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Ergonomic Evaluation of a Novel Endoscope Grip Adaptor Using Surface Electromyography

A Thesis submitted in partial satisfaction of the requirements
for the degree Master of Science

in

Bioengineering

by

Hyeongmin Kim

Committee in charge:

Professor Shanglei Liu, Chair
Professor John Thomas Watson, Co-Chair
Professor Nathan Joseph Delson
Professor Mary Lee Krinsky
Professor Bruce Christopher Wheeler

2022

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University of California San Diego

2022

DEDICATION

In recognition of the ceaseless support, luminous insight, infinite patience, and unwavering faith in me during this entire graduate journey, this thesis is dedicated to the love of my life – My Wife.

In recognition of fostering a sense of scientific curiosity, instilling a drive to push my limits, and teaching me the joy of learning, this thesis is also dedicated to my late father.

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LIST OF ABBREVIATIONS

ACGIH	American Conference of Governmental Industrial Hygienists
APB	Abductor pollicis brevis
DC	Duty cycle
EMG	Electromyography
FCR	Flexor carpi radialis
FDI	First dorsal interosseous
FRV	Fatigue risk value
MVC	Maximum voluntary contraction
MVICT	Maximum voluntary isometric contraction test
TLV	Threshold Limit Value

ACKNOWLEDGEMENTS

I would like to acknowledge Professor Shanglei Liu for his support as the chair of my committee. His guidance coming from an interdisciplinary background of bioengineering and surgery has proven to be invaluable. I would also like to acknowledge Professor Nathan Joseph Delson for his tremendous role in overseeing this interdisciplinary team of doctors and engineers as well as providing key mechanical insights. Lastly, I would like to acknowledge Professor Mary Lee Krinsky for providing guidance through her expertise in endoscopy.

In addition, I would like to acknowledge Professor Jason Gillette of Iowa State University and Professor Dominic Ferrey of UCSD Health for their assistance in verifying the surface electromyography-based ergonomics study design.

ABSTRACT OF THE THESIS

Ergonomic Evaluation of a Novel Endoscope Grip Adaptor Using Surface Electromyography

by

Hyeongmin Kim

Master of Science in Bioengineering

University of California San Diego, 2022

Professor Shanglei Liu, Chair
Professor John Thomas Watson, Co-Chair

Gastroenterologists suffer from high incidence rates (37% - 89%) of work-related musculoskeletal injuries due to the rigorous and repetitive nature of performing endoscopy procedures. We designed and evaluated the efficacy of a novel endoscope grip adaptor (EndoGrip) in improving the ergonomics of endoscopy by using surface electromyography to assess the change in muscle fatigue and risk of injury as 7 subjects performed simulated endoscopy with the

barehand, a competitor grip device, and the EndoGrip. Using the EndoGrip significantly reduced the mean fatigue in the first dorsal interosseous (FDI) and flexor carpi radialis (FCR) muscles when compared to those of the barehand trials for most male subjects, with an average reduction of 11.7 % MVC and 17.3 % MVC, respectively. As for the female subjects, using the EndoGrip resulted in a significant increase in the mean fatigue for the FDI with an average increase of 37.7 % MVC and no change in the mean fatigue for the FCR. Both groups displayed an upward trend in the mean fatigue of the abductor pollicis brevis (APB), with an average increase of 16.6 % MVC for the male subjects and 44.4 % MVC for the female subjects. These identified trends resulting from the comparison of the barehand, competitor grip, and EndoGrip trials offered insight into the mechanisms under which the EndoGrip impacts the ergonomics of endoscopy as well as how the EndoGrip compares to a commercially available product.

INTRODUCTION

Gastroenterologists are often at risk of developing musculoskeletal injuries and disorders due to the repetitiveness, physical and mental rigor, and unnatural postures involved in endoscopic procedures. Of these procedures, the colonoscopy is one of the most common and physically demanding procedures due to the high gripping and torquing forces required to manipulate a thin and lubricated endoscope. Although modern-day flexible video endoscopes have been designed with the safety of the patients in mind, the safety of the physicians has been largely overlooked. As a result, 39% of gastroenterologists who performed colonoscopies reported at least one injury or pain associated with colonoscopy, with this jumping to 47% for physicians who performed more than 30 colonoscopies per week (Shergill, 2009). Gastroenterologists in general have very high incidence rates of injuries, with a range of 37% to 89% reporting musculoskeletal injury and 21% seeking medical help (Bessone, 2021). These injuries can shorten the career and reduce the clinical volume of a gastroenterologist in the face of increasing demand for them due to the growing aging population and the lowered screening age for colon cancer.

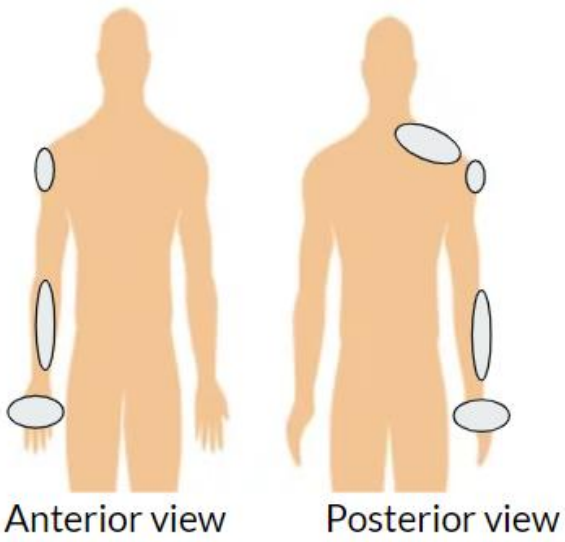

Figure 1: Commonly reported areas of pain and injury on the right side of endoscopists

As a continuation of a UCSD project started by the Delson Lab in the Department of Mechanical and Aerospace Engineering, we designed a novel endoscope grip adaptor (EndoGrip) to combat this continuing public health crisis. The EndoGrip attempts to address the right-hand side pains and injuries attributed to gripping and torquing of the endoscope by reducing the amount of forces necessary. This should lead to a reduction in muscle fatigue and decreased risk of injury.

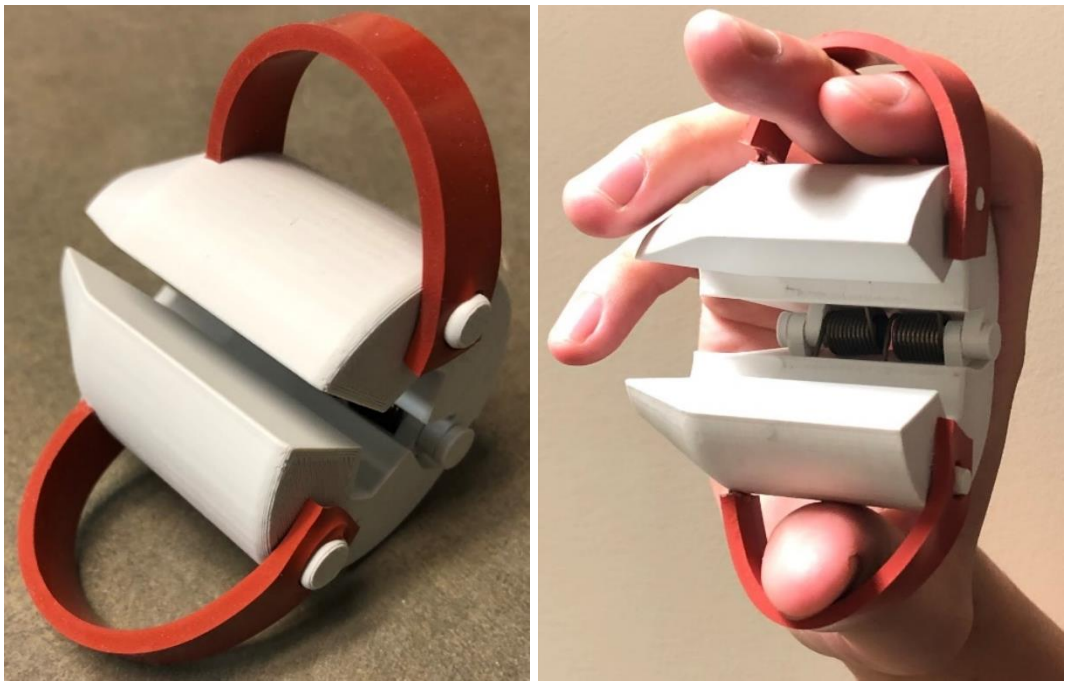

Figure 2: The EndoGrip – a novel endoscope grip adaptor

In this thesis, we evaluate the efficacy of our device by using surface electromyography (EMG) data to quantify the reduction in muscle fatigue and risk of injury during unidirectional (clockwise), statically simulated colonoscopies. These simulations were designed to be unidirectional in order to better isolate the effect of fundamental motions of colonoscopy on muscle fatigue. We utilize methodologies commonly reported in EMG-based ergonomics literature to compare the effects of the barehand, a competitor grip device, and the EndoGrip on the average muscle fatigue and the rate of muscle fatigue. We hypothesize that using the EndoGrip

will positively impact the ergonomics of colonoscopy by reducing the average muscle fatigue as well as the rate of fatigue.

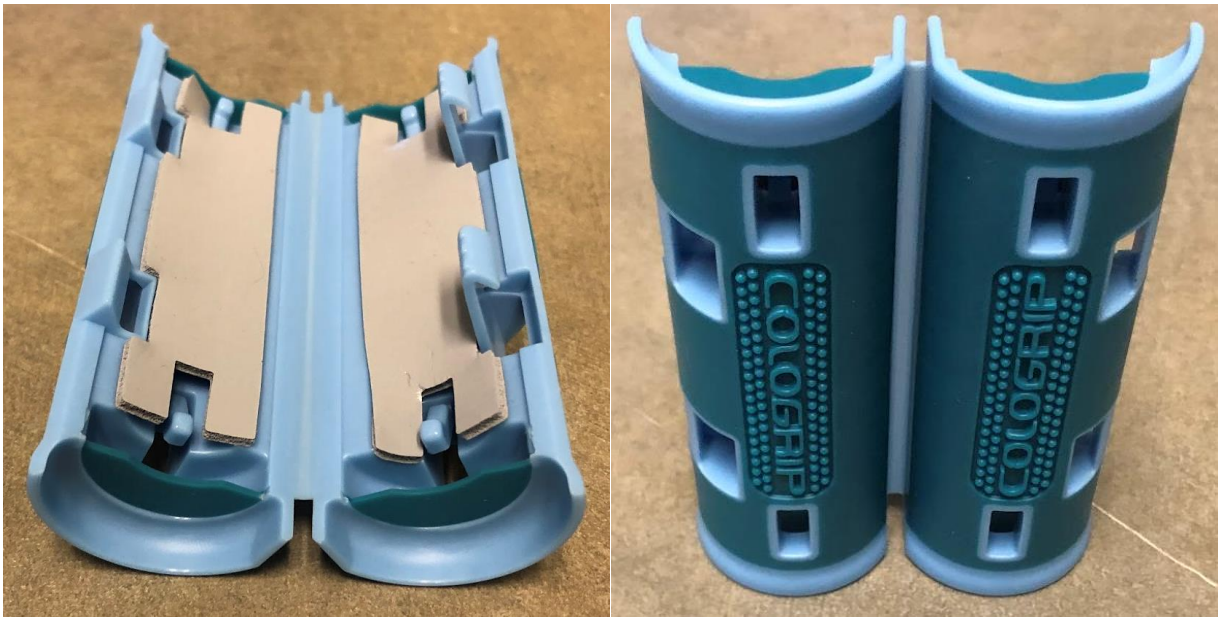

Figure 3: The ColoGrip – a commercially produced competitor device (Meditech Endoscopy Ltd., UK)

CHAPTER 1: EXPERIMENTAL SETUP

1.1 Electromyography basics

Electromyographic (EMG) signal is an electrical signal that propagates from contracting muscles. Muscles are fundamentally composed of motor units, which consists of one alpha motor neuron and the muscle fibers innervated by it. This means that the EMG signal is fundamentally composed of motor unit action potentials, which consists of electrical activity that emanates from contraction of a single motor unit. Continuous muscle contractions produce chains of action potentials, which results in a signal that is the temporal and spatial summation of all those action potentials. Finally, we measure this EMG signal at the surface of the skin, which will have been affected by the filtering properties of the tissues through which it has traveled.

1.2 Muscle selection

The aim of this thesis is to evaluate the efficacy of the EndoGrip in reducing muscle fatigue. Since our device is designed to address the right-hand side injuries attributed to the gripping and torquing of the endoscope, we have chosen muscles on the right upper extremities that facilitate the motions involved in colonoscopy. Other selection criteria for choosing the muscles to measure included being a commonly reported area of pain and injury, being a superficial muscle easily targeted by surface EMG, and having been studied in other literature.

The selected muscles of interest are the first dorsal interosseous (FDI), the abductor pollicis brevis (APB), and the flexor carpi radialis (FCR). FDI facilitates the abduction of fingers and assists in the adduction of the thumb which contributes to a strong gripping power. APB facilitates the abduction of the thumb from the plane of the palm and assists in forming a power grip with the hand, which is when the thumb opposes the four fingers as the whole palmar surface of the hand and fingers are used to grasp an object. This is the most powerful gripping position. FCR is one of

the primary wrist flexors and facilitates the flexion of the wrist which contributes to the clockwise torquing force enacted on an endoscope (Neumann, 2002).

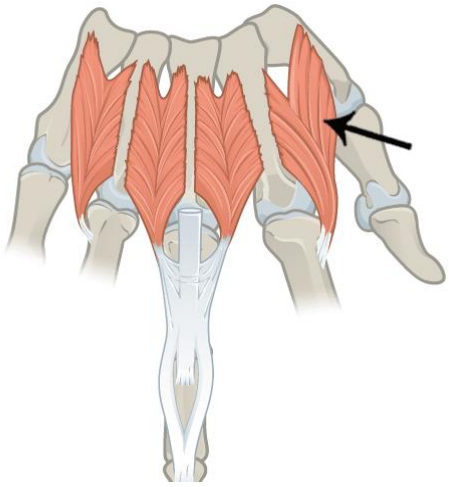

Figure 4: First dorsal interosseous (FDI) as seen from dorsal side of right hand (indicated by arrow)

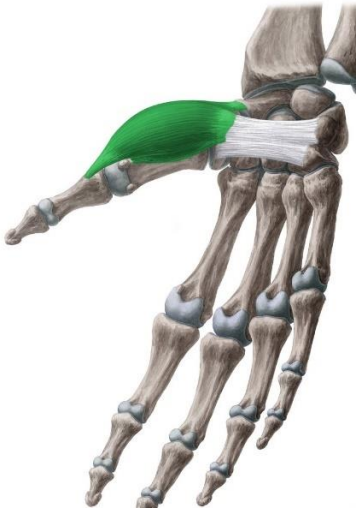

Figure 5: Abductor pollicis brevis (APB) as seem from palmar side of right hand (highlighted in green)

Figure 6: Flexor carpi radialis (FCR) as seen from anterior side of right forearm (highlighted in green)

1.3 Maximal voluntary contraction (MVC)

Surface EMG data can be fickle to capture and analyze properly as the exact location of the sensors, sweatiness at the skin, amount of hair, level of subcutaneous lipids, hydration level, and day-to-day physical condition of the subject can alter the quality and strength of the detected signals. In order to account for these variabilities and allow cross-subject or cross-temporal comparisons, we must normalize all acquired EMG data to the corresponding subject's maximal voluntary contraction (MVC). MVC is the maximum EMG amplitude measured from a muscle of interest during maximal isometric contraction of the muscle against a static resistance. Normalization of the EMG data leads to all EMG amplitudes having units of % MVC in the results. This creates a more meaningful dataset, as the EMG amplitudes are not raw voltages anymore, but rather a measure of *relative* muscle activation for a specific subject. Now that we are rid of raw EMG amplitudes which held ambiguous implications, we can more effectively and validly perform inter-subject comparisons.

1.4 Threshold Limit Values

The American Conference of Governmental Industrial Hygienists (ACGIH) has published a Threshold Limit Value (TLV) for upper limb localized fatigue. This TLV curve is an ergonomic

risk-assessment tool that serves as a guideline for acceptable levels of physical exertion (in units of % MVC) for given amounts of time the muscle is active during a task. Being above the threshold means that there is a potential risk of injury due to muscle fatigue and overuse arising from repetitive tasks. In this thesis, we use TLV to assess the levels of fatigue and risk of injury resulting from using different grip types.

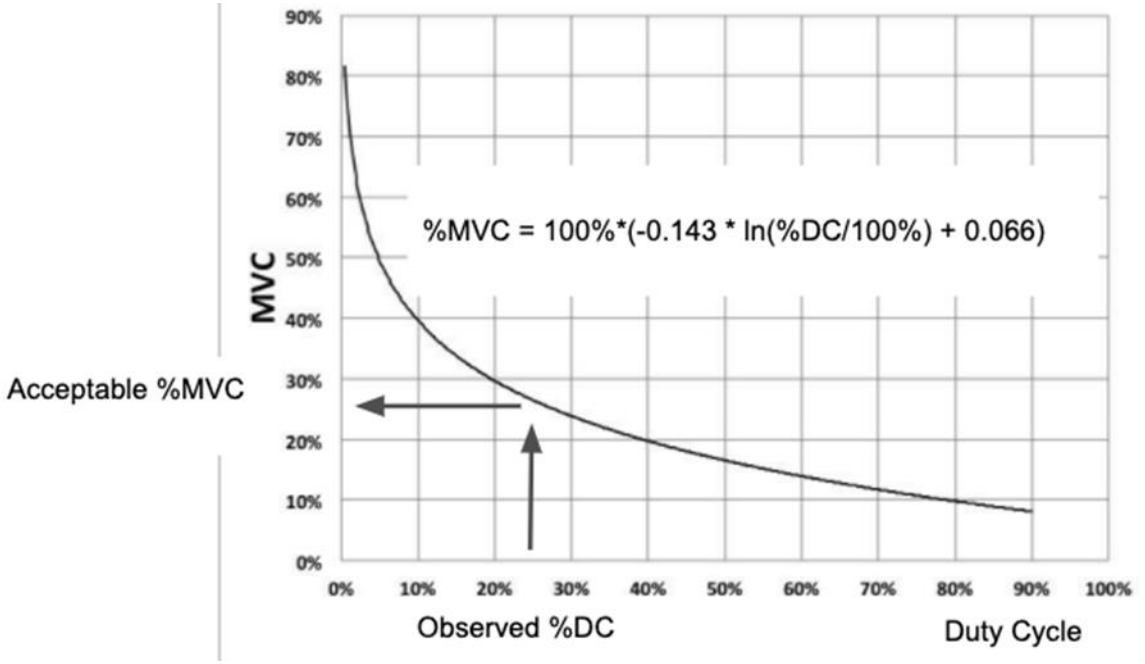

Figure 7: American Conference of Governmental Industrial Hygienists Threshold Limit Value Curve for Upper Limb Localized Fatigue (ACGIH, 2016)

1.5 General data processing

All EMG signals are inspected during and after data collection to remove any non-physiological artifacts, such as sensor detaching, electrode losing good contact with skin, and sensor bumping into surroundings.

Custom code was written in MATLAB for all data processing. Data was first filtered through a notch filter at 60 Hz to eliminate the powerline interference picked up by the wireless EMG sensors. Then, a bandpass filter from 20 Hz to 400 Hz was applied to remove high frequency noise. The filtered data then underwent full wave rectification so that all amplitudes are positive.

We applied a low-pass filter at 10 Hz to create a linear envelope of the signal. Lastly, we calculated the moving window average for a window size of 1 second. These general data processing steps are applied to all acquired EMG data.

1.6 Sensor type

The Trigno Lite System from Delsys, Inc was used to collect surface EMG data from the muscles of interest. The system consists of three fundamental components: sensors, base station, and USB receiver. For the sensors, we used the Trigno Duo Sensors, which have a sensor body and a cabled sensor head. The sensor body acts as a reference and the sensor head detects EMG signals from the targeted muscle. The sensors communicate with the base station and computer via USB receiver and transmits data using a proprietary RF protocol (2.4 - 2.483 GHz ISM Band) to time-synchronize all sensors and minimize sensor latency. Using differential amplification, we can obtain high fidelity, low noise EMG signals.

