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Effects of the Injury Recovery Process on Neuromuscular Activation in an Uninjured Ankle

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Effects of the Injury Recovery Process on Neuromuscular Activation in an Uninjured Ankle

A Thesis Presented
by
Mark Tankersley

To the Keck Science Department
of
Claremont McKenna, Scripps, and Pitzer Colleges
In Partial Fulfillment of The Degree of Bachelor of Arts Senior Thesis in Neuroscience
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Abstract

This study was conducted to observe the effects of changed activity levels due to a major lower extremity injury on ankle function in the uninjured leg. Neuromuscular activation in the Gastric Medialis (GAS) and Tibialis Anterior (TA), the muscles primarily responsible for movement at the ankle, was assessed in 8 athletes at the Claremont Colleges while walking on a flat surface, stepping up a 15° incline, and stepping up a 27° incline. Athletes were split into two groups based on injury condition: a “recovered” group (n=4) who had suffered a major lower extremity injury in the last two years in which the healthy limb was studied and a “healthy” group (n=4) in which either limb was selected. Electromyography (EMG) was used to measure neuromuscular activation and LabChart 8.0 was used to calculate the maximum activation level and integrated area of total activation for each respective step. Data was standardized between subjects by dividing the peak and integrated area from the 15° incline and 27° incline by the flat walking peak and integrated area for each subject. The new standardized values were plotted, and a two-way ANOVA was conducted to test for significant effects from injury condition, ramp height, or their interaction. Significance was found for the impact of ramp height (p=0.0175), subject health condition (p=0.0236), and their interaction (p=0.0472) on the integrated area of GAS activation. No significance was found for the impact of ramp height, health condition, or their interaction for GAS peak activation, TA peak activation, or TA integrated area of activation. There appears to be a trend towards decreased neuromuscular activation in the healthy limb of a recovered athlete compared to the limb of a healthy athlete especially during more demanding tasks. This suggests a reduced ability to recruit muscles to control an uninjured ankle following a
major lower extremity injury even after a full recovery. More research should be conducted to explore what implications this may have on optimal physical therapy and recovery protocols.
Introduction

Injuries can take athletes away from their sports for months and have long-term effects on their play and movement (Rui et al., 2019). At least 41% of sports-related emergency room visits for young athletes between 20-24 years of age were to the lower extremities. This makes the lower extremities the most commonly affected area for sports-related emergency room visits (Rui et al., 2019). These sports-related emergency room visits for 20-24 year-old athletes were most frequently caused by basketball, skating (ice, roller, or boarding), pedal cycling, soccer, and other unspecified activities (Rui et al., 2019). The most common form of injury in physically active populations is a lateral ankle sprain, leading to a large portion of patients with chronic ankle instability (Gribble et al., 2016).

A common trend in the treatment of most major injuries to the musculoskeletal system is the need for immobilization. Immobilization of skeletal muscles can quickly lead to atrophy, increased instability, and decreased neuromuscular activation (Booth, 1982; Geboers et al., 2000; Vandenbome et al., 1998). When a leg is injured and must be rested, through full immobilization or not, there is also a substantial change in the activity of the uninjured leg. While recovering from a lowering extremity injury, athletes are unable to run, lift, or move in other ways they typically would, causing muscles in both legs to have notably decreased usage. While the effect this has on the injured leg is well studied, the effects of this decrease in overall activity on the uninjured leg are still unknown.
Prolonged inactivity causes many adverse effects on muscular tissue and function. Prolonged bed rest has been shown to cause muscular atrophy and a loss of strength (Knight & Nigam, 2019; Paddon-Jones et al., 2006). These effects are shown to be mitigated in groups that implemented exercise routines that increased muscle use such as leg press or light jumps (Akima et al., 2001; Paddon-Jones et al., 2006). This suggests that the changes in muscular tissue and function during bed rest is due to a decreased usage of the muscles. This study aims to determine the effects of decreased activity due to lower-extremity injury on neuromuscular activation in uninjured ankles.

To properly study muscle function, we must first understand the basics of how the brain signals voluntary contractions in skeletal muscle. Signals must travel from the motor area of the cerebral cortex through the spinal cord to the neuromuscular junction. At the neuromuscular junction, acetylcholine is used to create electrical signals within the muscle fibers, causing them to contract (Evarts, 1979; Merton, 1972; Hof, 2003; Sam & Bordoni, 2023; Michel, 2013). Understanding how well this signal is transmitted to the muscle is a key component in understanding how well a muscle is functioning.

