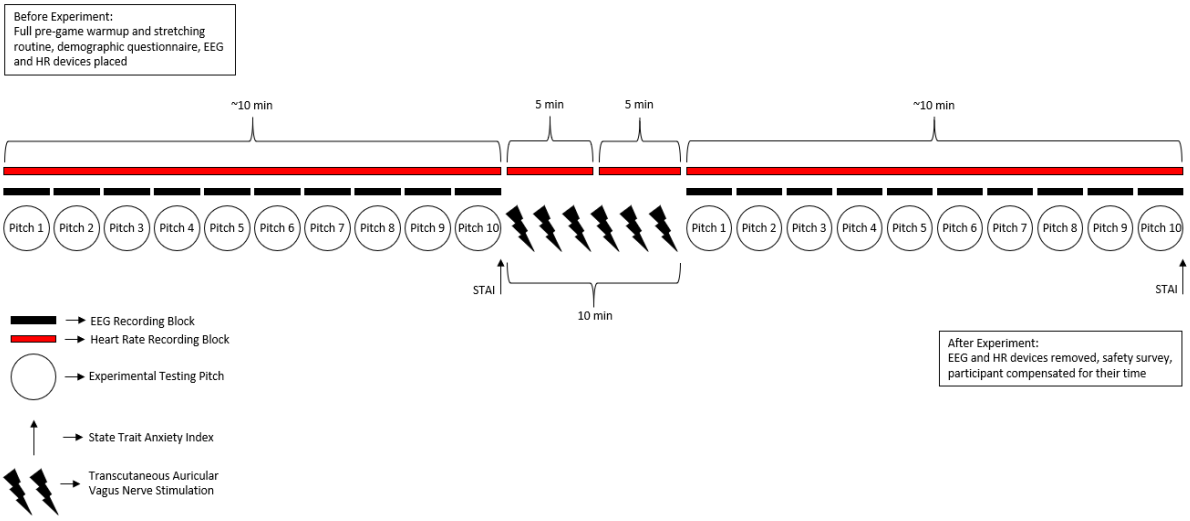


*Figure 2.* Feasible experimental procedure for testing effects of tVNS in baseball pitchers

Participant's stress was manipulated by setting a condition on the monetary compensation for completing the study. After the first set of pitches, the participants were told they needed to achieve a higher pitching performance score during the second block of pitches than the first block to earn the monetary compensation. Participants were then compensated after the completion of the study regardless of performance.

**Statistical Analysis**

A series of mixed analyses of variance (ANOVAs) were completed to identify the effect of stimulation Priming as a within-subject factor, stimulation Type as a between-groups factor, and the interaction effect of Priming×Type in the golf experiment.

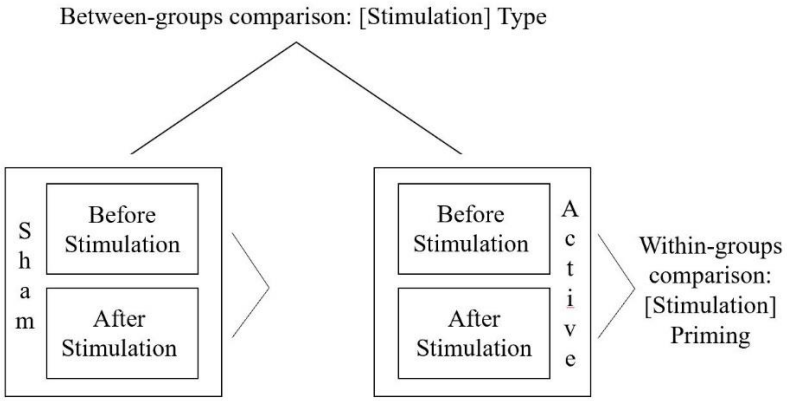


*Figure 3.* Between-groups and within-groups comparisons illustrated using the two experimental factors. Stimulation type as a between groups comparison, with sham as the control group and active as the experimental group; Stimulation Priming as the within groups factor. Priming does not have a true control condition.