The sensors are housed in an environmentally sealed enclosure made of durable polycarbonate with an internal magnetic switch. Lack of a mechanical switch allows for more durability and a seamless seal. The self-contained rechargeable lithium polymer battery is designed for continuous use between 2 - 6 hours, depending on sensor mode. The LED indicator on the sensor body gives user feedback in terms of battery charge monitoring and sensor status indicator. Although the sensors are environmentally sealed and water resistant, the sensors should not be submerged in liquid. The fixed parallel bipolar bar electrodes of length 12mm and interelectrode distance of 10mm on the sensor head and sensor body are made of 99.99% silver. While widely accepted, and even recommended, as optimal material for surface EMG sensor electrodes, silver can cause an allergic reaction in people with silver allergies and thus should not be used on such populations.

Lastly, the sensor body and sensor head are affixed to the skin via a 4-slot and 2-slot adhesive interface, respectively. The interface is made of a medical grade adhesive that has been approved for dermatological applications.

The electrodes are pure silver, which is quite soft and can be easily damaged. Sensors were handled with caution to prevent denting or scratching the electrodes. The sensors were also kept clean of dermis, skin oils, and other debris by wiping with isopropyl alcohol swabs. Although the adhesive interface is approved for dermatological use, subjects with sensitive skin may still experience mild temporary irritation and redness.

Figure 8: Trigno Lite System with its main components - sensor, base station, and USB receiver

Figure 9: Trigno Duo sensors with two cabled sensor heads

Figure 10: Sensor head measures EMG activity from muscles of interest and sensor body acts as reference, using differential amplification to obtain high fidelity, low noise EMG signal

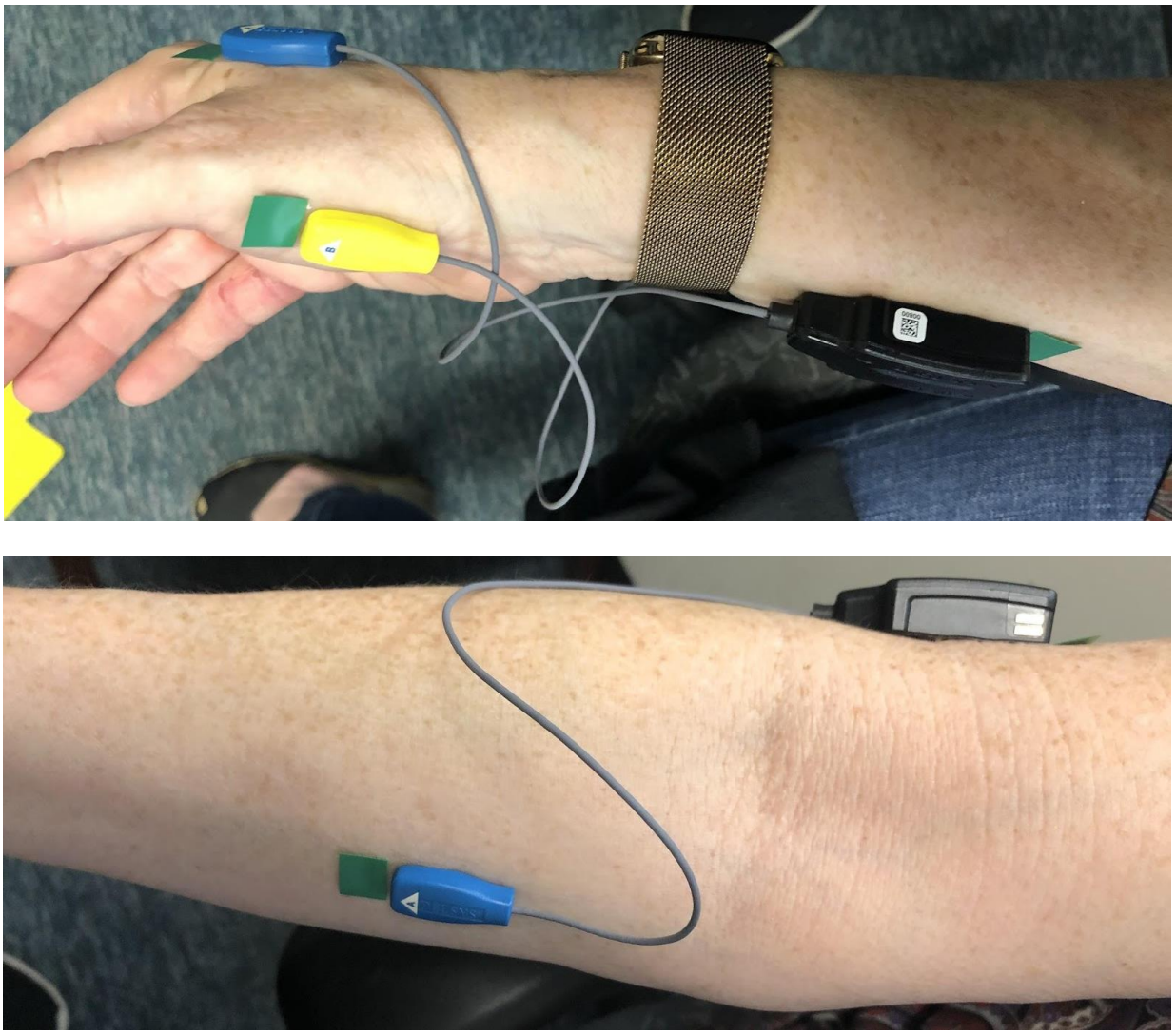

Figure 11: Trigno Duo sensors attached to subject via adhesive interfaces to measure EMG signals from first dorsal interosseous (FDI) and abductor pollicis brevis (APB) (top), and flexor carpi radialis (FCR) (bottom)

1.7 Placement

Before placement of sensors, the area of skin directly covering the targeted muscles was prepared appropriately. All excessive hairs should have been removed from the skin, although no subjects required this step of preparation. The skin was wiped clean with alcohol swabs. This allows for the best electrode-to-skin contact as it minimizes extraneous impedances observed at the sensor. Sensors were placed so that it is over the belly of the muscle (portion of muscle with

maximal mass during contraction) with the bar electrodes positioned perpendicular to the directionality of the muscle fibers (Hermens, 2000).

1.8 Locations

The sensor location is defined as a point at a relative distance along a line formed by two anatomical landmarks. The point acts as the center of the two bipolar electrodes. After placement, test contractions were carried out to ensure a good electrode-to-skin contact. Subjects carried out lower intensity versions of MVICT exercises for test contractions. We also used the sensor heads as probes to fine-tune the exact location on the muscle to acquire strongest signals.

For FDI, the sensor location is defined as the halfway point along the line formed by the proximal margins of the first and second metacarpophalangeal joints.

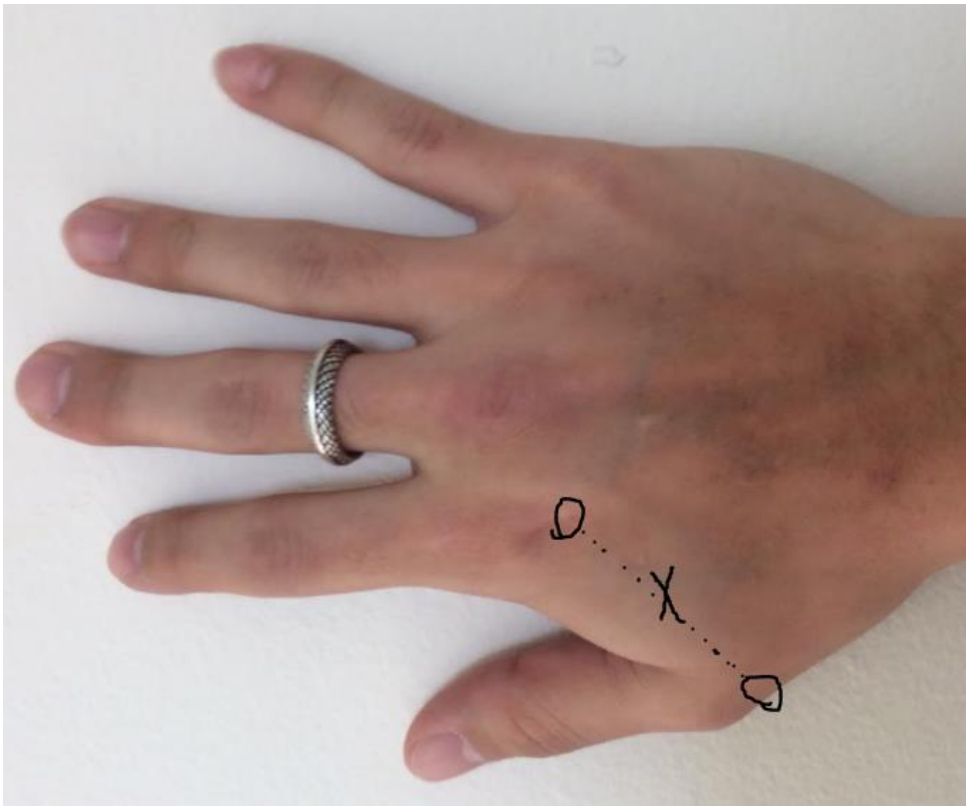

Figure 12: Sensor location for FDI (X = location, O = anatomical landmarks)

For APB, the sensor location is defined as the halfway point along the line formed by the first metacarpophalangeal joint and the scaphoid bone.

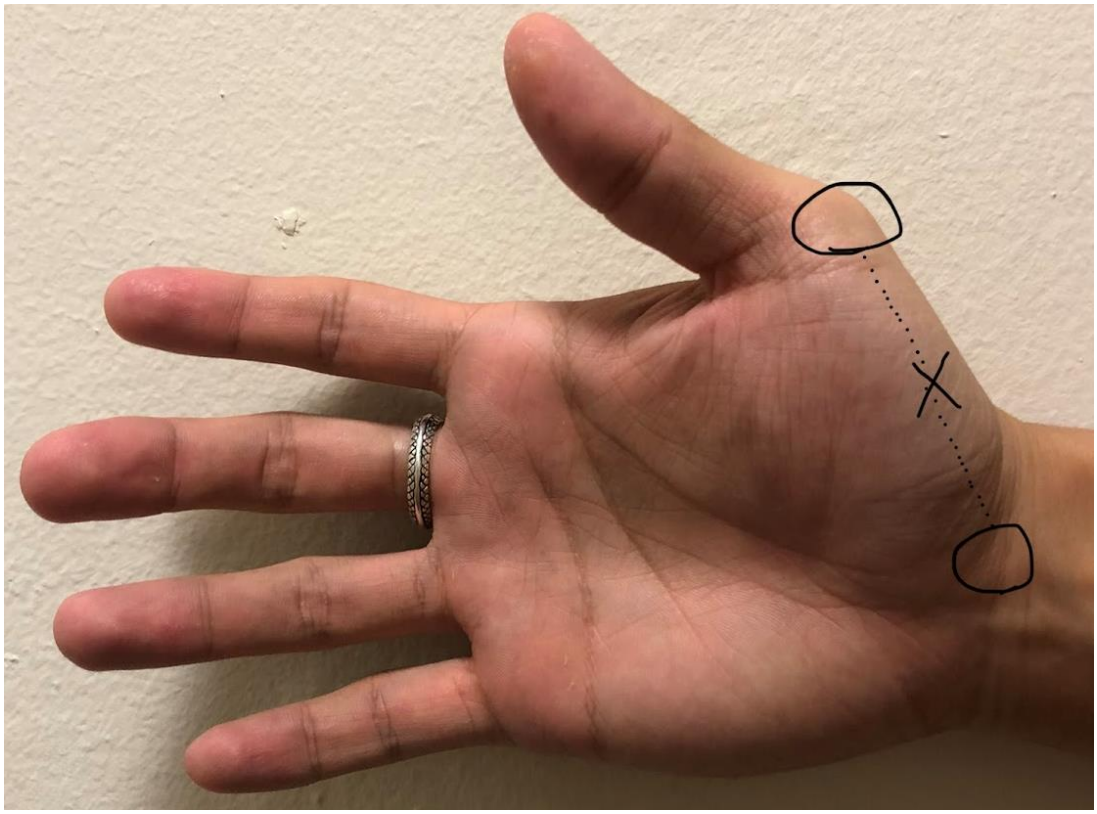

Figure 13: Sensor location for APB (X = location, O = anatomical landmarks)

For FCR, the sensor location is defined as the point at a third of the way from the medial epicondyle along the line formed by the medial epicondyle and the lateral-most tendon visible on the anterior distal forearm (proximal margin of the scaphoid bone).

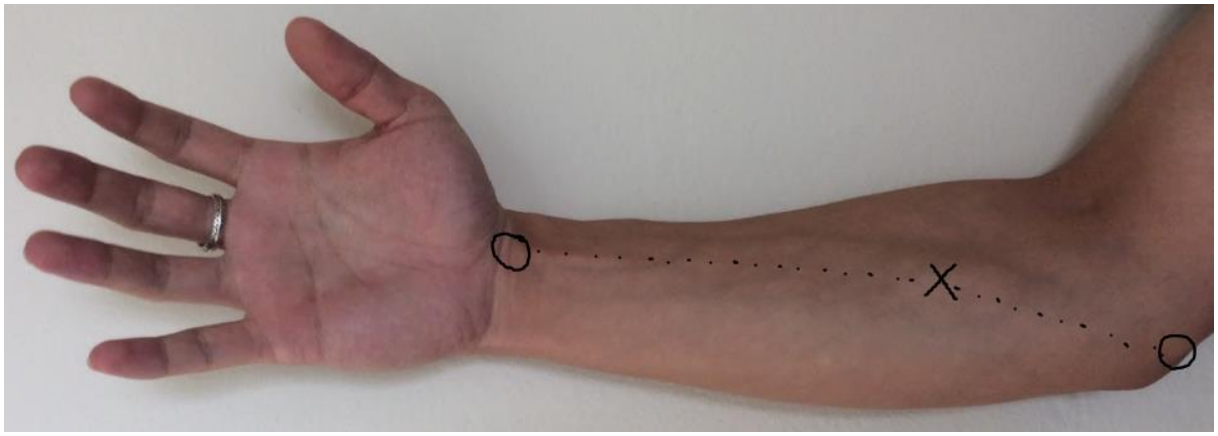

Figure 14: Sensor location for FCR (X = location, O = anatomical landmarks)

CHAPTER 2: EXPERIMENTAL PROCEDURE

2.1 Maximal Voluntary Isometric Contraction Test exercises

As discussed in chapter 1, we must normalize all EMG data to the corresponding subject's MVC since we aim to draw comparisons between different times and subjects. MVC is the maximum EMG amplitude measured from a muscle of interest during maximal contraction of the muscle. To standardize the MVC acquisition process, maximal voluntary isometric contraction test (MVICT) exercises verified and outlined in other literature were used for each muscle group. Each exercise was sustained for 5 seconds (3 second ramp up with 2 seconds at maximum). Three trials with 60 seconds of rest between each trial was carried out for each targeted muscle, with 60 seconds of rest between sets for each muscle. The subjects were verbally encouraged to generate a contraction as forceful as possible during these exercises.

For FDI and APB, the traditional way of measuring MVC from the hand (power grip test) was modified to differentiate between the varying diameters of the grip types (Dahlqvist, 2018). The exercise can be described as a maximal isometric grip using the different grip types against a static resistance, in the form of a rigid mock endoscope, while the shoulder and forearm are in neutral positions and the elbow is at a comfortable level of flexion so that the hand is at around waist height.

Figure 15: Power grip test, traditionally used for measuring MVC for the hand

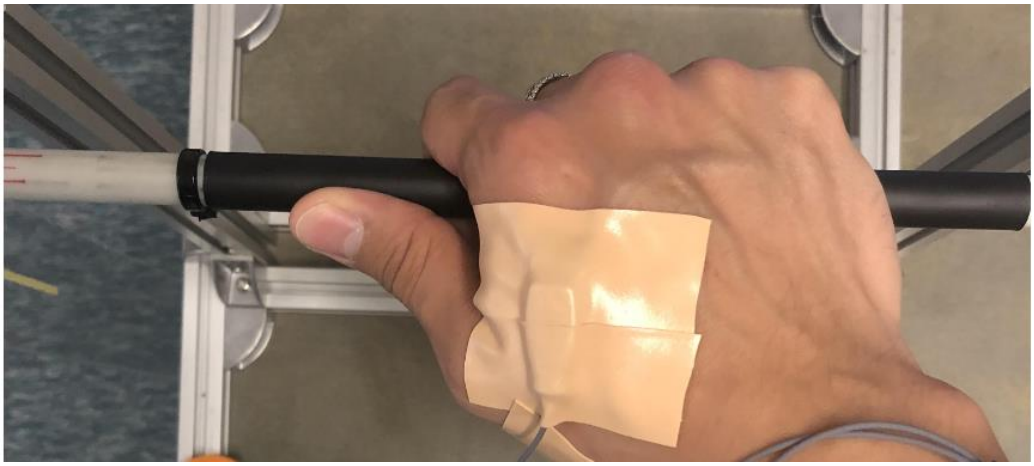

Figure 16: Barehand MVICT exercise for FDI and APB

Figure 17: Competitor grip MVICT exercise for FDI and APB

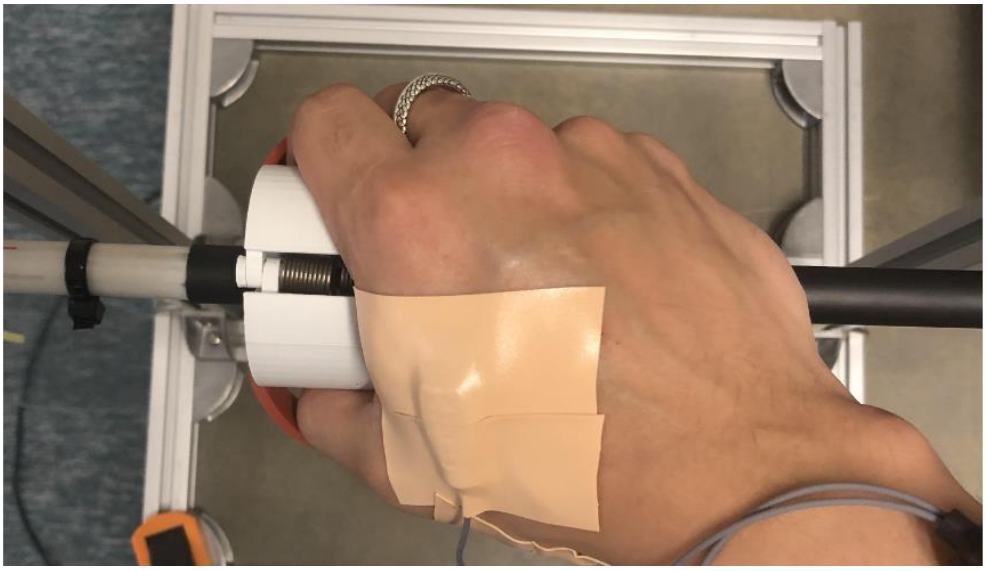

Figure 18: EndoGrip MVICT exercise for FDI and APB

For FCR, the exercise can be described as a maximal isometric wrist flexion against a static resistance, in the form of a yoga strap wrapped around the hand at the metacarpophalangeal joints, with forearm supinated and resting on an armrest at sitting height while the elbow is at a comfortable level of flexion and the shoulder is in neutral position.