Neuromuscular activation in skeletal muscles can be measured using electromyography (EMG). EMG uses electro-sensitive electrodes to measure a change in muscle activity. Figure 1 shows raw EMG data with time in seconds on the x-axis and muscle activity in mV on the y-axis.

Figure 1: Raw EMG Data with time in seconds on the x-axis and muscle activity in mV on the y-axis
in electrical potential between the electrodes and therefore the electrical activity in the muscle (Michel, 2013, Hof, 1984; Stegeman et al., 2000). For large muscles, this can be done on non-invasive surface electrodes (Michel, 2013, Stegeman et al., 2000). Surface electrodes stick to the skin outside of the muscle and are able to measure electrical signals in the muscle without needing a needle to enter the muscle. This allows us to collect EMG on muscles of interest with much less risk and reduced discomfort to the subjects.

The two muscles that are primarily responsible for ankle function are the Gastrocnemius Medialis (GAS) and Tibialis Anterior (TA). The GAS is responsible for plantar flexion: the flexion of the front of the foot down and away from the shin. The TA is the primary driver of dorsiflexion: the movement of the front of the foot up and towards the shin. Both of these muscles are critical in gait and balance (Brocket & Chapman, 2016; Wolfson et al., 1995). Because of how important these muscles are to gait and balance, a change in their function would have a large impact on the subject’s

Figure 2: TA muscle (left) and GAS muscle (right) in red (Sendic, 2023)
daily life. This made the GAS and TA the clear choice among muscles controlling the ankle to focus on in the study.

To observe changes in neuromuscular activation in response to stimulus athletes would encounter in their everyday life, common movements that taxed the GAS and TA to varying levels were needed. Walking, a type of gait, requires both the GAS and TA to be functioning to be performed. In previous experiments, walking on an incline was shown to have an increased demand on the GAS while having no increase in demand on the TA. Contrarily, walking on a decline was shown to have an increased demand of the TA but no increase in demand of the GAS (Alexander & Schwameder, 2016; Slider et al., 2012; Franz & Kram, 2012). These movements can be used to observe differences in responding to an increase in muscular demand between health condition groups. While measurements of both incline and decline were taken, only the incline ramp data is addressed in this thesis due to time constraints.
Methods

Participants

Participants were recruited from NCAA and club sports teams at the Claremont Colleges. All participants had been fully cleared to participate in their sports before participating in the study. Participants were split into two groups: 4 recently injured and 4 uninjured participants totaling 8 participants. The injured group was qualified as having had an injury below the waist that took them out of their sports for two weeks or more. Participants ranged from 18-22 years of age and were measured for weight and height.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Total (n=8)</th>
<th>Healthy (n=4)</th>
<th>Recovered (n=4)</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender (M/F)</td>
<td>6/2</td>
<td>4/0</td>
<td>2/2</td>
<td></td>
</tr>
<tr>
<td>Height (cm)</td>
<td>178.8±10.7</td>
<td>179.1±8.0</td>
<td>179.7±14.1</td>
<td>0.88</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>87.6±33.8</td>
<td>87.4±43.1</td>
<td>87.7±28.1</td>
<td>0.99</td>
</tr>
</tbody>
</table>

*Table 1: Participant statistics: gender, height, and weight of the “healthy” group, “recovered” group and total participants.*

EMG Set-Up

Neuromuscular activation was measured in the GAS and TA, the two muscles primarily responsible for control of the ankle. EMG was collected using ADInstruments PowerLab and LabChart 8.0 with electrodes placed vertically on the center GAS and TA without overlapping. Finally, a ground electrode was placed on the bony lateral malleolus on the ankle.
Walk and Ramp

Measurements of ankle neuromuscular activation were taken in participants while walking as well as stepping up a ramp onto a box. The ramp trials were separated into a 15º incline and a 27º incline. EMG was recorded while subjects repeated each movement for twenty seconds and the data was labeled for the timing of foot placement. Each subject repeated each movement (walking, 15º incline step, and 27º incline step) twice.
EMG Analysis

All EMG data was analyzed in LabChart 8.0. Data was smoothed with the “Smoothsec” function which calculates a moving average over 0.5 sec. The root mean square of the smoothed data was used to calculate the peak EMG and the integral over a 5-second period. This process was repeated for two separate steps in each subject; an average of these two steps was used at that subject’s data point. Ramp data was divided by the subject’s corresponding walking data to standardize between subjects.