The Type factor corresponds to the type of stimulation (active vs. sham) the participant received. The Priming factor corresponded to whether the participant was "primed" with stimulation or not; the non-primed condition refers to the block of the task before the participants received stimulation, whereas the primed condition was after the participants received stimulation in between blocks of the task. Because there was only one group included in the baseball dataset, only a within-subjects comparison of the priming effect was completed using paired t-tests. The effect sizes of all measures in the golf experiment were estimated using a partial eta squared calculation in the mixed ANOVAs; Cohen's d effect size estimate was used in the baseball experiment. The statistical analyses evaluated these two factors' effect on frontal EEG signals, STAI scores, feel during task, task performance, upper trapezius EMG, and heart rate for the baseball and golf experiments. All statistical analyses were completed in IBM Statistical Package for the Social Sciences (SPSS).

## Results

The results for the golf and baseball experiments as reported by group means before and after stimulation are seen in tables 1 and 2.

Table 1

*Table of means for pre- and post-stimulation in both golf groups*

| Metric | Group | Pre | Post | P-Value | Effect Size Estimate |
|---|---|---|---|---|---|
| Performance | Active | 3.83 ± 2.52 | 3.75 ± 2.54 | 0.923 | 0.001 |
| | Sham | 1.41 ± 1.96 | 1.28 ± 1.46 | | |
| Feel | Active | 6.83 ± 0.92 | 7.43 ± 0.73 | 0.500 | 0.031 |
| | Sham | 6.33 ± 1.42 | 6.57 ± 1.33 | | |
| Anxiety | Active | 41.10 ± 14.66 | 26.10 ± 4.10 | 0.182 | 0.116 |
| | Sham | 36.70 ± 13.39 | 29.57 ± 7.12 | | |
| Heart Rate | Active | 86.28 ± 17.59 | 85.17 ± 16.33 | 0.399 | 0.048 |
| | Sham | 83.88 ± 16.19 | 84.66 ± 15.04 | | |
| HRV | Active | 21.21 ± 3.96 | 21.35 ± 3.96 | 0.466 | 0.036 |
| | Sham | 17.86 ± 2.07 | 18.91 ± 2.50 | | |
| EMG Left | Active | 18.45 ± 15.15 | 10.99 ± 4.58 | 0.269 | 0.081 |
| | Sham | 16.66 ± 4.01 | 16.67 ± 6.98 | | |
| EMG Right | Active | 10.53 ± 5.77 | 8.93 ± 3.56 | 0.023* | 0.300 |
| | Sham | 13.72 ± 5.80 | 20.59 ± 10.49 | | |

*Note.* Effect size is estimated using partial eta squared ($\eta_p^2$). P-value indicates the significance of Priming×Type within-subjects interaction. Effect size estimates above 0.14 are considered large effects.

*$p < 0.05$

Table 2

*Table of means for pre- and post-stimulation in the baseball experiment*

| Metric | Pre | Post | P-Value | Effect Size Estimate |
|---|---|---|---|---|
| Performance | 83.11 ± 1.47 | 84.18 ± 1.47 | 0.210 | 0.727 |
| Feel | 6.03 ± 1.54 | 7.33 ± 1.24 | <0.001* | 0.926 |
| Anxiety | 37.00 ± 5.57 | 30.00 ± 1.00 | 0.075 | -1.749 |
| Heart Rate | 129.35 ± 21.00 | 131.45 ± 14.21 | 0.737 | 0.117 |
| HRV | 41.76 ± 41.76 | 474.63 ± 31.60 | 0.174 | -0.291 |

*Note.* Heart rate data included is the active heart rate during blocks of pitches. Effect size was estimated using Cohen's d effect size. Effect sizes with an absolute value above 0.8 are considered large effects.

*$p < 0.05$

**Performance**

**Golf**

There was no significant effect of Priming or Priming×Type on the performance measure during the golf task. The between-groups factor of stimulation Type was significant ($p = 0.031$) with a partial eta squared effect size estimate of 0.273, suggesting the performance of the active stimulation group was significantly than the performance of the sham group overall.

**Baseball**

There was no difference between pre- and post-stimulation performance means in the baseball experiment.

## Psychologic Measures

### Golf

In the golf experiment, Priming showed an effect on the participant's anxiety ($p = 0.001$) with a partied eta squared effect size estimate of 0.510. There was no significant effect of stimulation Type or Priming×Type interaction on the participant's feel or anxiety.

### Baseball

Participants exhibited improved feel after stimulation during the baseball experiment ($p < 0.001$) with a Cohen's d effect size of 0.93. Mean anxiety decrease after stimulation, though the effect was not significant ($p = 0.0745$) with a Cohen's d effect size of -1.75.