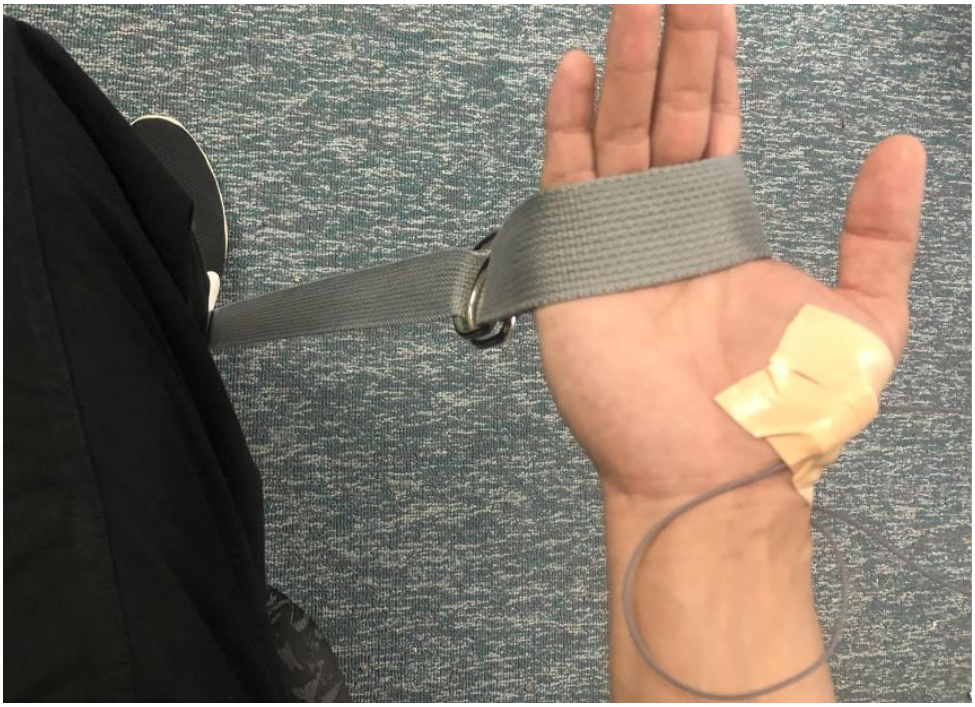

Figure 19: Resisted wrist flexion MVICT exercise for FCR

2.2 Statically simulated colonoscopy

After all the MVICT exercises had been completed, all 7 subjects performed statically simulated colonoscopy on the test bed. The test bed was designed so that fundamental motions involved in colonoscopies, such as gripping and torquing, could be executed. A rigid mock endoscope with a pendulum attached at one end is held between two journal bearings. This allowed for rotational movements which meant the torque forces enacted by the subjects could freely transfer through the mock endoscope. The weight and moment arm of the pendulum posed a controlled load opposing the subjects' torque forces.

On the test bed, subjects performed statically simulated colonoscopies by repeatedly gripping and torquing the mock endoscope clockwise with their right hands. At the start of the trial, the subject was prompted to grip and torque the mock endoscope clockwise so that the pendulum swung to at least 30 degrees. This position was held for 5 seconds before a 5 second rest period during which the grip was released, and the hand was relaxed. A single trial was 4 minutes

long and consisted of 24 cycles, with each subject performing three trials, one trial per grip type (i.e., barehand, competitor grip, and EndoGrip). The shoulder and elbow was flexed at comfortable angles while the feet were oriented slightly at an angle to facilitate comfortably gripping the test bed situated at waist height directly in front of the subject.

Figure 20: Test bed in idle (left) and test bed in active use by subject (right)

CHAPTER 3: EXPERIMENTAL RESULTS – MEAN FATIGUE RISK VALUE

3.1 Normalization

General data processing steps were applied to all EMG data as outlined in chapter 1. The MVC value is the highest mean EMG in a one second interval from the MVICT exercise dataset. The MVC values from three trials are then averaged to yield one MVC value for a given subject and muscle. We normalized the EMG data from the test bed trials in terms of % MVC so that

$$\% \text{ MVC} = (\text{EMG} / \text{MVC}) * 100\%.$$

For the test bed dataset, we now have continuous, changing % MVC over the time course of the trials, which allows for more intuitive interpretation of the data. Essentially, all EMG data from the test bed trials have been normalized to represent the amount of muscle activity *relative* to a given subject's maximal capacity.

3.2 Mean fatigue risk value assessment

In order to assess the impact of the different grip types on mean muscle fatigue reduction, we utilize the American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Value (TLV) curve for upper limb localized fatigue. The TLV curve characterizes recommended levels of % MVC based on duty cycle (DC), or the amount of time a muscle was active (i.e., % MVC > 5%) *relative* to the total duration of the task. Being above the recommended level means the muscle is overused and at risk of injury. DC is calculated as a percentage. With this known, we can input into the ACGIH TLV curve equation

$$\text{TLV} = 100 * (-0.143 * \ln (\text{DC}/100) + 0.066)$$

which yields TLV, or the acceptable level of % MVC for a given DC, above which risk of fatigue and injury exists.

The TLV (in units of % MVC) is subtracted from the mean normalized EMG amplitudes, which is the average level of relative muscle activity for all the times a muscle was active, in order to generate a fatigue risk value (FRV) for each muscle. The FRV is a metric that directly measures the distance of our data point from the TLV curve and is expressed as

$$FRV = \text{mean EMG} - TLV$$

Which serves as a predictor of potentially increased risk of injury (Gillette, 2019). It also allows for the consolidation of the EMG data for a given muscle and grip type into a representative state. A positive FRV will reflect that the mean normalized EMG amplitude is higher than the TLV (i.e., above the curve), and thus at higher than recommended levels of exertion and risk of injury. We use the FRVs of muscles resulting from the test bed trials to compare the impact of the barehand, competitor grip device, and the EndoGrip on overall muscle strain.

Each trial was 4 minutes long, with 24 cycles of the same motion (gripping and torquing clockwise). If the entire trial were treated as a single task, the mean normalized EMG would be a temporally diluted representation of the levels of fatigue since cycles from early on in the trial would have different responses than those from later on in the trial. Treating two consecutive cycles as a single event (i.e., treat each trial as a series of 12 events) allowed for more temporal resolution as well as decrease the standard deviations of the mean FRV within each subject.

The mean FRV was calculated for each of the 7 subjects (5 male, 2 female), 3 muscles, and 3 grip types. Within a given subject and muscle, three paired t-tests were performed comparing the mean FRV resulting from the different grip types (i.e., barehand vs competitor grip, competitor grip vs EndoGrip, barehand vs EndoGrip).

3.3 Results

Subject 1:

The mean FRV was significantly reduced in the FDI ($p=4.304 \times 10^{-6}$) and FCR ($p=2.476 \times 10^{-5}$) when comparing the barehand to the EndoGrip during statically simulated colonoscopies. On the other hand, the mean FRV was significantly increased in the APB ($p=6.214 \times 10^{-10}$) when comparing the barehand to the EndoGrip. Although there were significant differences across all the muscles, we observed no shift in polarity of the FRV values. That is, even though the mean FRV for FDI was reduced, it was still positive (meaning above the TLV). Similarly, the mean FRV for FCR was already negative (meaning below the TLV) for the barehand even though there was significant reduction in the EndoGrip. In addition, even though the mean FRV for APB was increased, it was already positive for the barehand. Lastly, the EndoGrip significantly outperformed the competitor grip in its FRV reducing capabilities for the FDI ($p=2.050 \times 10^{-7}$) and FCR ($p=3.512 \times 10^{-4}$), while not being any different in its effect on the APB ($p=0.5044$).

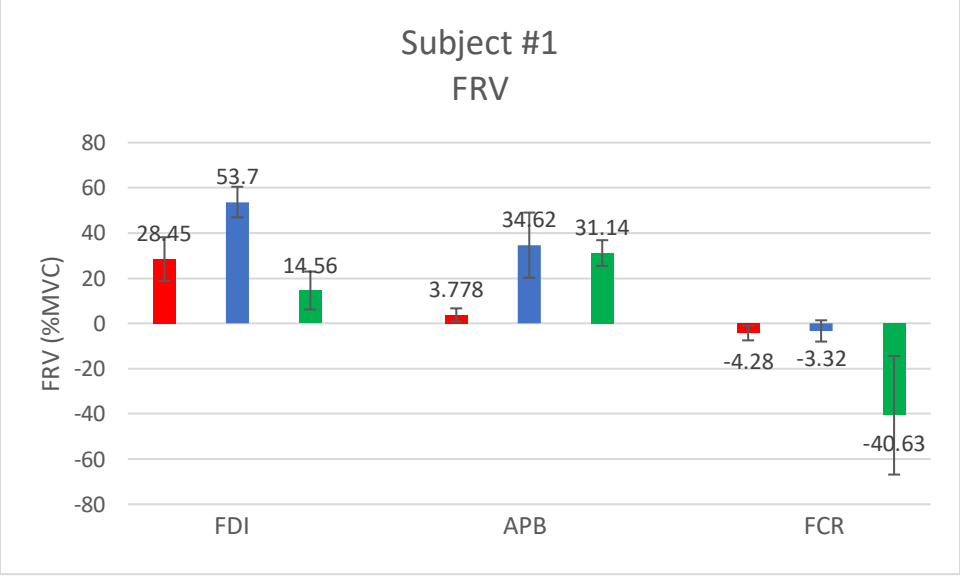

Figure 21: Mean FRV for each muscle and grip type for subject 1 (red – barehand, blue – competitor grip, green – EndoGrip)

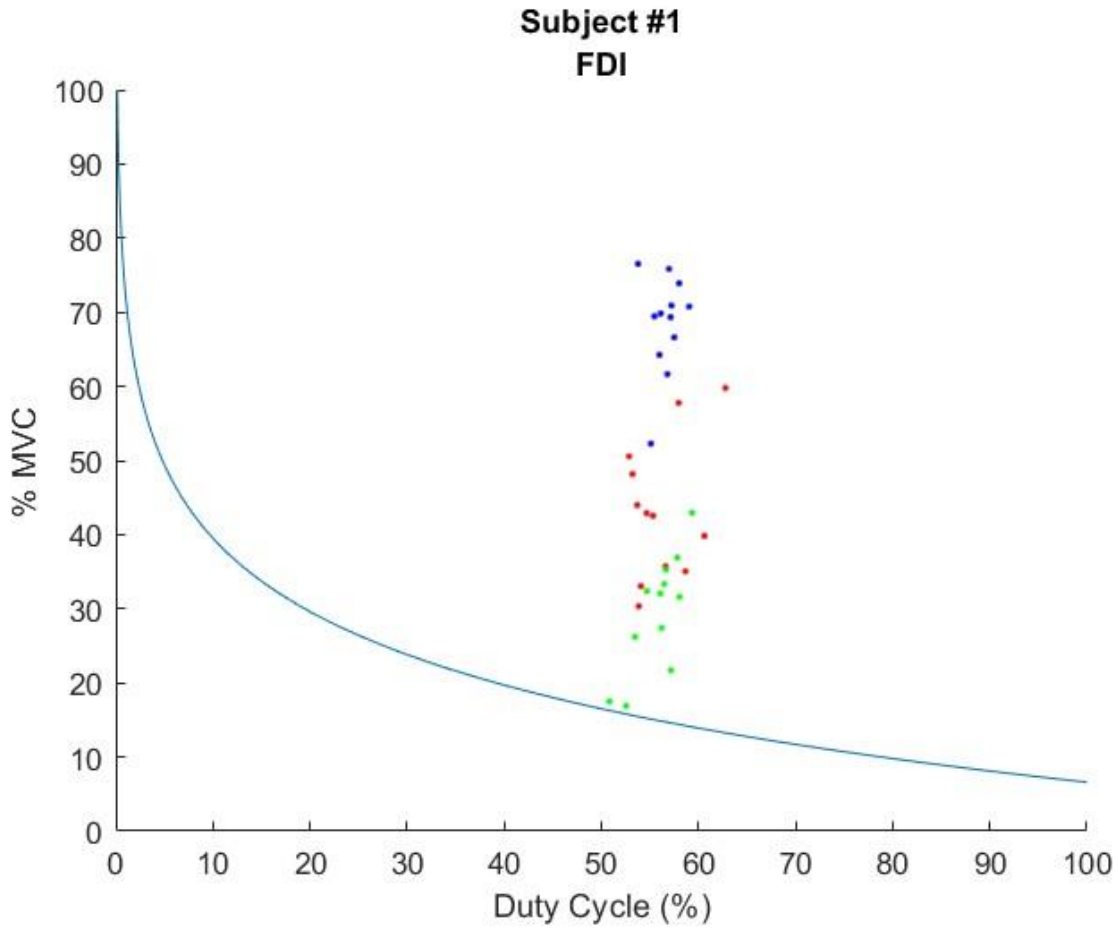

Figure 22: All events from each grip type plotted against TLV curve for FDI of subject 1 (red – barehand, blue – competitor grip, green – EndoGrip)

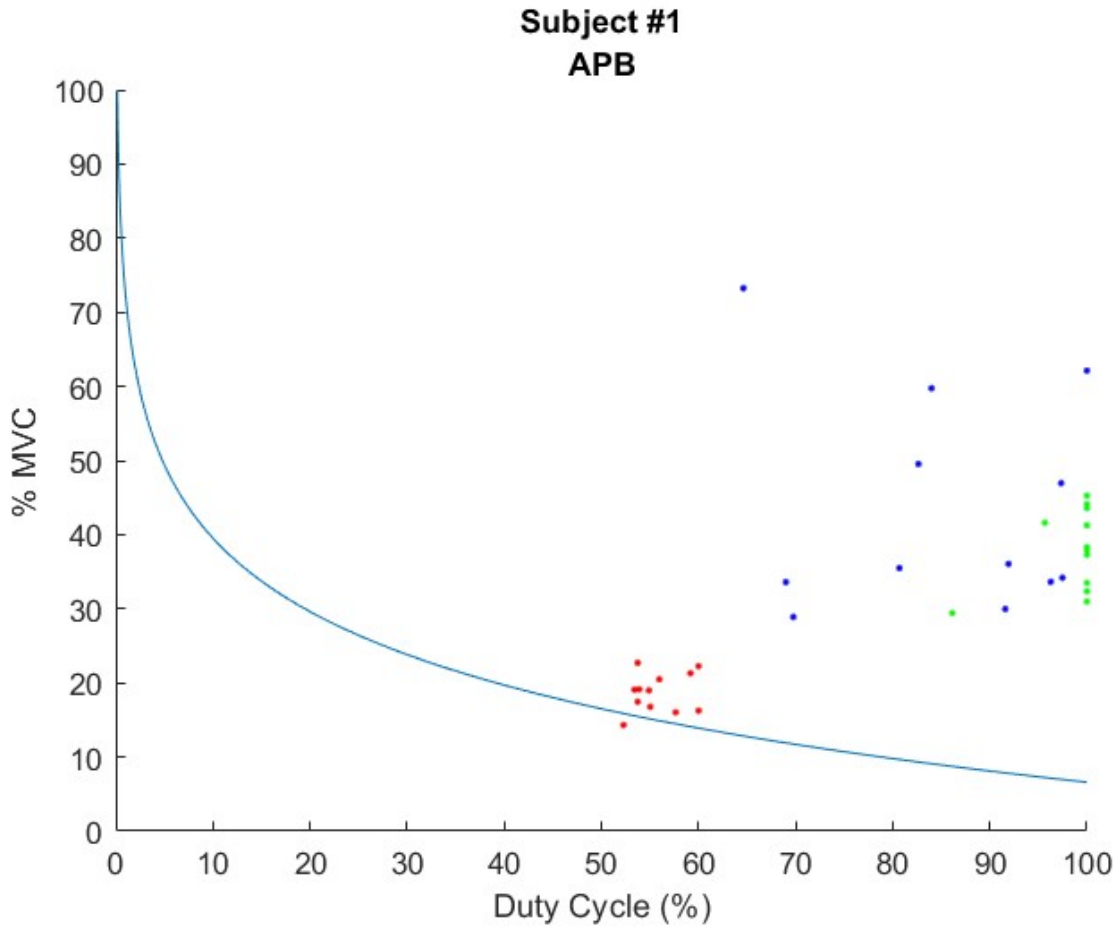

Figure 23: All events from each grip type plotted against TLV curve for APB of subject 1 (red – barehand, blue – competitor grip, green – EndoGrip)

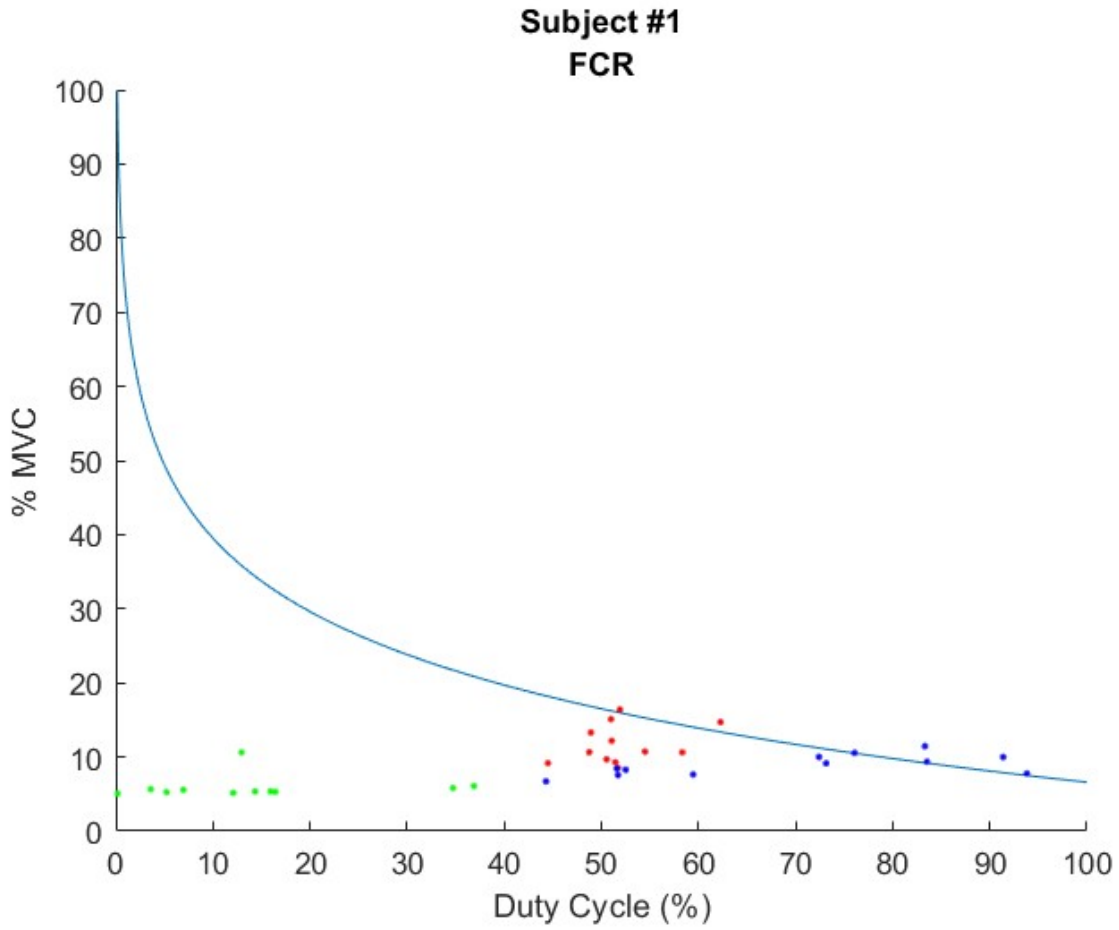

Figure 24: All events from each grip type plotted against TLV curve for FCR of subject 1 (red – barehand, blue – competitor grip, green – EndoGrip)

Subject 2:

The mean FRV was significantly reduced in the FDI ($p=5.562 \times 10^{-4}$) and FCR ($p=0.0019$) when comparing the barehand to the EndoGrip during statically simulated colonoscopies. On the other hand, the mean FRV was significantly increased in the APB ($p=2.476 \times 10^{-5}$) when comparing the barehand to the EndoGrip, as well as the competitor grip to the EndoGrip ($p=0.0394$). Although there were significant differences across all the muscles, we observed no shift in polarity of the FRV values. That is, even though the mean FRV for FDI was reduced, it was still positive (meaning above the TLV). Similarly, the mean FRV for FCR was already negative (meaning below the TLV) for the barehand even though there was significant reduction

in the EndoGrip. In addition, even though the mean FRV for APB was increased, it was already positive for the barehand. Lastly, the EndoGrip significantly outperformed the competitor grip in its FRV reducing capabilities for the FDI ($p=5.806 \times 10^{-6}$) and FCR ($p=0.0024$).