Test Statistic and Assumption Testing:

An ANOVA two-way test was performed to test for significantly different activation levels between groups. All calculations were performed using “R” in Google Colab. Tests of homogeneity of variance and normality of the data were performed to ensure the ANOVA two-way test assumptions were met.

Two-Way ANOVA Assumption Testing:

Gastrocnemius Peak:

Figure 5: Residuals vs Fitted Plot. The relationship between residual and fitted values does not appear to be significant, fitting the two-way ANOVA assumptions.
A Levene's test of homogeneity of variance was performed and a p-value of 0.455 was obtained. This value is greater than the threshold of significance at 0.05 so it fits the two-way ANOVA assumptions.

![Q-Q Plot](image.png)

Figure 6: Normality Plot of Residuals. The data approximately follows the reference line with a couple outliers.

The normality of residuals was plotted. The data approximately follows the reference line with two outliers. A Shapiro-Wilk normality test was performed and a p-value of 0.006979 was obtained. This failed the assumptions of a two-way ANOVA test. An ANOVA test was calculated regardless, but this failure of conditions should be considered when interpreting the data.
Gastrocnemius Integral:

Figure 7: Residuals vs Fitted Plot. No evident relationship between residual and fitted values is present, fitting the two-way ANOVA assumptions.

A Levene's test of homogeneity of variance was performed and a p-value of 0.141 was obtained. This value is greater than the threshold of significance at 0.05 so it fits the two-way ANOVA assumptions.

Figure 8: Normality Plot of Residuals. The data approximately follows the reference line.
The normality of residuals was plotted. The data approximately follows the reference line; this fits the assumptions of a two-way ANOVA. A Shapiro-Wilk normality test was performed and a p-value of 0.7368 was obtained. The GAS Integral data fits all assumptions, and a two-way ANOVA test was performed.

Tibialis Anterior Peak:

![Residuals vs Fitted Plot](image)

*Figure 9: Residuals vs Fitted Plot. A relationship between residual and fitted values is present, failing the two-way ANOVA assumptions.*

A Levene's test of homogeneity of variance was performed and a p-value of 0.455 was obtained. This value is greater than the threshold of significance at 0.05 so it fits the two-way ANOVA assumptions.
The normality of residuals was plotted. The data does not follow the reference line; this fails another assumption of a two-way ANOVA. A Shapiro-Wilk normality test was performed and a p-value of 0.01077 was obtained: another failure of two-way ANOVA assumptions. A two-way ANOVA test was performed anyway, but these failures of assumptions should be considered during the interpretation of the data.
Tibialis Anterior Integral:

A Levene's test of homogeneity of variance was performed and a p-value of 0.577 was obtained. This value is greater than the threshold of significance at 0.05 so it fits the two-way ANOVA assumptions.

The normality of residuals was plotted. The data approximately follows the reference line except for one large outlier; this still fails the assumptions of a two-way
ANOVA. A Shapiro-Wilk normality test was performed and a p-value of 0.06336 was obtained: fitting two-way ANOVA assumptions. The GAS data does not fit all assumptions, but a two-way ANOVA test was still performed. This should be considered when analyzing the results of the test.
Results

Gastrocnemius Peak:

GAS peak activation appears to be larger and more variable on the 27° ramp than on the 15° ramp. There also appears to be higher peak GAS activation in the healthy subjects than in the recovered group. There is one large outlier in the 27° healthy group that had a much larger peak activation (compared to walking) than any other subject.

Figure 13: Gastrocnemius activation peak (standardized by dividing by each subject’s walking peak) in mV plotted for two different ramp heights. Blue represents the healthy group and Yellow represents the healthy leg of a recovered subject.
Two-Way ANOVA Results

<table>
<thead>
<tr>
<th>Variable</th>
<th>F Value</th>
<th>P Value</th>
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<tbody>
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<td>Health Condition</td>
<td>2.482</td>
<td>0.141</td>
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<tr>
<td>Ramp Height</td>
<td>1.698</td>
<td>0.217</td>
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<tr>
<td>Combined Effect</td>
<td>1.092</td>
<td>0.317</td>
</tr>
</tbody>
</table>

*Table 2: Two-way ANOVA Results for GAS Integral*

A two-way ANOVA test found no statistical significance for ramp height (p=0.217), health condition (p=0.141), or their interaction (p=0.317) with GAS peak activation to support any of the visual trends.