## Physiologic Measures

### Golf

There were no significant effects of Priming, Type, or Priming×Type interaction on EEG power in the golf experiment. The Priming×Type interaction was shown to be a significant factor in right upper trapezius EMG amplitude ($p = 0.023$). This suggests a depression effect of stimulation on upper trapezius muscle activation. This effect was not observed in the left upper trapezius EMG amplitude ($p = 0.269$). There were between-group differences in right upper trapezius EMG amplitude and HRV measures as well, suggesting overall higher upper trapezius muscle excitation and heart rate variability in the sham group.

### Baseball

Fp1 and Fp2 Beta power decreased significantly after stimulation in the baseball experiment. In Fp1, Beta 2 power (21-30 Hz) and Gamma power (31-44 Hz) significantly ($p = 0.04$ and $p = 0.01$, respectively). Only Fp2 Gamma power exhibited significantly lower

values after stimulation ($p = 0.007$), though the mean decrease in Fp2 Beta 2 power was trending toward significance ($p = 0.09$). No significant difference was exhibited in other EEG frequencies, heart rate, or heart rate variability in the baseball experiment.

### Safety

Participant's were asked to complete a safety survey immediately after and 24 hours after their participation in the baseball and golf experiments which included questions about various sensations or side effects that could have been seen from the VNS intervention. Out of the 21 total participants in the baseball and golf experiments, there were no significant adverse events that could have been caused by the VNS intervention either immediately after or 24 hours after experiment participation.

## Discussion

The improvement of performance during any task is a desirable outcome whether it may be in cognition or motor tasks. VNS in motor tasks, specifically sports, has not been investigated likely due to the mechanistic ambiguity of its observed effects. However, improving the performance of athletes can have significant impacts on their lives including emotional stability and financial wellness. Although there were no significant effects tVNS on the primary measure of performance in the baseball or golf task, there were other observations made that require further analysis.

The psychologic effects of Priming, the change in the response variables between pre- and post-stimulation, were significant in the golf and baseball experiments. Figures 4 and 5 show the effects of Priming on state and trait anxiety as well as feel exhibited during the baseball and golf tasks.

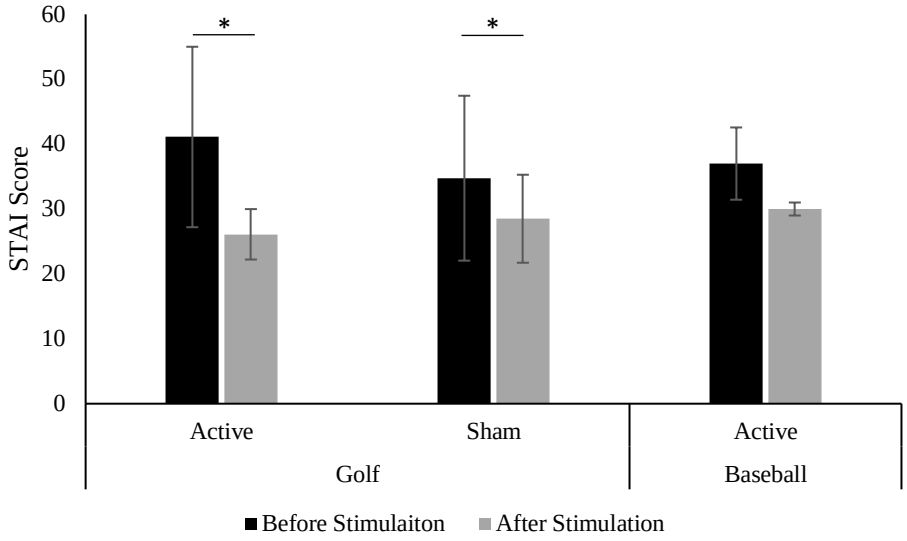


*Figure 4.* STAI results before and after stimulation, both sham and active, exhibiting the effects of Priming on state and trait anxiety with a higher score corresponding to increased anxiety. A significant decrease in anxiety was seen in both active and sham groups of the golf experiment as measured by the STAI survey ($p = 0.002$ and $p = 0.041$, respectively).