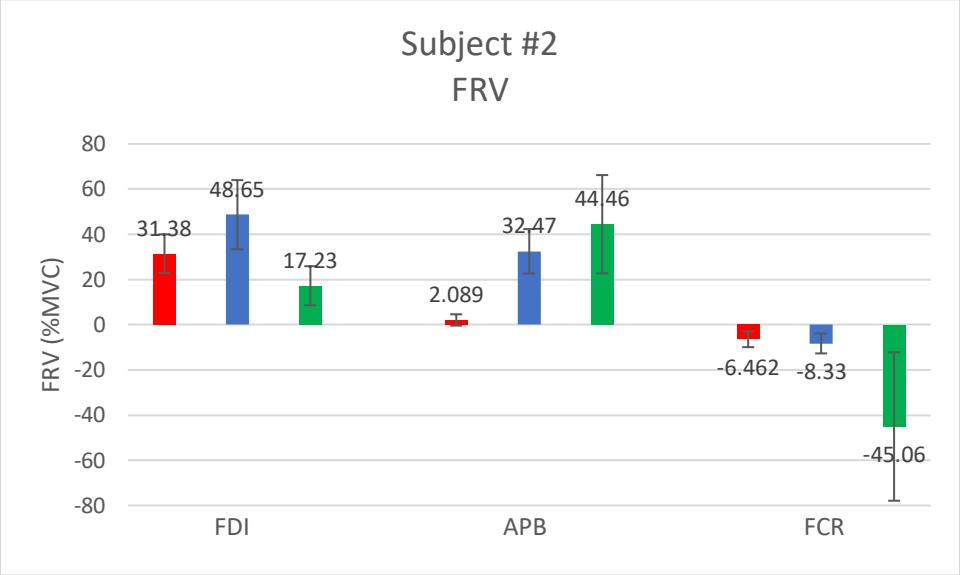

Figure 25: Mean FRV for each muscle and grip type for subject 2 (red – barehand, blue – competitor grip, green – EndoGrip)

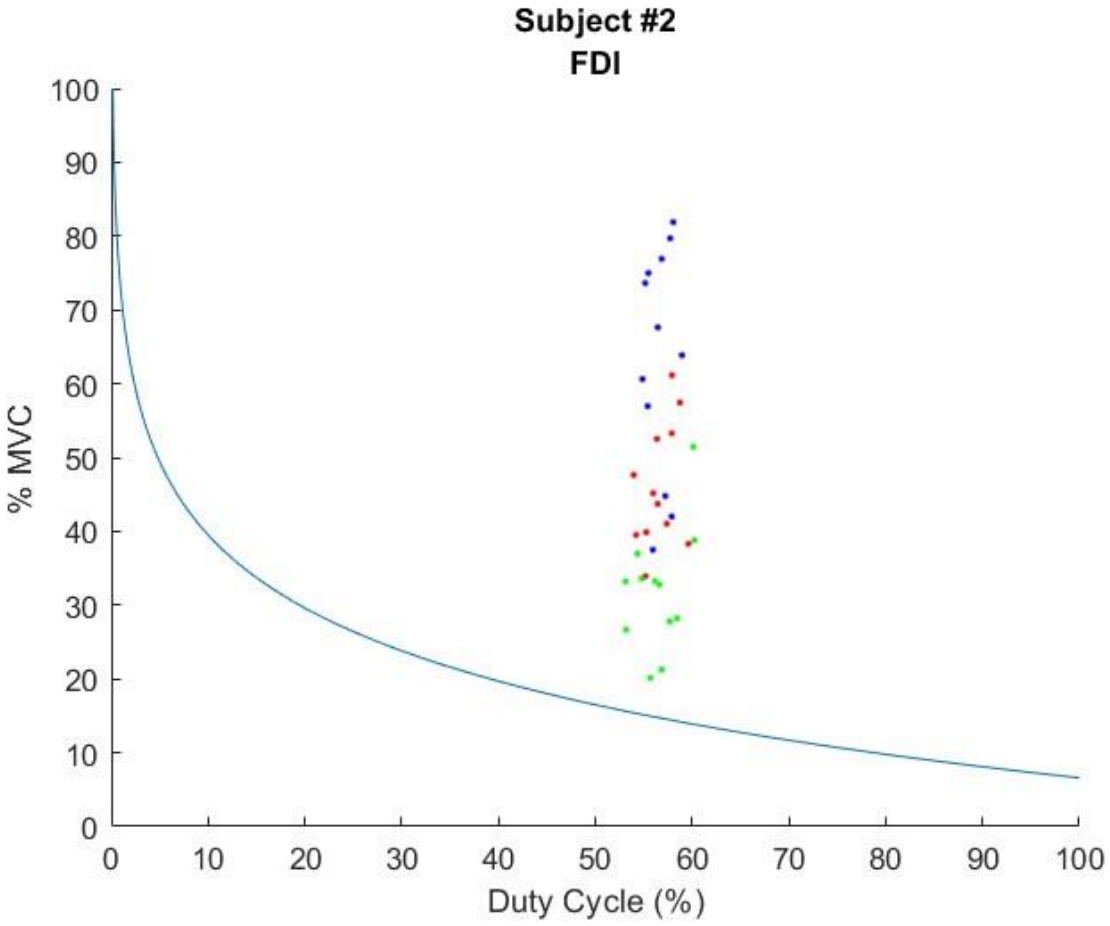

Figure 26: All events from each grip type plotted against TLV curve for FDI of subject 2 (red – barehand, blue – competitor grip, green – EndoGrip)

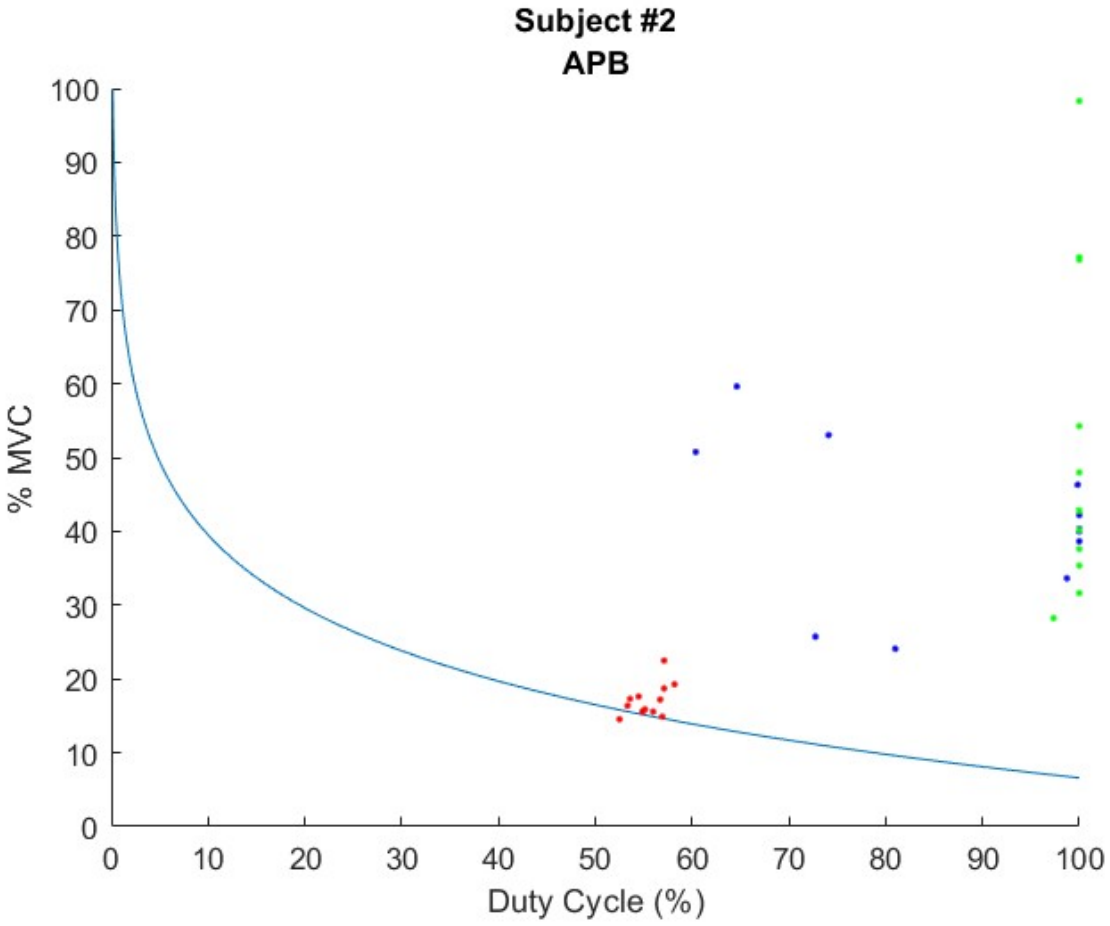

Figure 27: All events from each grip type plotted against TLV curve for APB of subject 2 (red – barehand, blue – competitor grip, green – EndoGrip)

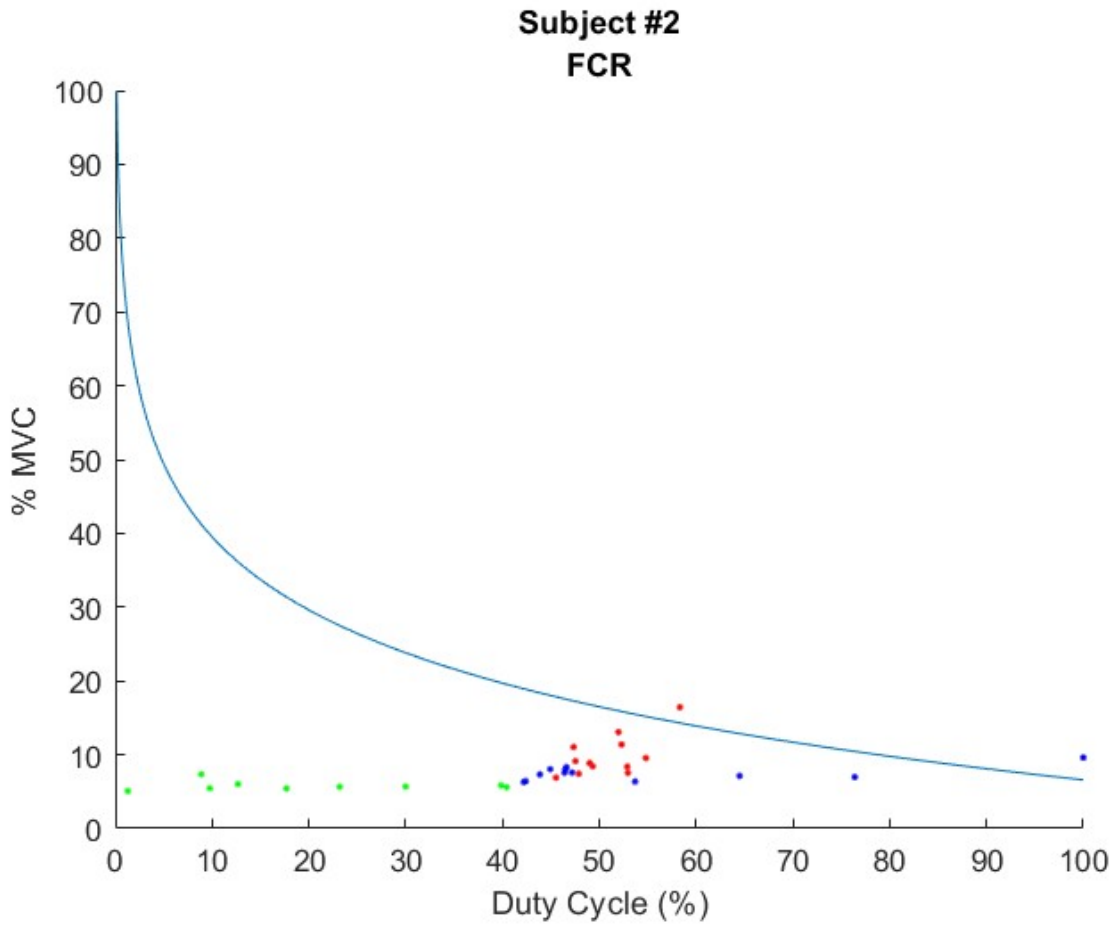

Figure 28: All events from each grip type plotted against TLV curve for FCR of subject 2 (red – barehand, blue – competitor grip, green – EndoGrip)

Subject 3:

The mean FRV was significantly reduced in the APB ($p=7.530 \times 10^{-5}$) and FCR ($p=1.288 \times 10^{-4}$) when comparing the barehand to the EndoGrip during statically simulated colonoscopies. We observed no shift in polarity of the FRV values when comparing the barehand to the EndoGrip. That is, even though the mean FRV for APB was reduced, it was still positive (meaning above the TLV). Similarly, the mean FRV for FCR was already negative (meaning below the TLV) for the barehand even though there was significant reduction in the EndoGrip. Lastly, the EndoGrip significantly outperformed the competitor grip in its FRV reducing capabilities for the FDI ($p=0.006$).

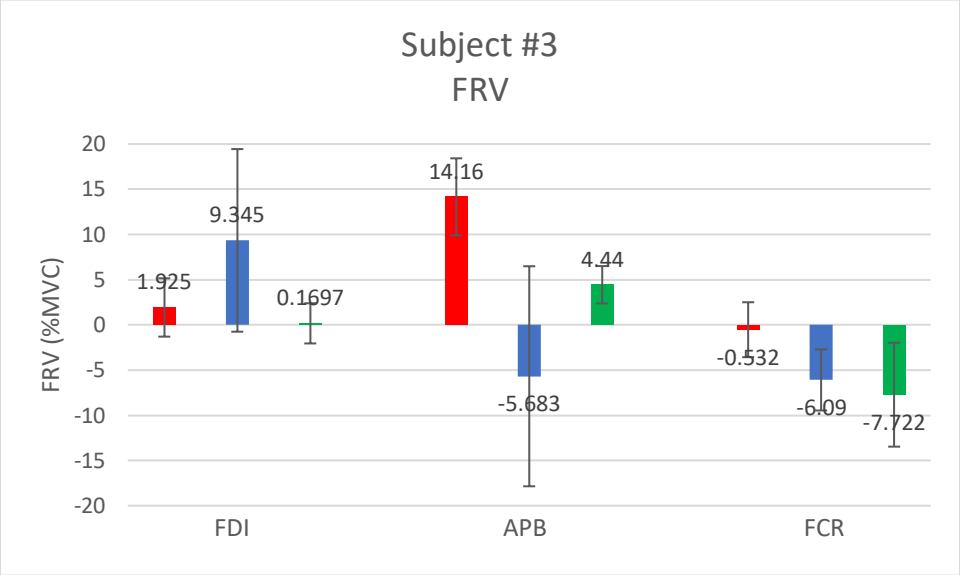

Figure 29: Mean FRV for each muscle and grip type for subject 3 (red – barehand, blue – competitor grip, green – EndoGrip)

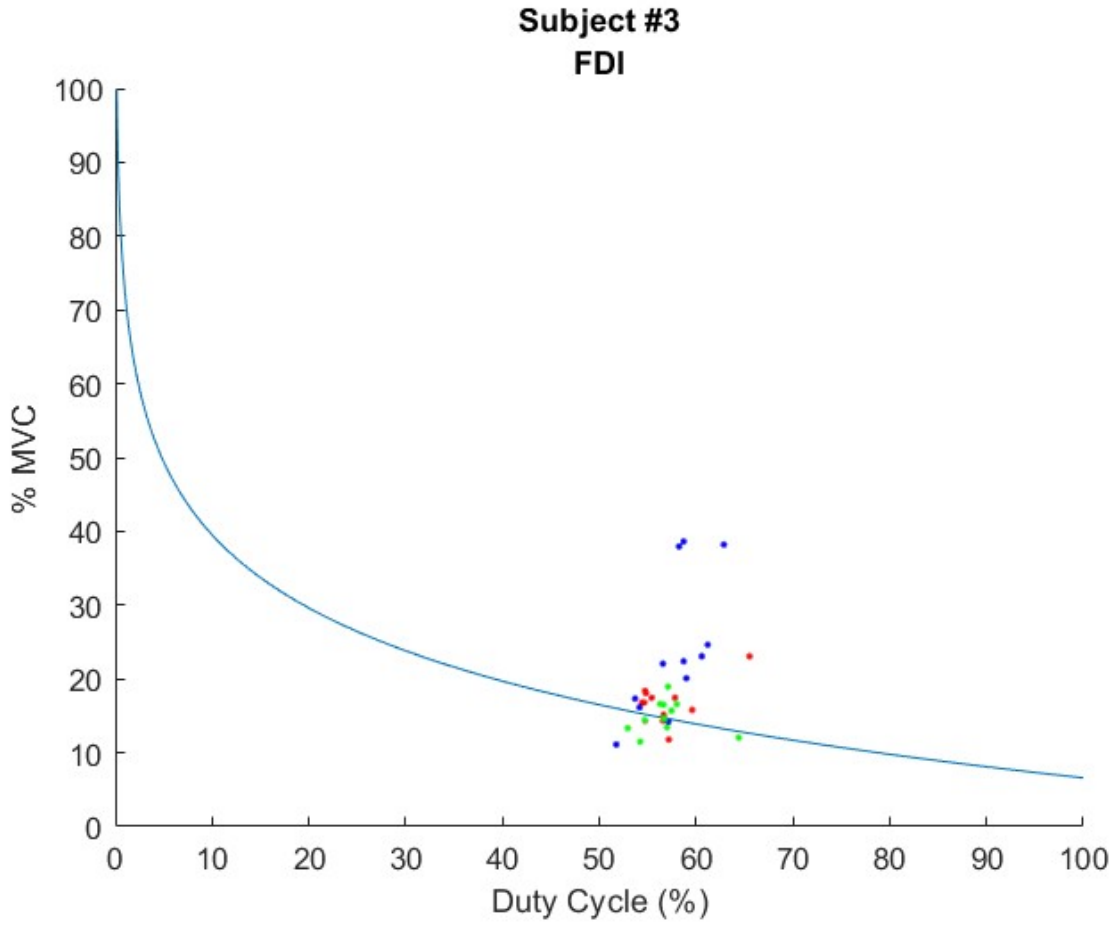

Figure 30: All events from each grip type plotted against TLV curve for FDI of subject 3 (red – barehand, blue – competitor grip, green – EndoGrip)

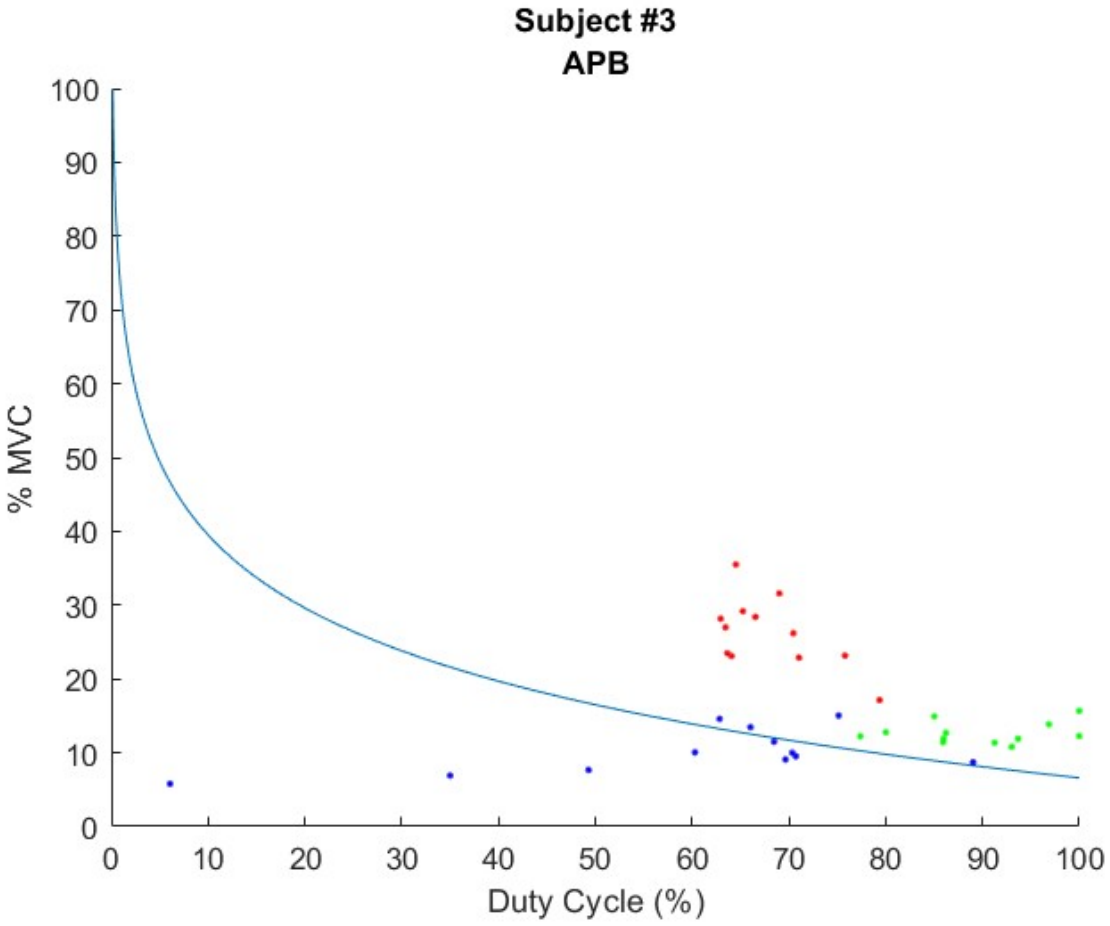

Figure 31: All events from each grip type plotted against TLV curve for APB of subject 3 (red – barehand, blue – competitor grip, green – EndoGrip)