**Gastrocnemius Integral:**

*Figure 14: Gastrocnemius activation Integral (standardized by dividing by each subject’s walking integral) in mV plotted for two different ramp heights. Blue represents the healthy group and Yellow represents the healthy leg of a recovered subject.*
The GAS activation integral appears similar between the healthy and recovered group for the 15° ramp but largely dissimilar for the 27° ramp. The healthy group shows a massive jump in integrated activation from the 15° ramp to the 27° while the recovered group’s activation integral does not appear to increase much if at all between the two groups.

Two-Way ANOVA Results:

<table>
<thead>
<tr>
<th>Variable</th>
<th>F Value</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Health Condition</td>
<td>6.709</td>
<td>0.0236</td>
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<tr>
<td>Ramp Height</td>
<td>7.571</td>
<td>0.0175</td>
</tr>
<tr>
<td>Combined Effect</td>
<td>4.889</td>
<td>0.0472</td>
</tr>
</tbody>
</table>

*Table 3: Two-way ANOVA Results for GAS Integral*

Statistical significance was found for ramp height, health condition, and their interaction with the GAS activation integral supporting the visual trends observed above.

**Tibialis Anterior Peak:**

![Tibialis Anterior activation peak](image)

*Figure 15: Tibialis Anterior activation peak (standardized by dividing by each subject's walking peak) in mV plotted for two different ramp heights. Blue represents the healthy group and Yellow represents the healthy leg of a recovered subject.*
TA activation peak appears to be higher for the healthy group than for the recovered group in both ramp conditions. There also appears to be an increase in TA activation peak for the 27° ramp compared to the 15° ramp in both groups. The difference between ramps is better defined in the recovered group but possibly larger in the healthy group. There is one large outlier for both ramp conditions in the healthy group with very large levels of activation compared to walking.

Two-Way ANOVA Results:

<table>
<thead>
<tr>
<th>Variable</th>
<th>F Value</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Health Condition</td>
<td>0.132</td>
<td>0.7225</td>
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<tr>
<td>Ramp Height</td>
<td>3.206</td>
<td>0.0986</td>
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<tr>
<td>Combined Effect</td>
<td>0.065</td>
<td>0.8028</td>
</tr>
</tbody>
</table>

*Table 4: Two-way ANOVA Results for GAS Integral*

Statistical significance was not found for health condition (p=0.7225), ramp height (p=0.0986), or their combined effect (p=0.8028). While not below the 0.05 significance threshold that is standard for the field, a p-value < 0.1 for the ramp height condition should be noted.
**Tibialis Anterior Integral:**

![Box plot showing TA activation integral](image)

*Figure 16: Tibialis Anterior activation integral (standardized by dividing by each subject's walking integral) in mV plotted for two different ramp heights. Blue represents the healthy group and Yellow represents the healthy leg of a recovered subject.*

There does not appear to be any significant change in integrated TA activation for either the health or ramp condition.

**Two-Way ANOVA Results:**

<table>
<thead>
<tr>
<th>Variable</th>
<th>F Value</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Health Condition</td>
<td>1.021</td>
<td>0.332</td>
</tr>
<tr>
<td>Ramp Height</td>
<td>0.039</td>
<td>0.847</td>
</tr>
<tr>
<td>Effect</td>
<td>0.208</td>
<td>0.656</td>
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</table>

*Table 5: Two-way ANOVA Results for GAS Integral*

No statistical significance was found for ramp height (p=0.332), health condition (p=0.847), or their interaction (p=0.656) for GAS peak activation.
Discussion

The main objective of this study was to investigate the effect of changed activity levels during injury recovery on neuromuscular activation in an uninjured ankle. Despite the small sample size (n=8), a significant effect of health condition (p=0.0236), ramp height (p=0.0175), and their interaction (p=0.0472) was found in the integrated area of GAS activation. As seen in Figure 14, the difference in activation levels between health conditions was much larger for the 27° ramp than for the 15° ramp. This suggests the reduction of neuromuscular activation in the healthy limb of recovered individuals compared to healthy individuals becomes more consequential as tasks increase in muscular demand.