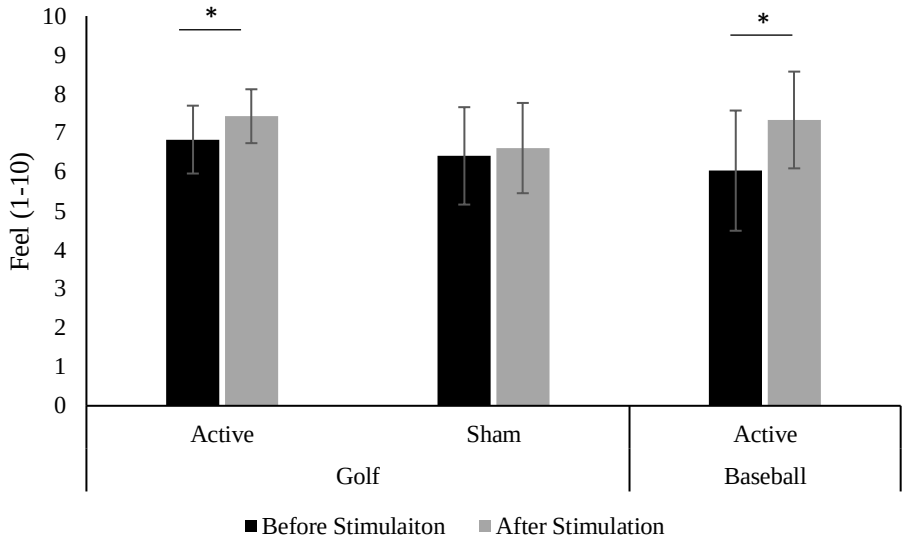


*Figure 5.* Average perceived quality of each repetition, or "feel," before and after stimulation. The active group in the golf experiment and all participants in the baseball experiment exhibited significant increases in feel after stimulation ($p = 0.026$ and $p < 0.001$, respectively)

As seen in figures 4 and 5, mean feel and STAI scores both improved after stimulation in golf and baseball. Although the trends were similar in all groups with multiple groups improving significantly after stimulation, the effect of the Priming×Type interaction was not found to be significant in either measure. However, the Priming×Type interaction had an effect size estimate ($\eta_p^2 = 0.116$) on STAI scores that suggested a medium effect on anxiety in golf. In addition, participants in the baseball experiment exhibited greater feel after stimulation ($p<0.001$) with an effect estimate ($d = 0.93$) that suggests Priming may have a large effect on Feel. Priming also had a large estimated effect size ($d = -1.75$) on anxiety in the baseball experiment which suggests that Priming may also influence anxiety while pitching, though the change in means before and after stimulation was insignificant ($p = 0.075$) It must also be noted that there was not a control group in the baseball experiment, so the effect of Priming in either of these measures cannot be determined without further experimentation. The trends and effects observed from tVNS as well as the observed changes before and after stimulation in the baseball experiment provide considerable evidence to further investigate tVNS effects on the psychology of sports populations. Not all measures were significantly affected by tVNS, but the consistent trends and effects sizes observed provide evidence of possible relationships between vagus nerve activity and psychologic wellness.

In the baseball experiment, there were significant differences in EEG power observed before and after stimulation. Beta 2 power and Gamma power both showed significant decreases after stimulation, with similar trends seen in the golf experiment. The EEG changes in the baseball experiment are seen in figures 6 and 7.