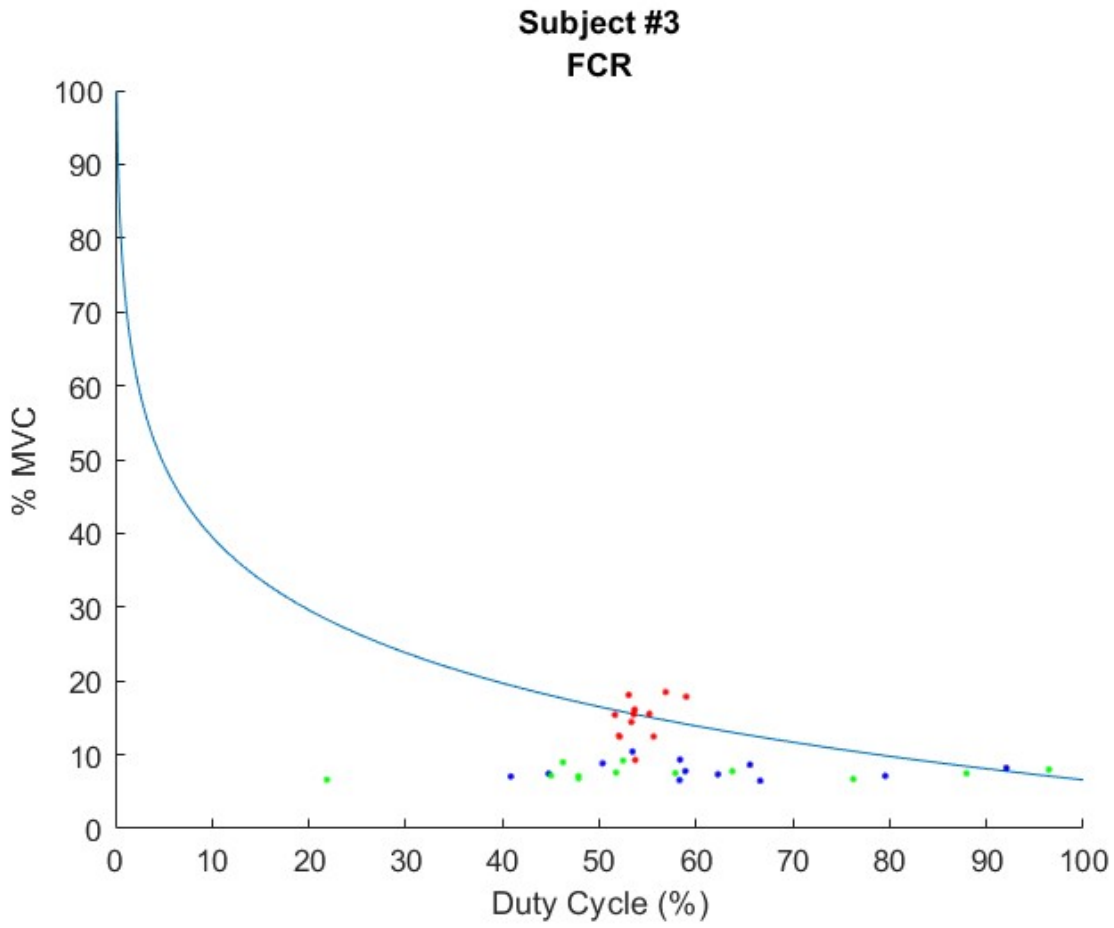

Figure 32: All events from each grip type plotted against TLV curve for FCR of subject 3 (red – barehand, blue – competitor grip, green – EndoGrip)

Subject 4:

The mean FRV was significantly reduced in the FCR ($p=3.391 \times 10^{-5}$) when comparing the barehand to the EndoGrip during statically simulated colonoscopies. We observed a shift in polarity of the mean FRV of the FCR when comparing the barehand to the EndoGrip. That is, the mean FRV for FCR was reduced and transitioned from positive to negative (meaning below the TLV). Lastly, the EndoGrip significantly outperformed the competitor grip in its FRV reducing capabilities for the FDI ($p=1.662 \times 10^{-4}$).

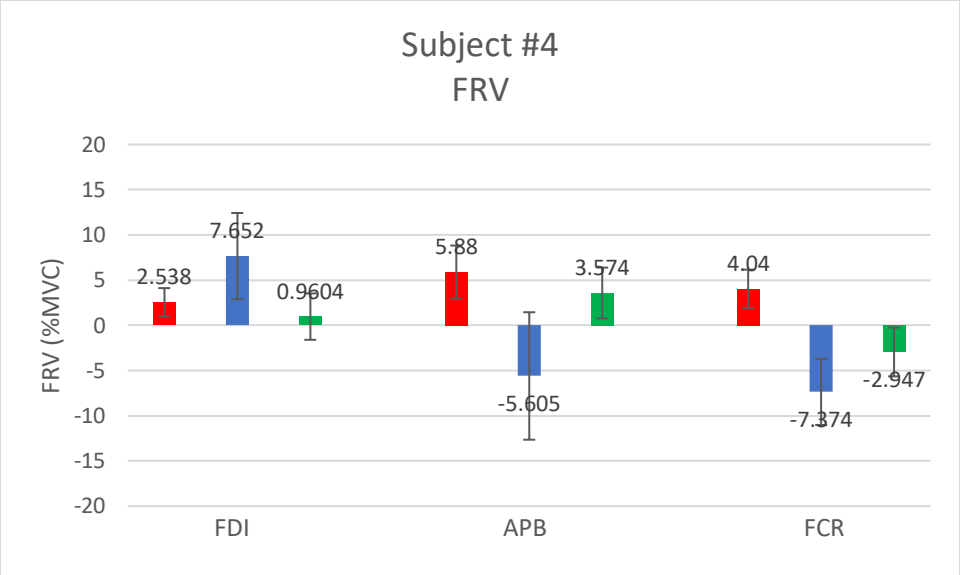

Figure 33: Mean FRV for each muscle and grip type for subject 4 (red – barehand, blue – competitor grip, green – EndoGrip)

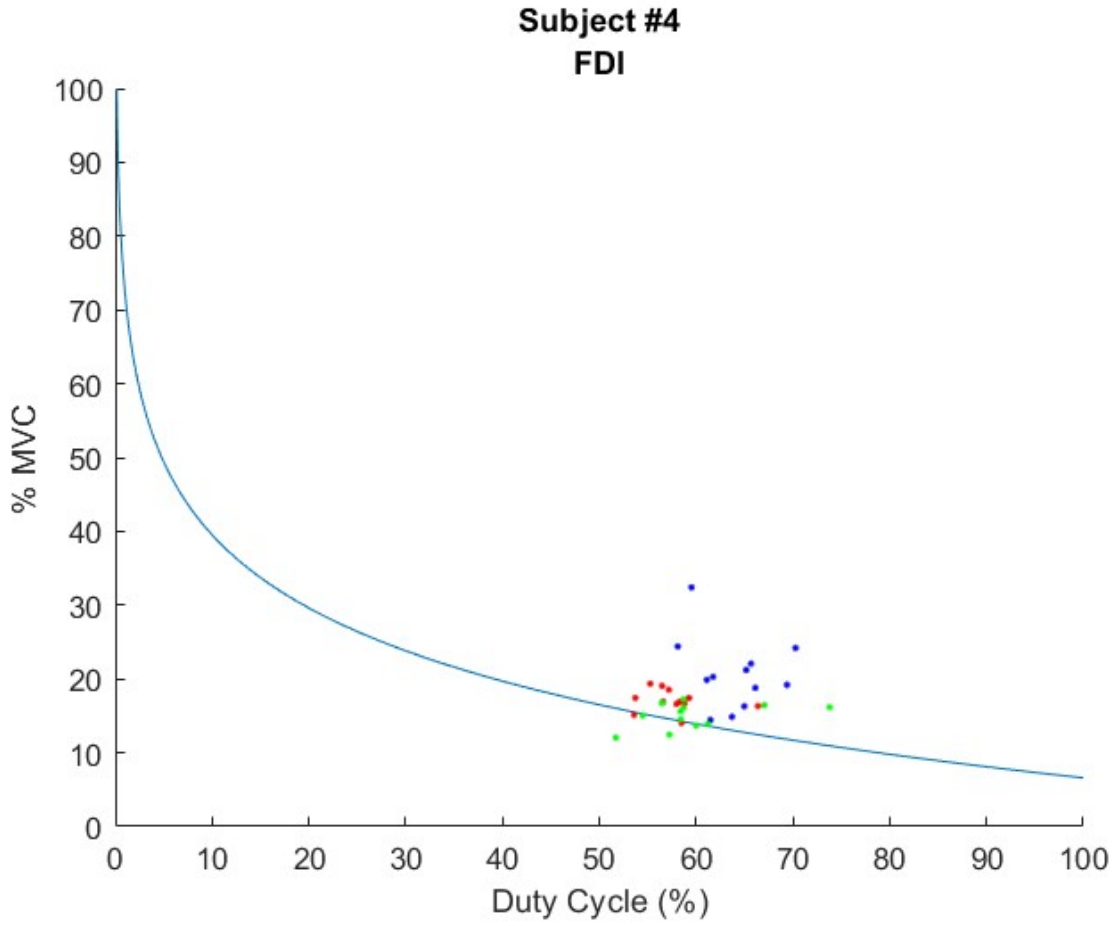

Figure 34: All events from each grip type plotted against TLV curve for FDI of subject 4 (red – barehand, blue – competitor grip, green – EndoGrip)

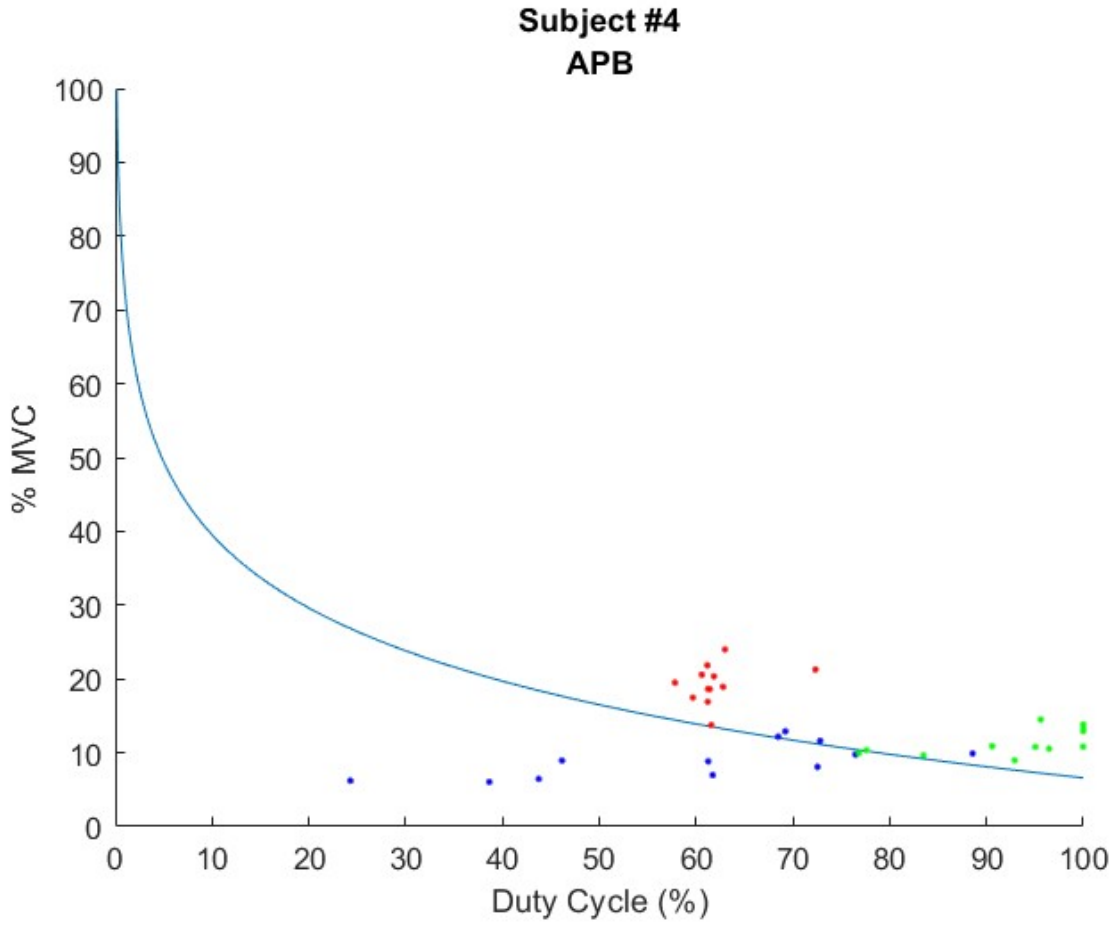

Figure 35: All events from each grip type plotted against TLV curve for APB of subject 4 (red – barehand, blue – competitor grip, green – EndoGrip)

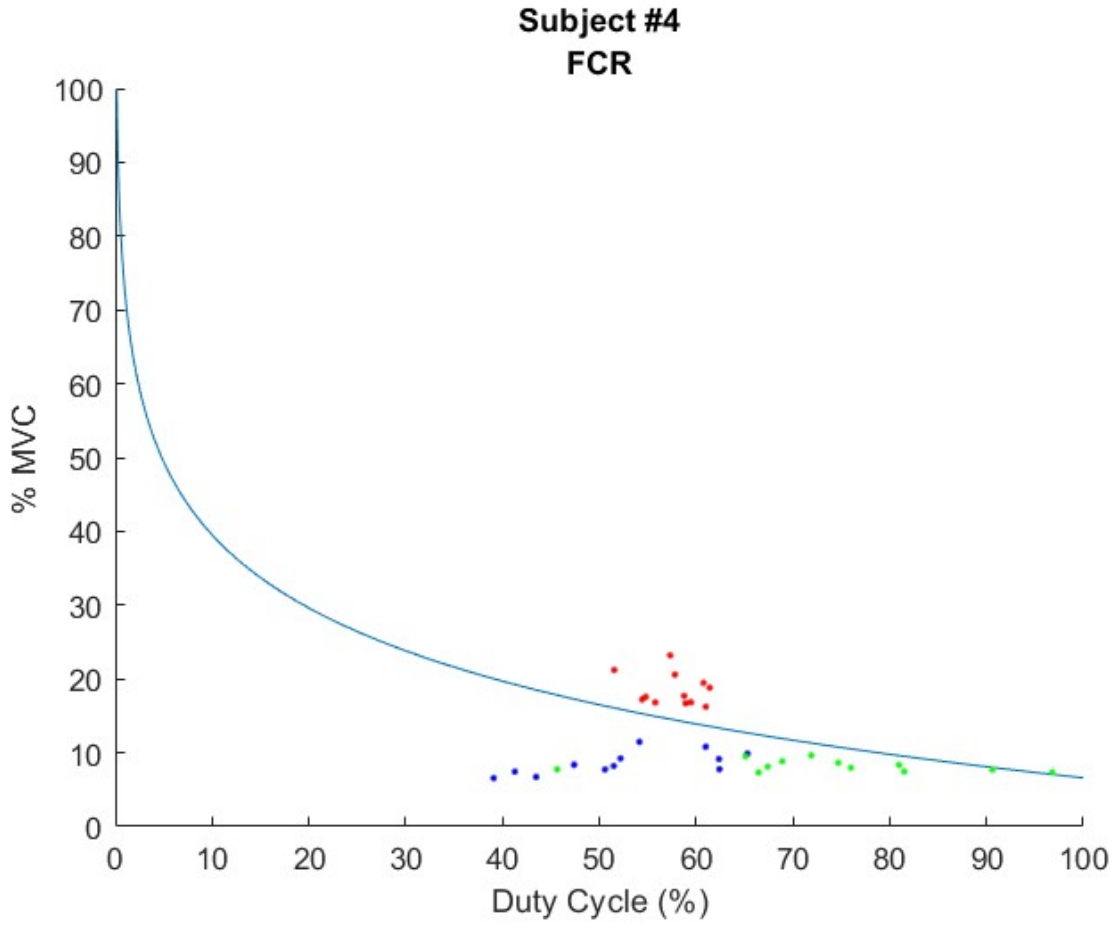

Figure 36: All events from each grip type plotted against TLV curve for FCR of subject 4 (red – barehand, blue – competitor grip, green – EndoGrip)

Subject 5:

The mean FRV was significantly reduced in the FDI ($p=1.070 \times 10^{-6}$) when comparing the barehand to the EndoGrip during statically simulated colonoscopies. On the other hand, the mean FRV was significantly increased in the APB ($p=1.744 \times 10^{-6}$) when comparing the barehand to the EndoGrip. We observed no shift in polarity of the FRV values in FDI and FCR. That is, even though the mean FRV for FDI was reduced, it was still positive (meaning above the TLV). Similarly, the mean FRV for FCR was already negative (meaning below the TLV) for the barehand. In contrast, we did observe a polarity shift in the APB when comparing the barehand to

the EndoGrip. Lastly, the EndoGrip significantly outperformed the competitor grip in its FRV reducing capabilities for the FDI ($p=4.532 \times 10^{-6}$) and FCR ($p=9.545 \times 10^{-4}$).