It is important to note that subjects were standardized by dividing each subject’s ramp data by the subject’s walking data. This changes all the data to a ratio of activation compared to walking instead of raw activation levels for any given task: a subtle but important distinction when interpreting the data. This means that the data demonstrates a reduced increase in neuromuscular activation as tasks increase in difficulty rather than overall lower levels of activation.

When looking at Figure 13, the GAS activation peak shows similar trends to that of the GAS activation integrated area. Despite no significance found by the two-way ANOVA for health condition (0.141), ramp height (p=0.217), or their interaction (p=0.317), this visual trend is still worth noting as significance is difficult to attain with such a small sample size. If the lack of significance is only caused by the small sample size, overall GAS activation ability is likely diminished for athletes who have recovered from a major lower extremity injury. If the lack of significance observed in GAS peak
activation indicates a lack of difference between health conditions, then recovered athletes appear to have an issue not with their maximum activation level, but rather with their ability to maintain high levels of activation over the entirety of the foot placement. This could be explored further with a more robust version of this study.

GAS activation appears to increase between the 15º ramp and the 27º ramp. This increase is expected as the GAS is the primary muscle responsible for plantar flexion, which becomes more demanding as ramp steepness increases. This visual trend holds statistical significance for the GAS integrated area of activation (p=0.0175) but not for GAS peak activation (p=0.217). This indicates that the increase in muscular demand for the steeper ramp increases demand for sustained activation rather than maximum activation.

TA peak activation, when observed visually in Figure 15, appears to be reduced in the recovered group compared to the healthy group. TA peak activation also appears to increase in the 27º ramp from the 15º ramp. These trends would imply an increased demand from the TA from steeper ramps and a decreased ability to compensate for that extra demand from the recovered group. These differences, however, do not hold statistical significance. This could indicate both no change in demand of the TA with a change in ramp height and no change in peak TA activation between health conditions.

At this point in data interpretation, it is important to consider that our data values being compared are indicative of an increase in activation when compared to walking rather than raw activation levels. This means the data more precisely measures the ability to increase activation levels in response to an increase in muscular demand. Due to no increase in muscular demand of the TA being observed between ramp heights, it
may also be the case that no increase in TA muscular demand exists between flat walking and the ramp. If no increase in muscular demand is present, there is no reason a difference between health conditions would be present, even if a difference in the ability to compensate for difficult tasks is present. To further test any changes in peak TA activation due to injury recovery, a movement with a higher TA demand than walking or a way to standardize subjects other than walking data must be utilized.

When visualizing the integrated area of TA activation in Figure 16, the difference in TA activation between the 15° ramp and the 27° ramp appears to be very small or not present at all. The small visual difference between ramps is not supported by statistical significance (p=0.847) suggesting that sustained TA activation is not affected by the steepness of the incline, an important consideration when interpreting the impact of injury recovery on TA activation.

Both visually in Figure 16 and numerically (p=0.332) there appears to be no effect of health condition on the integrated area of TA activation while stepping up an incline. This may indicate one, or both, of two possible interpretations. The first and most obvious interpretation is that recovery from a major lower extremity has no effect on sustained TA neuromuscular activation on the uninjured leg. It is also important to consider another possible reason for the data collected. If the sustained level of TA activation does not change between the 15° ramp and 27°, it is likely that there is not an increased demand for TA activation between walking and stepping up a ramp. Further evidence of this can be seen in the confidence interval of both the integral and peak TA activation in Figures 15 and 16. The confidence interval of all conditions in these figures either includes or approaches a value of 1 on the Y-axis. This indicates little or no
difference in TA activation between the walking and ramp trials. Due to the TA being primarily responsible for dorsiflexion, it is likely that muscular demand does not increase while stepping on an incline. If there is no change in demand of the TA between flat and stepping on an incline, any changes in TA activation due to injury recovery would not show in the ratio. While either one of these interpretations could be sufficient to justify the data observed, it is certainly also possible that both are true. A change of procedure to a movement that increases the demand of the TA when compared to walking or a different method of standardizing subjects would be needed to make further determinations of which effect(s) is(are) being observed.