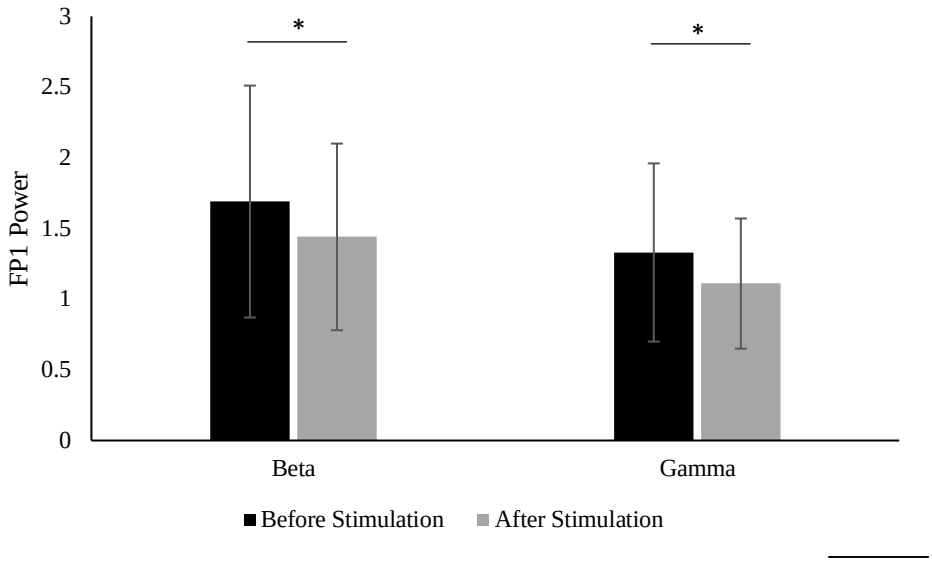


*Figure 6.* FP1 Beta 2 and Gamma power before and after stimulation in the baseball experiment

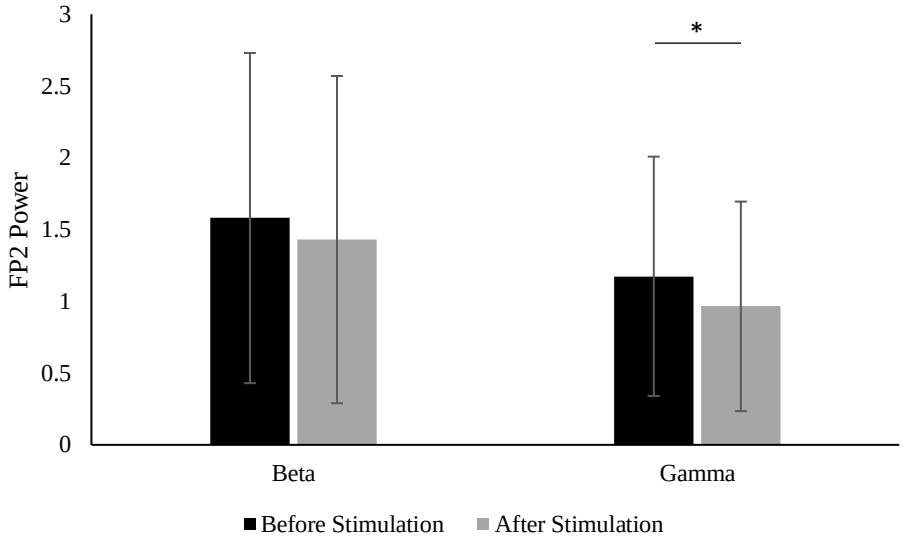


*Figure 7.* FP2 Beta 2 and Gamma power before and after stimulation in the baseball experiment.

Beta power, which includes Beta 2 and this distinction of Gamma frequencies is sometimes associated with increases in energy, anxiety and performance (Abhang, Gawali, & Mehrotra, 2016). This difference observed after stimulation in baseball with similar trends in

golf further supports the possible psychologic effects of tVNS in sports applications. The Priming×Type interaction effect was not a significant effect in Beta power in the golf experiment but had a medium estimate of effect size ($\eta_p^2 = 0.114$) on Beta power in FP2 suggesting a possible relationship that could be observed with further experimentation and a large sample size. As mentioned with the psychologic results in the baseball experiment, the lack of a control inhibits a conclusion about the effect of tVNS alone on EEG. However, the EEG trends in conjunction with the subjectively reported psychologic measures support the existence of a tVNS effect on sport psychology.

In addition to the EEG as a physiologic effect, the reduction in muscle excitation exhibited by the active stimulation group suggests a possible muscle relaxation effect of tVNS in athletes which could offer significant improvements in performance or performance mindset. The trends in left and right upper trapezius EMG amplitude are seen in figure 8.