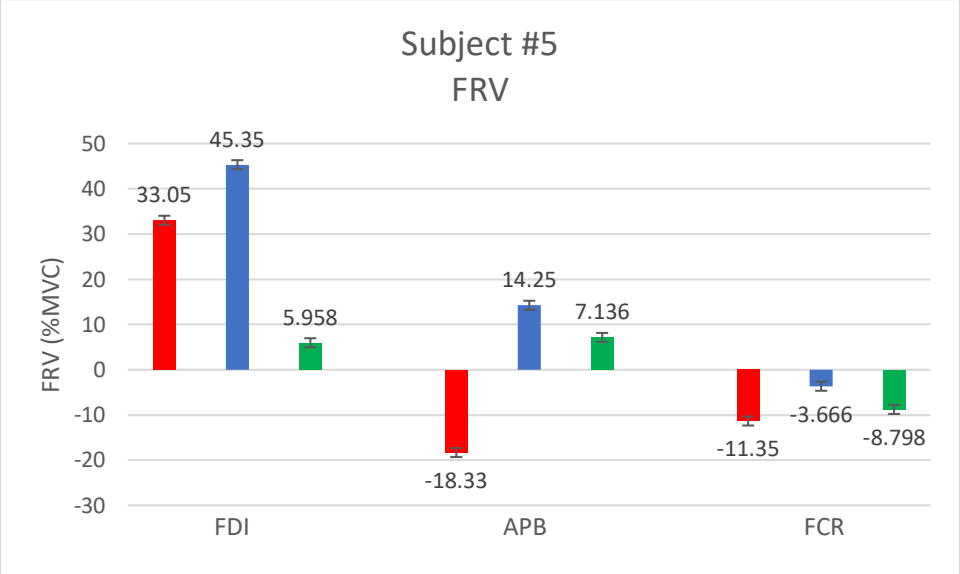

Figure 37: Mean FRV for each muscle and grip type for subject 5 (red – barehand, blue – competitor grip, green – EndoGrip)

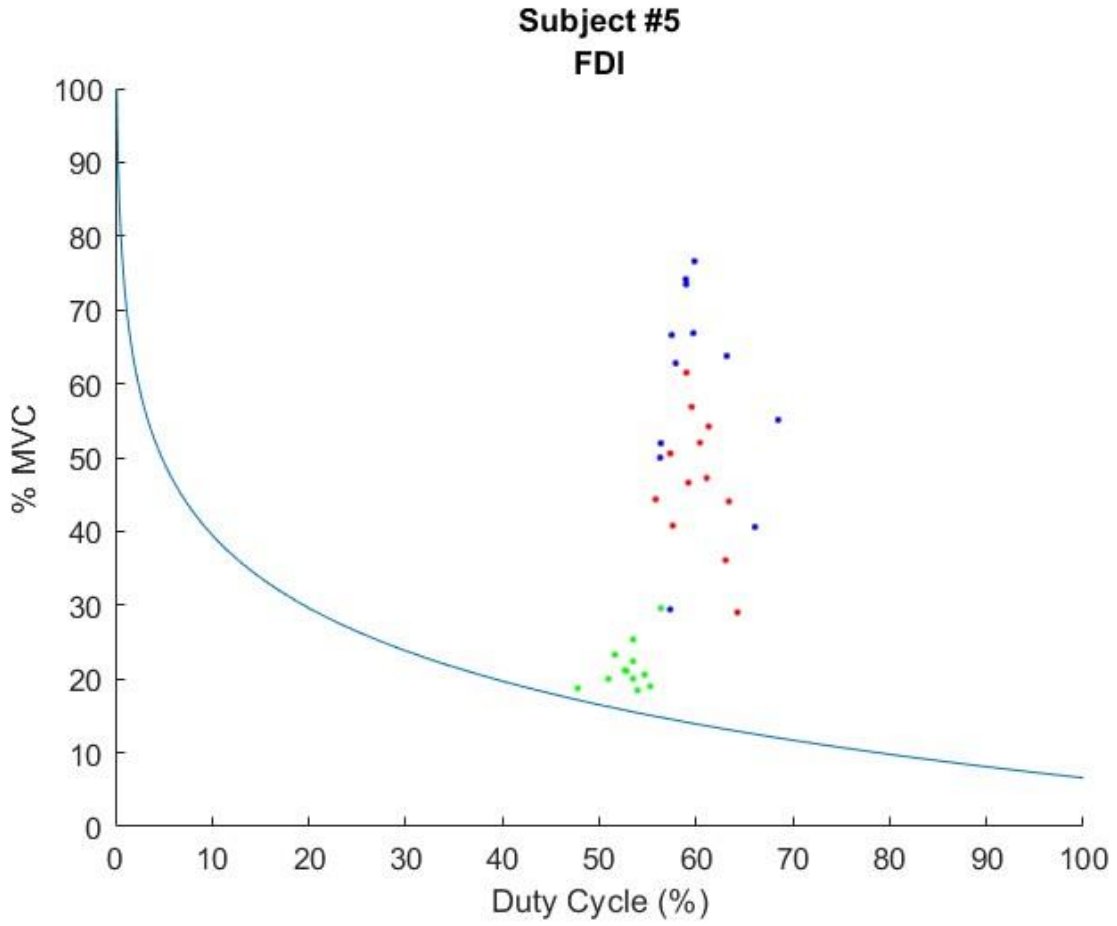

Figure 38: All events from each grip type plotted against TLV curve for FDI of subject 5 (red – barehand, blue – competitor grip, green – EndoGrip)

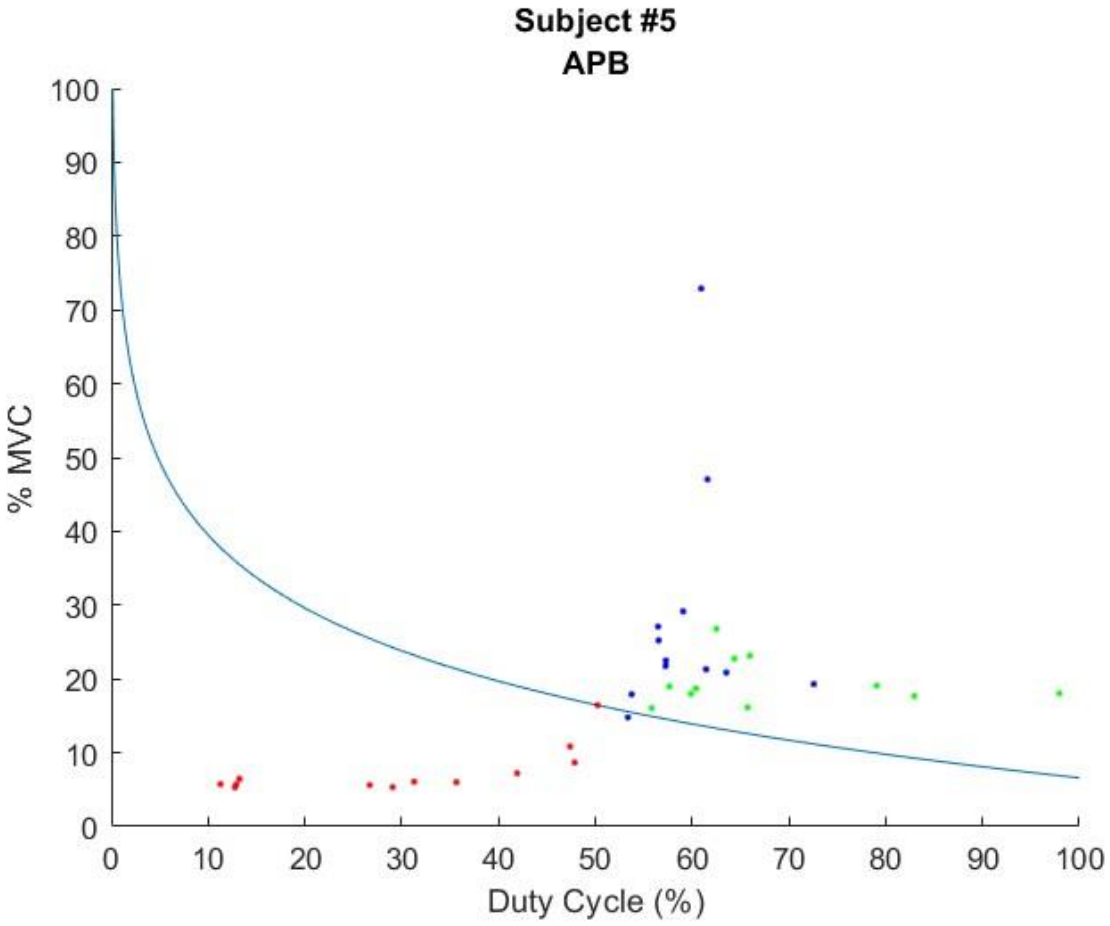

Figure 39: All events from each grip type plotted against TLV curve for APB of subject 5 (red – barehand, blue – competitor grip, green – EndoGrip)

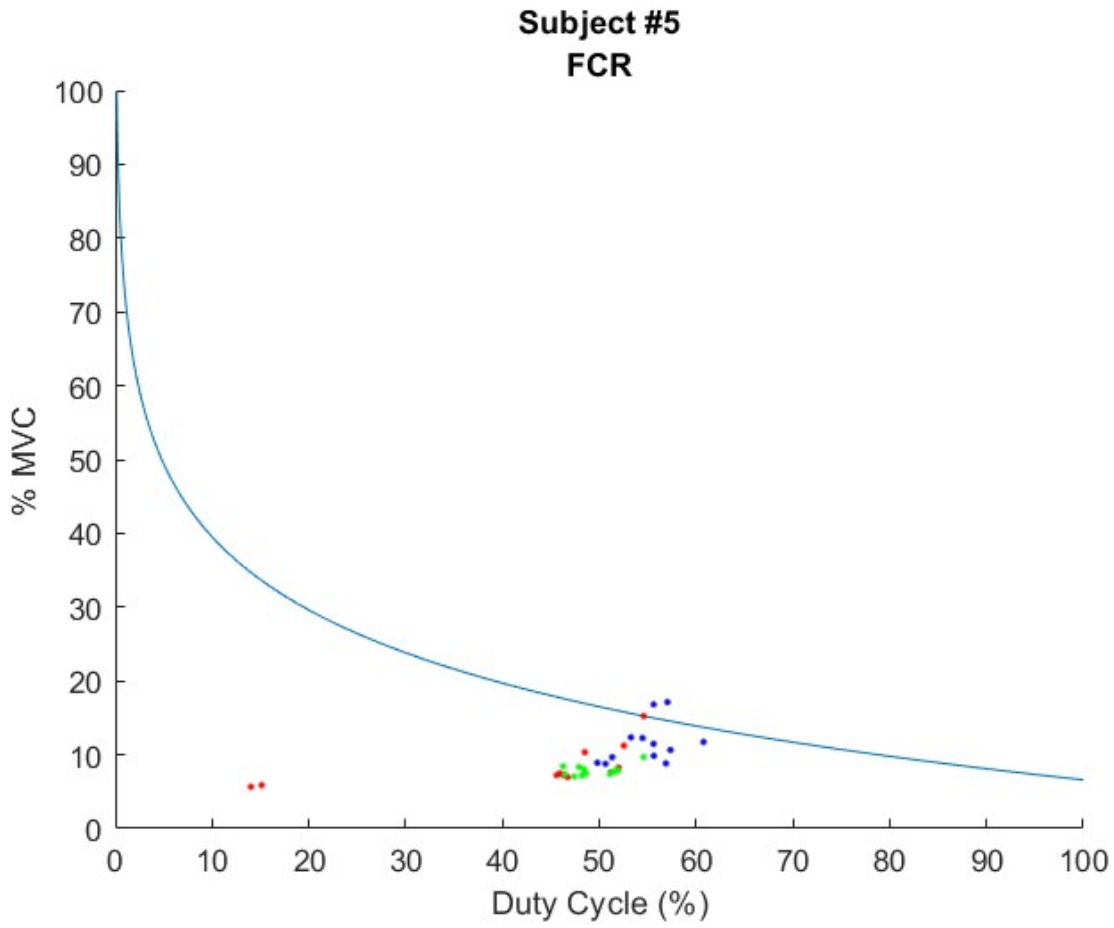

Figure 40: All events from each grip type plotted against TLV curve for FCR of subject 5 (red – barehand, blue – competitor grip, green – EndoGrip)

Subject 6:

The mean FRV was significantly increased in the FDI ($p=3.258 \times 10^{-7}$) and APB ($p=4.659 \times 10^{-7}$) when comparing the barehand to the EndoGrip during statically simulated colonoscopies. We observed no shift in polarity of the FRV values. That is, even though the mean FRV for FDI and APB were increased, they were already positive (meaning above the TLV).

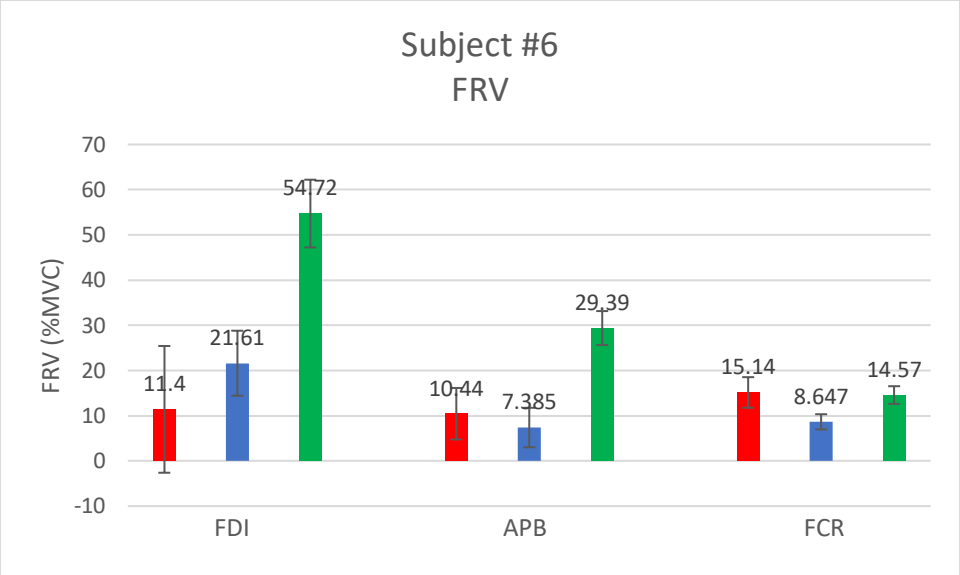

Figure 41: Mean FRV for each muscle and grip type for subject 6 (red – barehand, blue – competitor grip, green – EndoGrip)

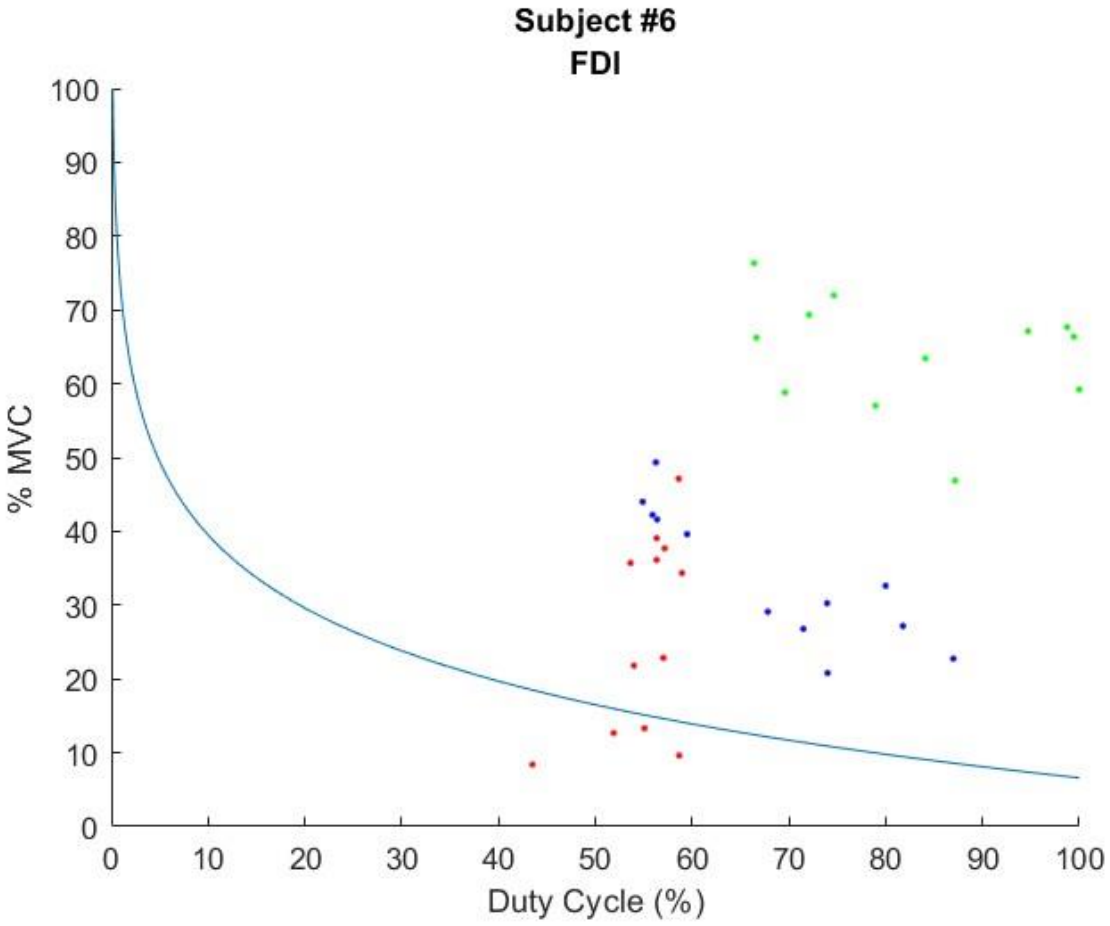

Figure 42: All events from each grip type plotted against TLV curve for FDI of subject 6 (red – barehand, blue – competitor grip, green – EndoGrip)

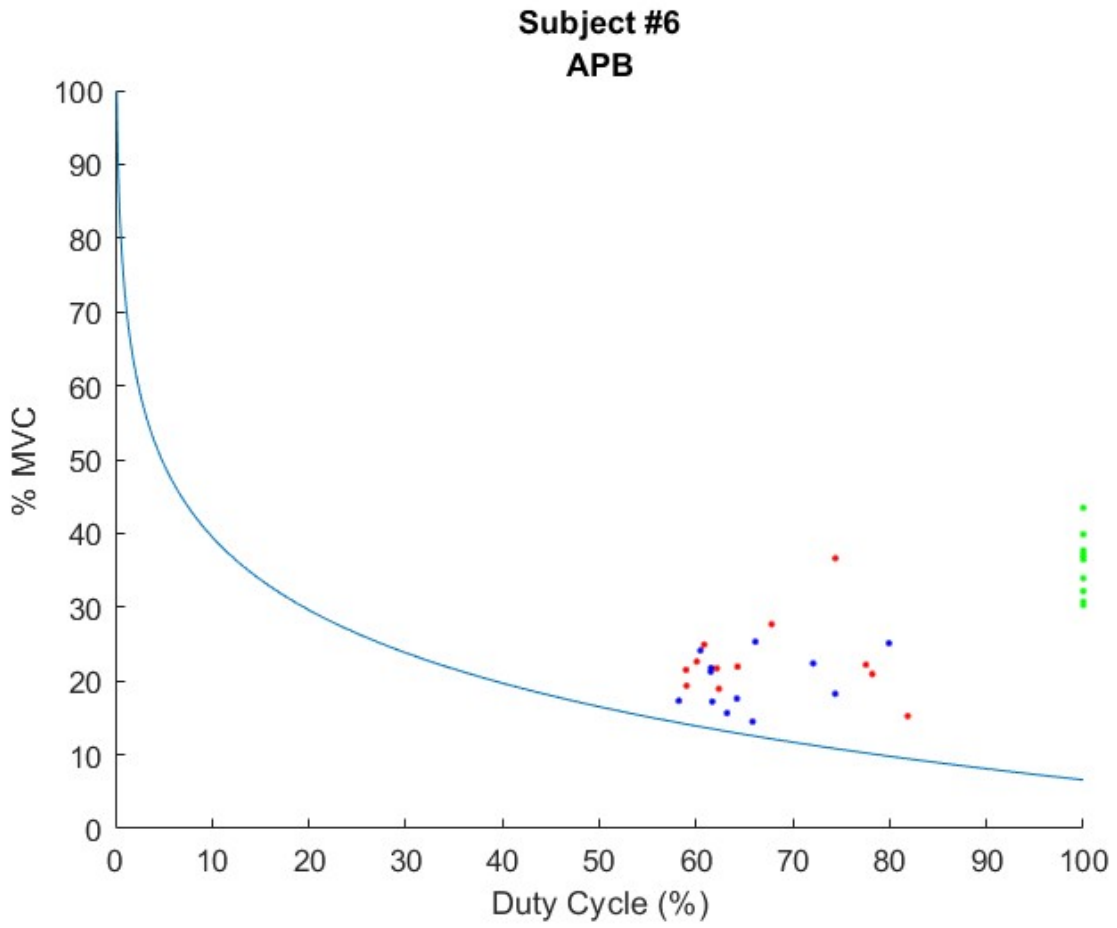

Figure 43: All events from each grip type plotted against TLV curve for APB of subject 6 (red – barehand, blue – competitor grip, green – EndoGrip)