While this study provides some valuable insight into a very understudied and relevant subject matter, there were some difficulties encountered that should be considered when determining the weight of its results. Due to a limited time frame and several difficulties that came with performing a unique experiment for the first time, the sample size of usable data (n=8) was smaller than ideal. This small sample size limited statistical power and made it difficult to detect any impacts of ramp or health conditions that were not extreme.

In addition, there were several sources of possible bias. First, health condition groups were not controlled for gender or sport played which could affect GAS or TA activation levels. Due to limited resources and a limited pool to sample from, we were not able to control for the severity of injury, method of recovery, or time since injury aside from the injury taking the subject out of their sport for 2 weeks or more in the last 2 years. Additionally, due to the nature of injury, it is impossible to complete a double-blind study. While the researchers were not aware of any subject’s health
condition while collecting the data, a subject’s knowledge of their own injury could affect the way the movements were executed. It is also important to consider how fatigue between multiple trials, while likely slight, may have an effect on neuromuscular activation.

Finally, due to time restrictions, a large quantity of the data collected could not be analyzed. Data was collected from a total of 17 subjects before data collection was forced to a halt due to issues with the location of the data collection. The majority of the subjects’ data sets were incomplete and could not be used for analysis. Additionally, subjects completed a step down the decline of the same ramps as well as tests of isokinetic dorsiflexion and plantar flexion strength. Maximum force produced was recorded for the isokinetic measurements and EMG was recorded for both the isokinetic tests and the decline step. The decline step could provide valuable information on the effects of TA activation and the isokinetic data could give insight on activation, strength, their interaction, and the relation of all that to injury. Subjects were also recorded with a Qualisys motion capture system. This data would be relevant in understanding the effects of injury on gait mechanics and range of motion during natural movements (walking flat, incline, and decline).

Despite the shortcomings of this study, I think it is an important indication of the need to study the effects of injury and the recovery process on uninjured parts of the body. There is very little available in the literature about the effects of major lower extremity injuries and the recovery process on the function of the uninjured leg despite its relevance to so many people. Observing statistically significant differences of integrated GAS activation between health conditions (p=0.0236) with a sample size of 8
indicates a clear impact of injury on an uninjured ankle is present and sizable. Further and improved study of the effects of lower extremity injuries on uninjured ankles and more generally, the effects of major injuries on uninjured body parts would be highly clinically relevant. Physicians and physical therapists could use information from these studies to better inform both recovery and rehabilitation procedures to minimize effects on the uninjured limb from the recovery process and maximize recovery from these effects.

There are many steps further studies could take to build and improve upon the results found in this study. The first would be an increase in the robustness and sample size of the study. A study with a larger sample size would have more statistical power to accept or reject any effects of injury recovery on the uninjured limb as well as detect effects that are smaller in magnitude. An overall more robust study may also be able to control for more possible confounding variables including gender, sport played, time since injury, severity of injury, and treatment undergone. Future studies should also record more steps from each subject to average together and minimize errors from measurement or differences between steps. Future research should also be conducted to look at the effects of injuries and the recovery process on other parts of the body and the movements they are responsible for. Included in this, the TA should be observed with a more relevant movement. Finally, research should be conducted to look at the effects of injury and the recovery process on factors outside of neuromuscular activation. Strength, atrophy, bone density, range of motion, and biomechanics are all well-studied effects of injury that are largely understudied in the uninjured leg and all carry immediate clinical relevance.
Despite the difficulties encountered in this study, it is an important first step in understanding an understudied aspect of human injuries and injury recovery. The reduction in the integrated area of GAS activation observed in the uninjured limb of athletes who have recovered from a major lower extremity injury when compared to healthy athletes indicates an important effect of injury and the recovery process on uninjured ankles. Further study of the effect of injuries and the recovery process on uninjured body parts should be conducted and used to direct future recovery and rehabilitation protocols.
Acknowledgments

I would like to thank my first reader, Professor Monroy, for her continued guidance, support, and patience throughout this entire study and thesis. I would like to also thank my second reader, Professor Solomon-Lane for her advice and encouragement. Thank you to Professor Kohn for his help with the statistical analysis and to my lab partners Caitlyn Pham and Joey Asta for their tireless efforts in the study design and data collection process. Finally, I would like to thank my family and friends for their constant support and encouragement.
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