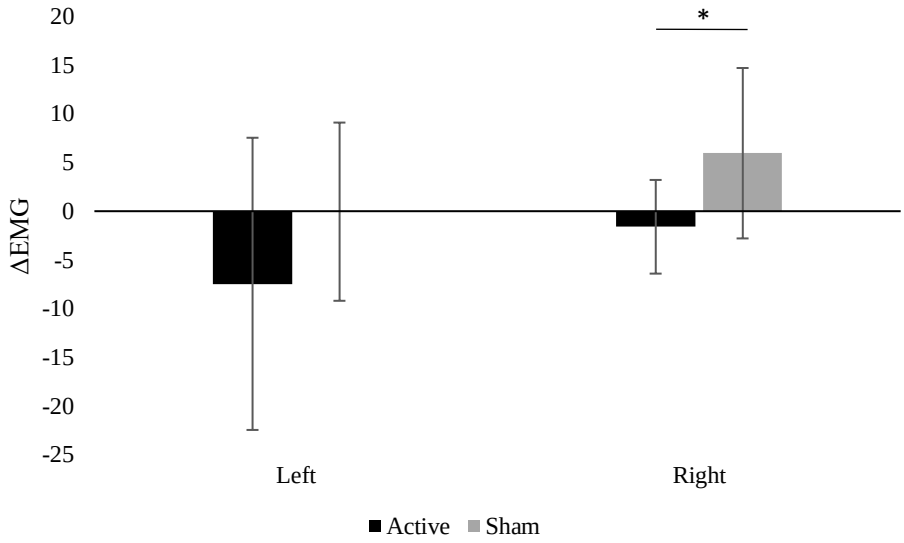


*Figure 8.* Change in average EMG from pre-stimulation to post-stimulation in the left and right upper trapezius muscle. There was a Priming×Type interaction effect ($p = 0.023$) on right upper trapezius EMG amplitude with a large estimated effect size ($\eta p2 = 0.114$).

The resulting EEG, EMG, and reduction in anxiety are trends that are expected after stimulating the vagus nerve due to its parasympathetic responsibilities. Reduction in EEG, EMG, and anxiety can be associated with a calming effect, which is a promising finding from this pilot study. In high stress and high anxiety situations, a calming effect could transfer to improved human performance, especially in sports with high mental demand and the requirement of exceptional fine motor control performance.

The lack of improvement exhibited in performance after stimulation in either the sham or active stimulation groups should not be used as evidence against the application of VNS in the tested tasks. Although performance is the primary response variable that sports science attempts to improve, it is difficult to accurately assess performance in such a controlled environment that is greatly removed from an in-game setting. There are many factors that contribute to in-game performance including confidence (Hays, Thomas, Maynard, & Bawden, 2009; Levy, Perry, Nicholis, Larkin, & Davies, 2015), which may be related to the improvement in anxiety and perceived quality of the athletes performance seen as effects of stimulation. If confidence and other performance modulators including anxiety and stress can be improved over the long run using tVNS, this should be taken into consideration when evaluating the efficacy of tVNS instead of direct performance measures alone.

**Limitations**

There are limitations to the interpretation of the present study's results outside of proving feasibility. Due to time constraints, time of year, and the overall lack of participants recruited for the baseball study, there was not enough data included in the baseball

experiment to make valid conclusions about the competitive pitching population. One of the participant's data was not included in the study due to lack of competitive baseball experience which created a floor-type error in the performance measure, and one participant who did not pitch competitively in high-school-level baseball was included despite his lack of experience because the floor effect was not exhibited. Although this data is useful to determine feasibility and prove the concept of applying electrical nerve stimulation in athletic sports, it cannot be used to make valid conclusions about the efficacy of VNS in improving physiologic measures, psychologic measures, or performance of competitive pitchers.

The baseball experiment included only 3 subjects, only one of which was independent from the Tyler Lab and Arizona State University. Two of the participants in the baseball experiment were researchers in the Tyler Lab who contributed to the design and execution of the experiment. Due to the timing of the experiment, current competitive baseball players were preparing for the upcoming season which often keeps them from participating in activities that increase the workload on their arms and bodies. The time allotted for participant recruitment did not account for this obstacle, which resulted in minimal independent data being collected for the experiment.

Additionally, the baseball and golf experiments did not randomize the experimental and control group assignments which causes aliasing in the results. Interpreting these results can be difficult and invalid if there are unknown nuisance variables that cannot be controlled. Randomization is important to provide the experimenters with as true of a control as possible. The sham group (control) is ideally a group that is nearly identical to the active stimulation group (experimental) to effectively remove as many nuisance factors from the

results to interpret the independent effect of stimulation on the various response variables. Due to the lack of randomization, this function of the sham group is not robust, though preliminary conclusions and hypotheses can be made for further testing. For the effects of priming, the results are aliased with, but not limited to, the training effect. The exhibited improvements of the response variables in the within-group analysis before and after stimulation could be affected by the comfort level of the participant after completing the task once. This must be considered when applying the findings of priming effects from the present study. These limitations are considerations that should be made with further experimentation in athletic populations and in other future behavioral work with VNS. In all, I was unable to reject the null hypothesis that there was no effect of stimulation Priming, stimulation Type, or Priming×Type on sports performance, but the results from the present study are supportive of further investigations with refined experimental methods to identify the effects of tVNS on in game performance.