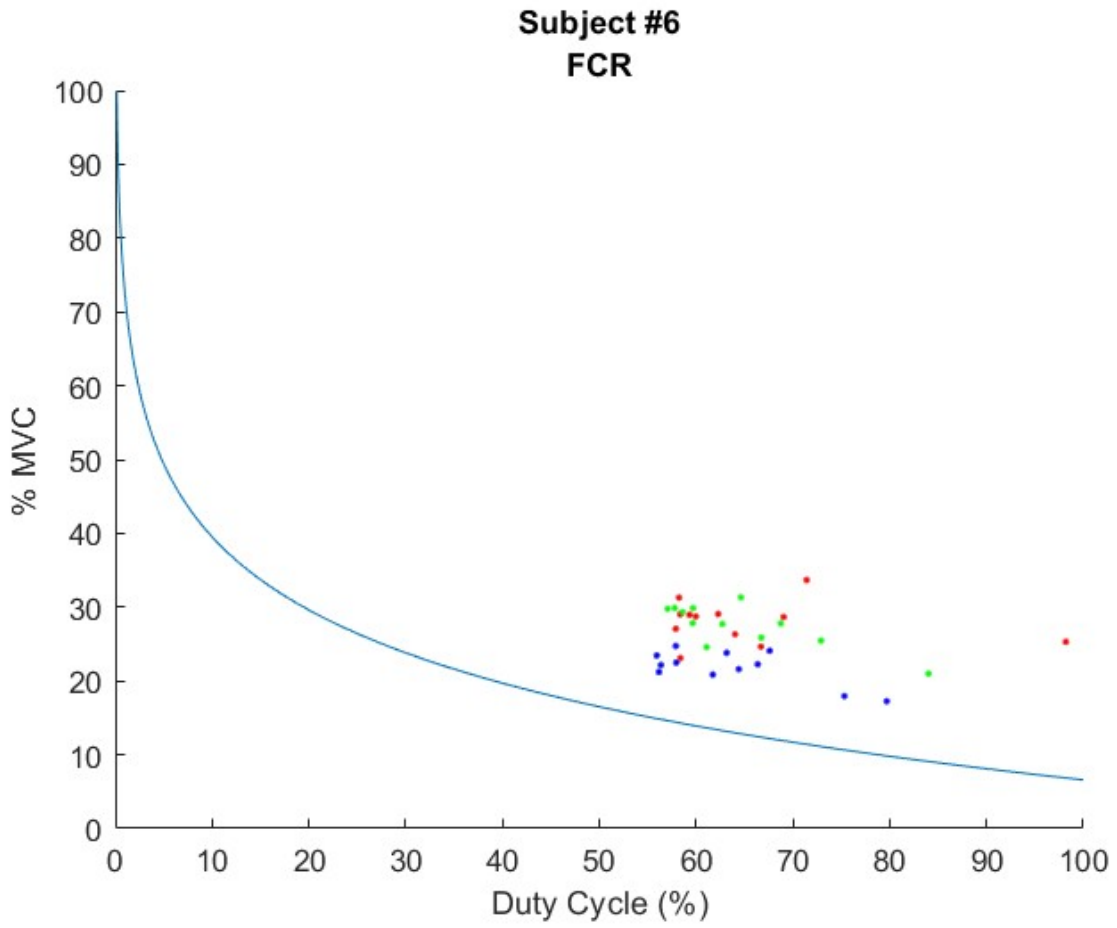

Figure 44: All events from each grip type plotted against TLV curve for FCR of subject 6 (red – barehand, blue – competitor grip, green – EndoGrip)

Subject 7:

The mean FRV was significantly increased in the FDI ($p=1.149 \times 10^{-4}$) and APB ($p=8.880 \times 10^{-10}$) when comparing the barehand to the EndoGrip during statically simulated colonoscopies. We observed no shift in polarity of the FRV values in FDI. That is, even though the mean FRV for FDI was increased, it was already positive (meaning above the TLV). On the other hand, we observed a polarity shift in the APB when comparing the barehand to the EndoGrip, going from negative to positive (meaning above the TLV).

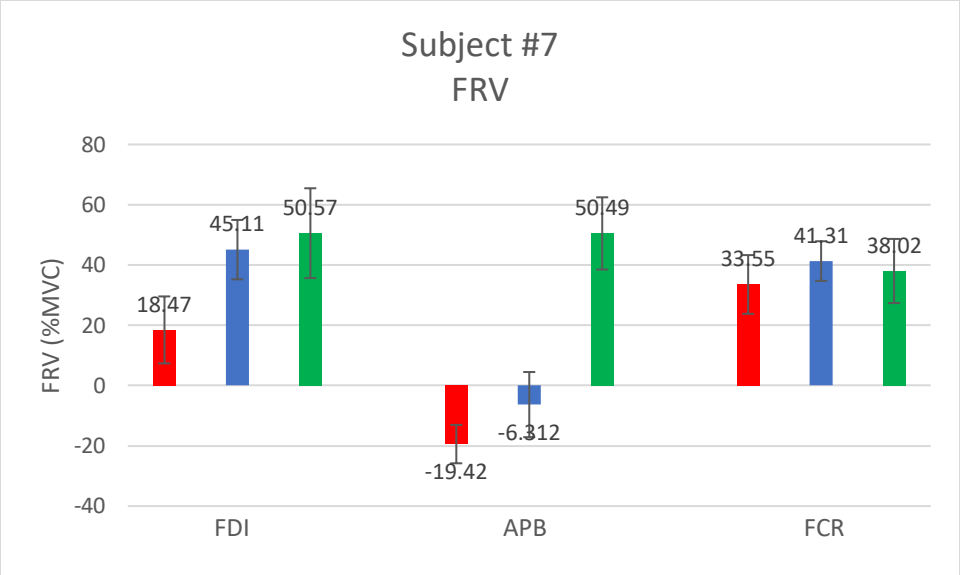

Figure 45: Mean FRV for each muscle and grip type for subject 7 (red – barehand, blue – competitor grip, green – EndoGrip)

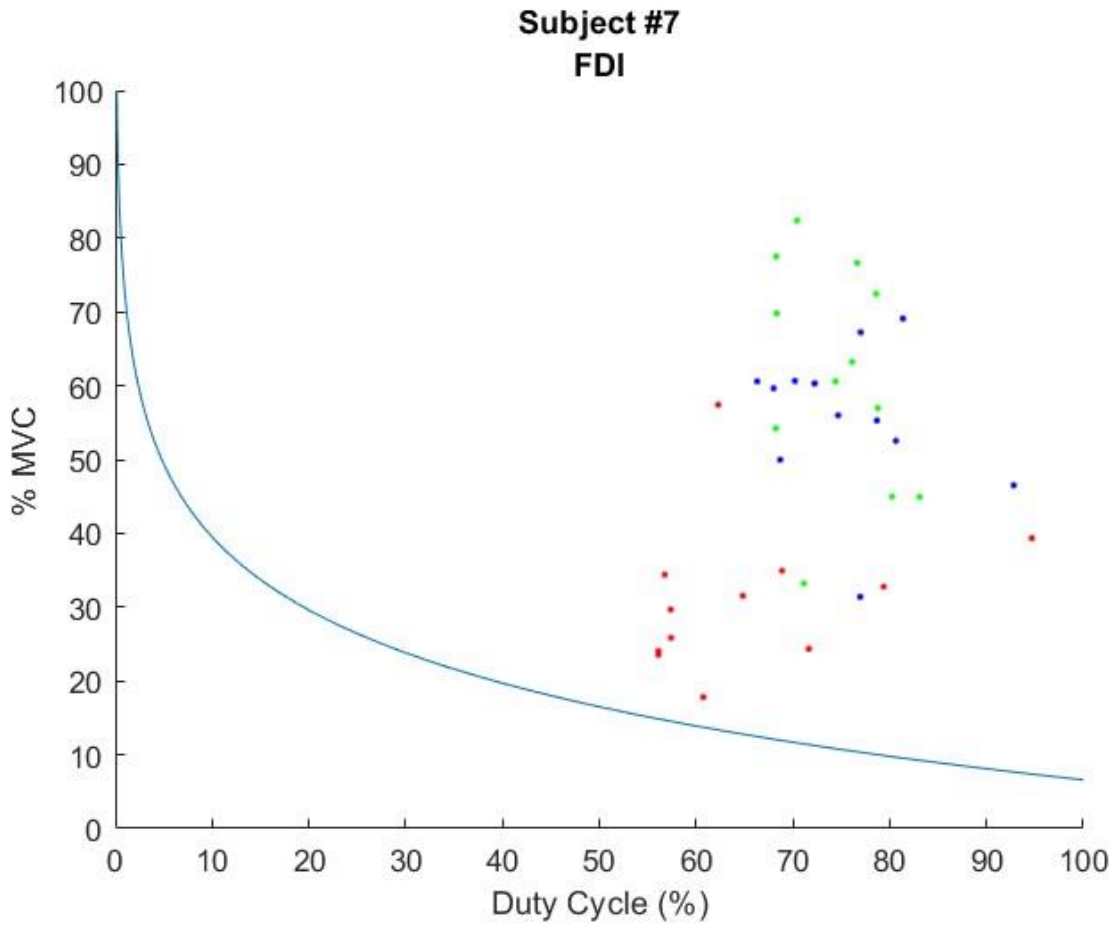

Figure 46: All events from each grip type plotted against TLV curve for FDI of subject 7 (red – barehand, blue – competitor grip, green – EndoGrip)

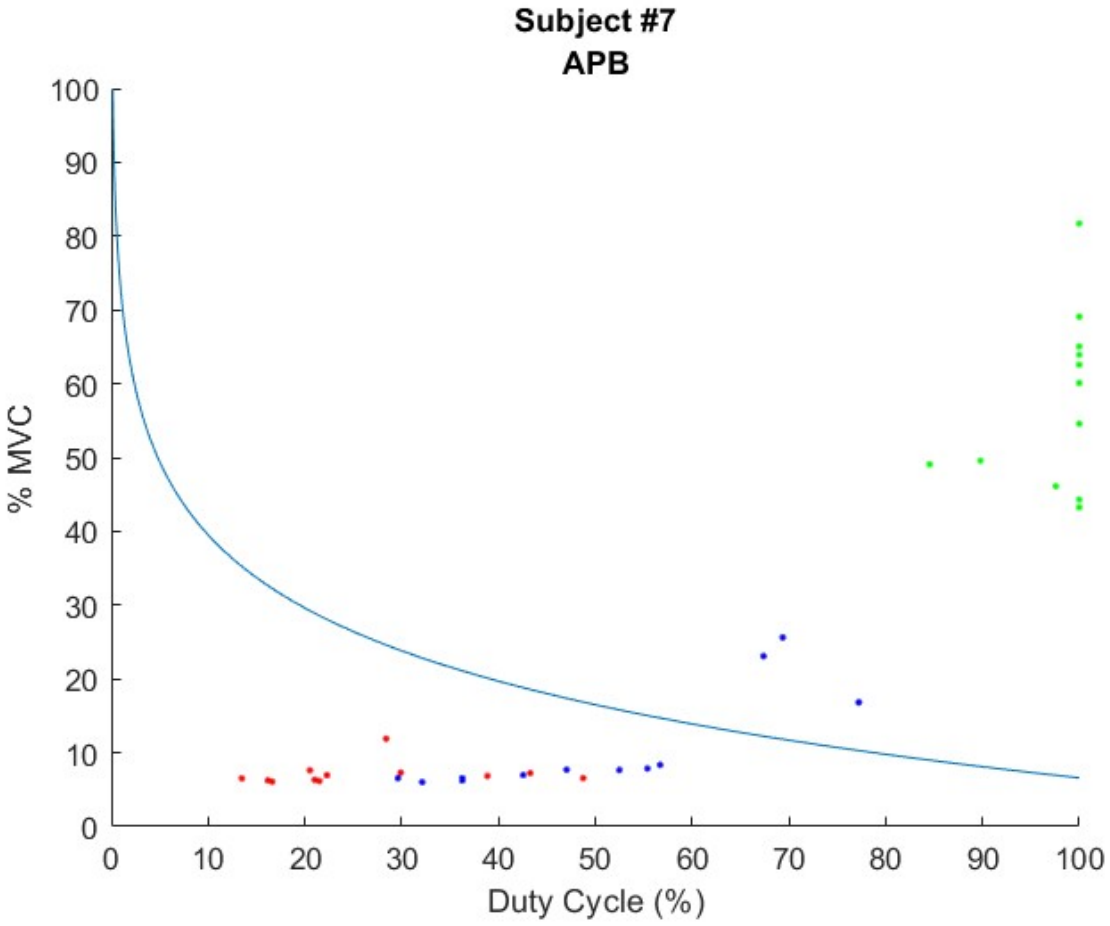

Figure 47: All events from each grip type plotted against TLV curve for APB of subject 7 (red – barehand, blue – competitor grip, green – EndoGrip)

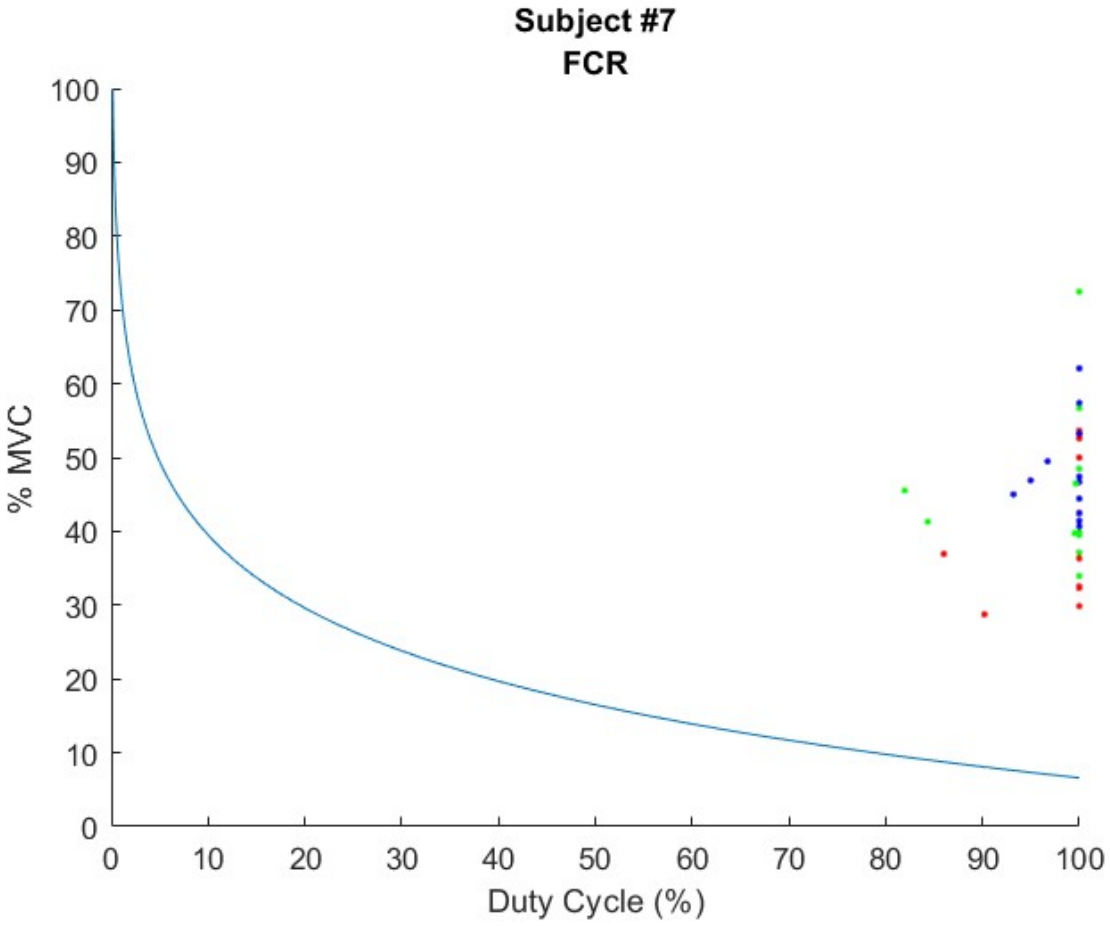

Figure 48: All events from each grip type plotted against TLV curve for FCR of subject 7 (red – barehand, blue – competitor grip, green – EndoGrip)

Table 1: Summary of mean (SD) FRV in units of % MVC and p-values for t-tests (B = barehand, C = competitor grip, E = EndoGrip, Pa = p-value for B vs C, Pb = p-value for C vs E, and Pc = p-value for E vs B)

Subject	**FDI**	**APB**	**FCR**
1	B: 28.45 (9.670) C: 53.70 (6.764) E: 14.56 (8.385)	B: 3.778 (2.883) C: 34.62 (14.42) E: 31.14 (5.690)	B: -4.280 (3.210) C: -3.320 (4.692) E: -40.63 (26.24)
	Pa: 2.809 x 10^{-5} **Pb: 2.050 x 10^{-7}** **Pc: 4.304 x 10^{-6}**	**Pa: 2.602 x 10^{-5}** Pb: 0.5044 **Pc: 6.214 x 10^{-10}**	Pa: 0.4696 **Pb: 3.512 x 10^{-4}** **Pc: 4.069 x 10^{-4}**
2	B: 31.38 (8.573) C: 48.65 (15.31) E: 17.23 (8.634)	B: 2.089 (2.509) C: 32.47 (9.815) E: 44.46 (21.73)	B: -6.462 (3.484) C: -8.330 (4.396) E: -45.06 (32.83)
	Pa: 0.0064 **Pb: 5.806 x 10^{-6}** **Pc: 5.562 x 10^{-4}**	**Pa: 1.392 x 10^{-7}** **Pb: 0.0394** **Pc: 2.476 x 10^{-5}**	Pa: 0.0977 **Pb: 0.0024** **Pc: 0.0019**
3	B: 1.925 (3.225) C: 9.345 (10.10) E: 0.1697 (2.221)	B: 14.16 (4.265) C: -5.683 (12.17) E: 4.440 (2.064)	B: -0.5320 (3.037) C: -6.090 (3.375) E: -7.722 (5.743)
	Pa: 0.0500 **Pb: 0.0060** Pc: 0.2623	**Pa: 3.693 x 10^{-5}** **Pb: 0.0223** **Pc: 7.530 x 10^{-5}**	**Pa: 0.0010** Pb: 0.3581 **Pc: 1.288 x 10^{-4}**
4	B: 2.538 (1.575) C: 7.652 (4.771) E: 0.9604 (2.566)	B: 5.880 (2.945) C: -5.605 (7.050) E: 3.574 (2.809)	B: 4.040 (2.118) C: -7.374 (3.658) E: -2.947 (2.701)
	Pa: 0.0031 **Pb: 1.662 x 10^{-4}** Pc: 0.0866	**Pa: 1.465 x 10^{-4}** **Pb: 0.0040** Pc: 0.1072	**Pa: 4.523 x 10^{-6}** **Pb: 0.0049** **Pc: 3.391 x 10^{-5}**

Table 1: Summary of mean (SD) FRV in units of % MVC and p-values for t-tests (B = barehand, C = competitor grip, E = EndoGrip, Pa = p-value for B vs C, Pb = p-value for C vs E, and Pc = p-value for E vs B), Continued

Subject	**FDI**	**APB**	**FCR**
5	B: 33.05 (8.781) C: 45.35 (14.31) E: 5.958 (3.503)	B: -18.33 (10.56) C: 14.25 (16.48) E: 7.136 (3.776)	B: -11.35 (8.544) C: -3.666 (3.273) E: -8.798 (1.256)
	Pa: 0.0138 **Pb: 4.532×10^{-6}** **Pc: 1.070×10^{-6}**	**Pa: 4.930×10^{-4}** Pb: 0.1835 **Pc: 1.744×10^{-6}**	**Pa: 0.0027** **Pb: 9.548×10^{-4}** Pc: 0.3666
6	B: 11.40 (14.02) C: 21.61 (7.193) E: 54.72 (7.488)	B: 10.44 (5.693) C: 7.385 (4.366) E: 29.39 (3.761)	B: 15.14 (3.386) C: 8.647 (1.676) E: 14.57 (1.958)
	Pa: 0.0074 **Pb: 2.944×10^{-9}** **Pc: 3.258×10^{-7}**	Pa: 0.1442 **Pb: 9.811×10^{-10}** **Pc: 4.659×10^{-7}**	**Pa: 1.135×10^{-4}** **Pb: 8.455×10^{-8}** Pc: 0.6983
7	B: 18.47 (11.11) C: 45.11 (9.848) E: 50.57 (14.90)	B: -19.42 (6.374) C: -6.312 (10.81) E: 50.49 (11.98)	B: 33.55 (9.742) C: 41.31 (6.582) E: 38.02 (10.64)
	Pa: 6.402×10^{-4} Pb: 0.2644 **Pc: 1.149×10^{-4}**	**Pa: 0.0065** **Pb: 1.012×10^{-10}** **Pc: 8.880×10^{-10}**	**Pa: 0.0096** Pb: 0.1639 Pc: 0.1743

All subjects:

The change in mean FRV (in units of % MVC) for each muscle when comparing the barehand to the EndoGrip were averaged across all the subjects separated into two groups: male (subjects 1 through 5) and female (subjects 6 and 7). We observed that for the male group, the average changes in the mean FRV for FDI and FCR were negative (-11.69 % MVC and -17.31 % MVC, respectively), while the average change in mean FRV for APB was positive (16.63 %

MVC). In contrast, we observed that for the female group, the average changes in the mean FRV for FDI and FCR were positive (37.71 % MVC and 1.950 % MVC, respectively), while the average change in mean FRV for APB was also positive (44.43 % MVC).