**Future work**

Despite the small sample of baseball athletes included in this experiment, when combined with results from healthy populations in a golf experiment, the resulting data supports the need for further experimentation in baseball, golf, and other athletic tasks. This would involve larger samples of participants, more consistent competition levels, and longitudinal type designs to further understand the long-term effects tVNS may have on motor control and athletic performance.

To minimize some of the nuisance factors in the baseball and golf experiments, a finer participant screening can be deployed to only include data from participants with

consistent skill levels that match the skill level of the population the results are aimed to be applied. A valid sham group should also be created to control for the various nuisance factors still apparent in the data. This could entail using a within-group comparison, by having the participants come two or more times to receive sham stimulation during one session and active stimulation during the other, or just by matching, pairing, and randomizing the groups to construct control and experimental groups that are as equivalent as possible. Including a true control group that does not receive sham or active stimulation would be helpful to eliminate the training effects from the within-group analysis as well. Within-group designs create a challenge for participant recruiting due to the time requirement of the participants, and matching groups requires a large enough sample size of participants with equivalent skill levels. The heightened difficulty of recruitment must be accounted for by either allotting more time in the experimental process for recruiting subjects or providing larger monetary compensation for the participant's time. In addition, accessibility to elite athletes is a problem that many sports science researchers face; however, an extended period allotted for data collection and heightened compensation should allow for high quality participants to be recruited for both acute and longitudinal-type study designs.

The controlled and comfortable characteristics of the baseball and golf tasks could have affected the relationship between stimulation and sport performance. The improvements in anxiety and feel were not related to an increase in task performance in either experiment, which could have been a function of lacking performance anxiety. Authentic competitive sports environments include a degree of psychologic pressure from various factors including rewards for exceptional performance and the attendance of spectators that are difficult to

create in a controlled research environment. It can be hypothesized that with heightened levels of psychologic pressure in authentic competition environments, improvements in state and trait anxiety as well as feel of each repetition could be significant factors in sport performance. This should be considered for future studies to create valid and authentic competition environments.

Many behavioral investigations of VNS effects deploy it as a longer-term therapy than one 10 minutes session between two blocks of athletic tasks (De Couck et al., 2016; Desbeaumes Jodoin, Lespérance, Nguyen, Fournier-Gosselin, & Richer, 2015). This should be taken into consideration when designing future studies into tVNS effects on athletic sports performance because the feasibility demonstrated by this study suggests that it could be a therapy used throughout a season or career for those who exhibit positive effects from its use. 10 minutes of VNS can be applied before games, between innings in baseball or tee shots in golf, before practice, or daily at a convenient time during the day if chronic effects are exhibited. Many products are currently being developed to provide this type of therapy but require further research to determine their long-term safety and efficacy.

Finally, although the mechanism by which VNS modulates human performance is not currently understood, the lack of adverse events and the consistently reported safety of tVNS allows researchers to be confident that behavioral research can and should continue to maximize the impact of the observed benefits from VNS. Discovering novel applications for developing technology on healthy populations allows the impact of technological development to be as broad as possible. Not to replace the research and development of

bioelectric therapies for pathologic populations but widening the scope of similar research is a step forward for improving overall human performance.

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## Biographical Sketch

Kyle Lindley was born in Placer County, California where he grew up with one older sister in Loomis, California. After completing his high school education at Del Oro High School in 2014, he moved to Tempe, Arizona to complete his Bachelor of Science degree in Biomedical Engineering at Arizona State University. He was admitted to the Master of Science Biomedical Engineering program at ASU in the spring of 2017 to begin in the Fall. During the summer of 2017, he spent three months in Kent, Washington interning at Driveline Baseball where he learned applied principles of biomechanics and collected biomechanics data from pitchers to help improve pitcher performance and health. After completing his undergraduate degree in May of 2018, he spent the summer working for Noraxon, USA as an R&D engineering intern to develop software applications for new biosensor technology. Following the completion of his Master of Science degree in the Spring of 2019 he will be pursuing a career in research and development engineering.