Table 2: Change in mean FRV when comparing barehand to EndoGrip trials in units of % MVC, with negative values indicating reduction of mean FRV

Subject	**FDI**	**APB**	**FCR**
1	-13.89	27.36	-36.35
2	-14.15	42.37	-38.6
3	-1.755	-9.720	-7.190
4	-1.578	-2.306	-6.987
5	-27.09	25.47	2.552
6	43.32	18.95	-0.5700
7	32.10	69.91	4.470

Table 3: Average change in mean FRV when comparing barehand to EndoGrip trials in units of % MVC, grouped by subject gender

Group	**FDI**	**APB**	**FCR**
Male	-11.69	16.63	-17.31
Female	37.71	44.43	1.950

3.4 Discussion

For the male subjects, we observed few distinct, overlapping trends in their mean FRV in relation to the different grip types used. First, 60% of male subjects showed a significant reduction in the mean FRV for FDI when comparing the barehand trials to the EndoGrip trials, with an

average reduction of 18.38 % MVC. The other 40% of male subjects still showed a non-significant trend of mean FRV reduction for the FDI.

This trend can be explained by understanding the change in grip position that occurs when a subject goes from using their barehand to using the EndoGrip. When using the barehand to grip the endoscope, the subjects employ a pinch grip position (gripping motion commonly used to hold and turn keys) (Shergill, 2009). When using the EndoGrip, the subjects naturally switch to a power grip position (gripping motion commonly used to hold baseball bats). Stronger grip strength arises from the latter position since pinch grip utilizes the thumb pad and the side of the index finger (gripping force coming only from index finger and thumb) whereas power grip utilizes all the fingers with the thumb opposing the fingers (gripping force coming from whole hand). The power grip is strongest when the tips of the index finger and opposing thumb barely touch as the whole hand wraps around an object to grip it. Since using the EndoGrip results in the power grip position, other parts of the hand contribute to the overall gripping power and, thus, reduces the load on the FDI.

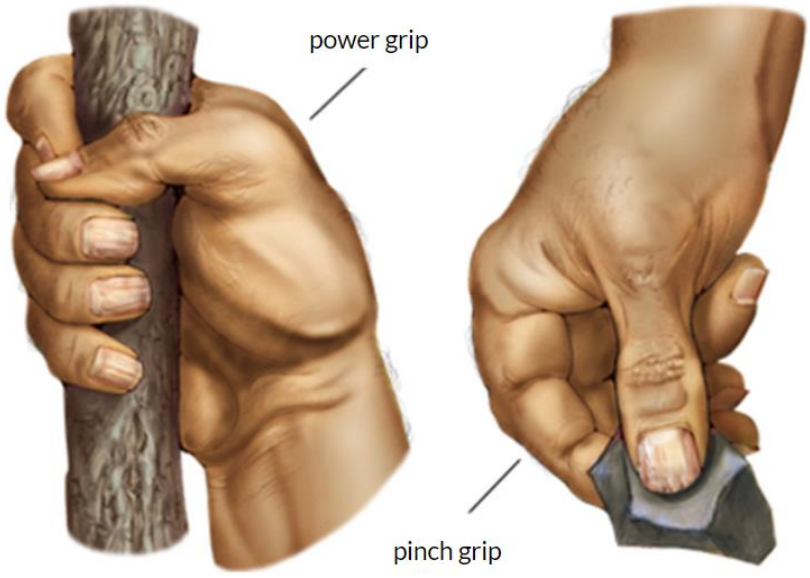

Figure 49: Examples of power grip and pinch grip

Second, 80% of male subjects showed a significant reduction in the mean FRV for FCR when comparing the barehand trials to the EndoGrip trials, with an average reduction of 22.28 % MVC.

This trend can be attributed to the increased outer diameter of the EndoGrip. The larger outer diameter increases the moment arm distance between the center of the endoscope and the contact point of the hand, at which forces are applied to enact torque onto the endoscope. This increase in the moment arm distance in turn decreases the amount of force required to apply the same amount of torque the barehand can generate alone with no gripping device (McDowell, 2012).

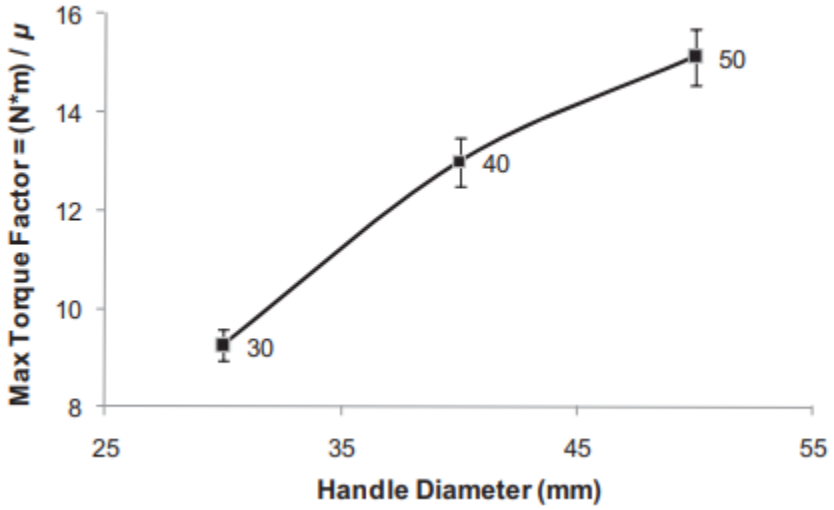

Figure 50: Positive relationship between cylindrical handle diameter and theoretical maximum torque factors (McDowell, 2012)

As for the female subjects, we observed the opposite trend for their mean FRVs for FDI when comparing the barehand trials to the EndoGrip trials. All female subjects showed a significant increase in the mean FRV for FDI when comparing the barehand trials to the EndoGrip trials, with an average increase of 37.71 % MVC. Additionally, all the female subjects did not

show any significant differences in the mean FRV for FCR when comparing the barehand trials to the EndoGrip trials.

Both trends can be justified by taking into consideration the relatively large size of the EndoGrip for female subjects. Maximum grip strength is achieved in the power grip position, with grip strength declining as gripping diameter increases (i.e., the distance between the tips of the thumb and index finger increases as the grip diameter surpasses the optimal level for a given hand size) (Rossi, 2012). Since the EndoGrip size is relatively too large, the FDI must endure the load of further abducting the fingers to fit the large grip diameter as well as the load of the gripping forces. As for the FCR, the larger grip diameter increases the circumference around which the wrist must flex in order to apply torque onto the endoscope. This results in the wrist needing to flex and travel more to reach the same level of rotation which may be cancelling out the beneficial effects of decreasing the amount of force necessary to apply the same amount of torque as the barehand.

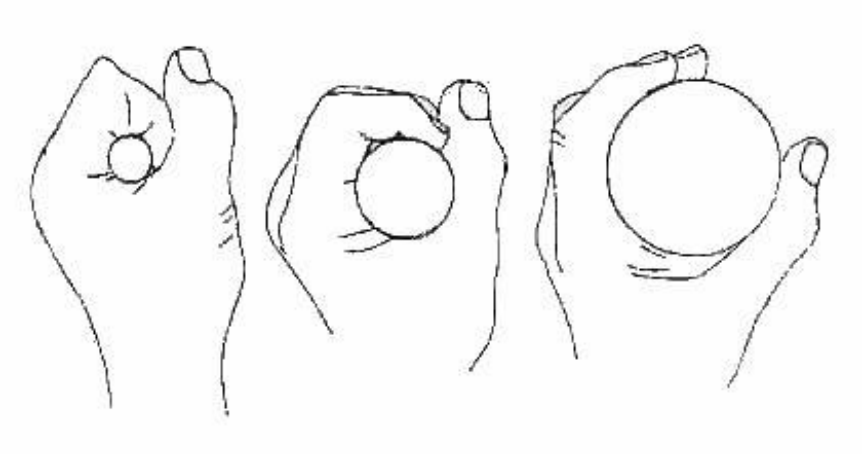

Figure 51: Various power grip diameters and the resulting hand posture

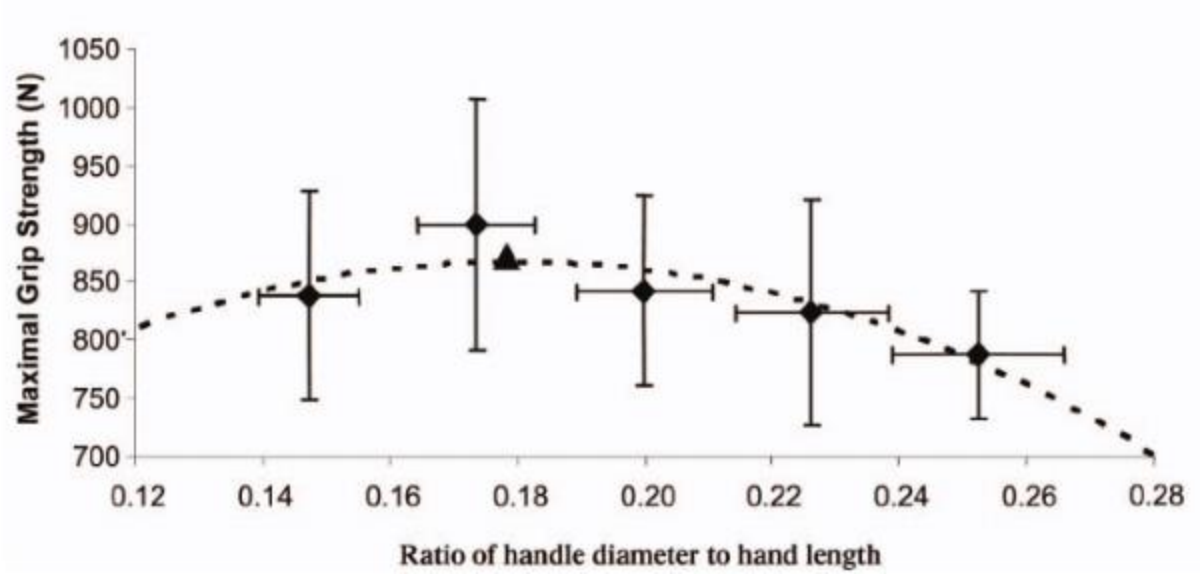

Figure 52: Maximal grip strength profile for range of handle diameter to hand length ratios (Rossi, 2012)

For both the male and female subjects, we observed an overlapping trend in their mean FRV for APB when comparing the barehand trials to the EndoGrip trials. First, 60% of male subjects showed a significant increase in the mean FRV for APB when comparing the barehand trials to the EndoGrip trials, with an average increase of 16.63 % MVC. Similarly, all female subjects showed a significant increase in the mean FRV for APB when comparing the barehand trials to the EndoGrip trials, with an average increase of 44.43 % MVC.

These trends can also be explained by considering the shift in grip position that occurs when moving from the barehand trials to the EndoGrip trials. Switching to a power grip requires more abduction of the thumb than that of the pinch grip, and the APB is more engaged to facilitate that position. This means the APB endures the load of holding the thumb in position as well as the load of the gripping forces. The significantly larger increase in the mean FRV for APB in female subjects compared to that of the male subjects further supports this, as the smaller hand sizes would require even further abduction of the thumb, and, thus, increase the load.

Finally, in a comparison between the competitor grip trials and the EndoGrip trials, all male subjects showed a significant reduction in the mean FRV for FDI, with an average reduction of 25.16 % MVC. In addition, 60% of male subjects showed a significant reduction in the mean FRV for FCR when comparing the competitor grip to the EndoGrip, with average reduction of 26.39 % MVC.

We may attribute these improvements to the difference in the grips' design elements, specifically the larger outer diameter and the more ergonomic shape of the EndoGrip that allows for an optimal power grip position.

CHAPTER 4: EXPERIMENTAL RESULTS – RATE OF FATIGUE RISK VALUE

4.1 Rate of fatigue risk value assessment

As a multi-faceted approach to understanding the impact of the different grip types on muscle strain, we also assessed the change of FRV over the duration of each trial. These rates of FRV were obtained by first calculating the FRV for each of the 12 events in a trial in chronological order. Within a given subject and muscle, FRV values and their corresponding times for the three grip types are plotted on a scatterplot. Finally, we fit a linear model to quantify the rates of FRV in terms of slope and intercept. The resulting three lines, each representing the rate of FRV for the corresponding grip types, were tested for statistically significant differences in their slopes and intercepts using multiple linear regression.

4.2 Multiple linear regression

Within a given subject and muscle, we have three different samples: barehand events, competitor grip events, and EndoGrip events. For each grip type, there exists an independent variable, which is time and represented as x, and a dependent variable, which is the FRV and represented as y. There also exists two coefficients, the intercept coefficient and the slope coefficient which are represented as b_0 and b_1, respectively. As an equation, this is written as

$$y = b_0 + b_1*x$$

One method of testing for differences in slopes and intercepts of different grips is by using multiple linear regression. First we combine them into one sample with dummy indicator variables C and E. We also added interaction terms C*x and E*x as independent variables. The resulting regression model takes the form of

$$y = b_0 + b_1*x + b_2*C + b_3*E + b_4*C*x + b_5*E*x$$

Which can be rearranged as

$$y = (b_0 + b_2*C + b_3*E) + (b_1 + b_4*C + b_5*E)*x$$

For FRV data from the barehand events, since C, E = 0, the intercept is b_0 and the slope is b_1. For FRV data from the competitor grip events, since C = 1 and E = 0, the intercept is b_0+b_2 and the slope is b_1+b_4. For FRV data from the EndoGrip events, since C = 0 and E = 1, the intercept is b_0+b_3 and the slope is b_1+b_5. Thus, if there is no difference between the rate of FRV for the barehand and competitor grip events (i.e., the intercepts and slopes are the same), then we expect the coefficients b_2 and b_4 to be zero. Similarly, if there is no difference between the rate of FRV for the barehand and EndoGrip events, then we expect the coefficients b_3 and b_5 to be zero. Since the coefficients are calculated with corresponding p-values in this regression test, we simply evaluate those to detect significance. For example, if the p-value for coefficients b_3 and b_5 are less than the alpha value of 0.05, we conclude that there is a significant difference in the rate of FRV between the barehand and the EndoGrip in their slopes and intercepts.

4.3 Results

Subject 1:

The rate of FRV for the FDI was significantly different for both the competitor grip and the EndoGrip when compared to the baseline (i.e., the rate of FRV for the FDI when using the barehand). The competitor grip's rate of FRV differed in both the intercept ($p=2.28 \times 10^{-10}$) and the slope ($p=8.48 \times 10^{-5}$) whereas the EndoGrip's rate of FRV differed in only the intercept ($p=0.0155$).

The rate of FRV for the APB was significantly different for both the competitor grip and the EndoGrip when compared to the baseline (i.e., the rate of FRV for the APB when using the barehand). The competitor grip's rate of FRV differed in both the intercept ($p=3.20 \times 10^{-9}$) and the

slope (p=0.000933) whereas the EndoGrip's rate of FRV differed in only the intercept (p=0.000215).

The rate of FRV for the FCR was significantly different for only the EndoGrip when compared to the baseline (i.e., the rate of FRV for the FCR when using the barehand). The EndoGrip's rate of FRV differed in only the intercept ($p=7.24 \times 10^{-5}$).

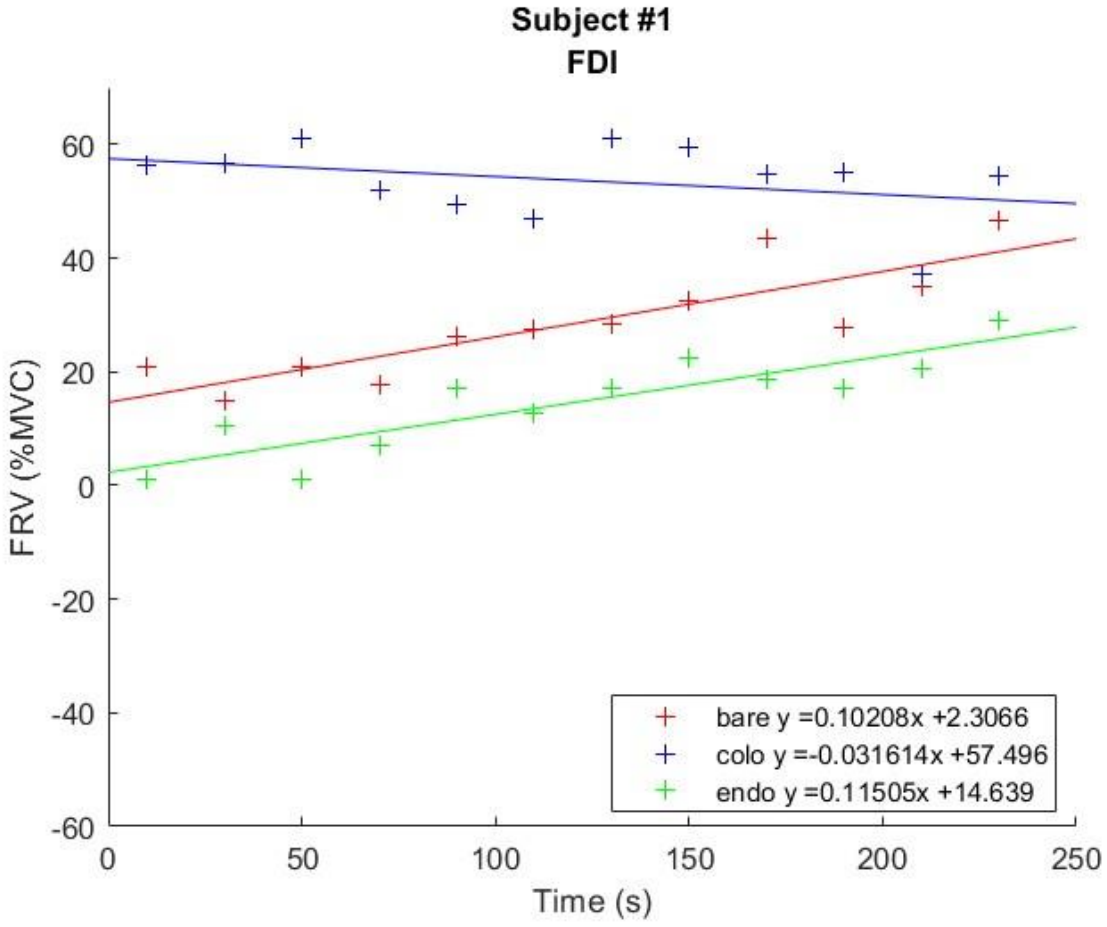

Figure 53: Linear models of change in FRV over time for FDI in subject 1 (red – barehand, blue – competitor grip, green – EndoGrip)

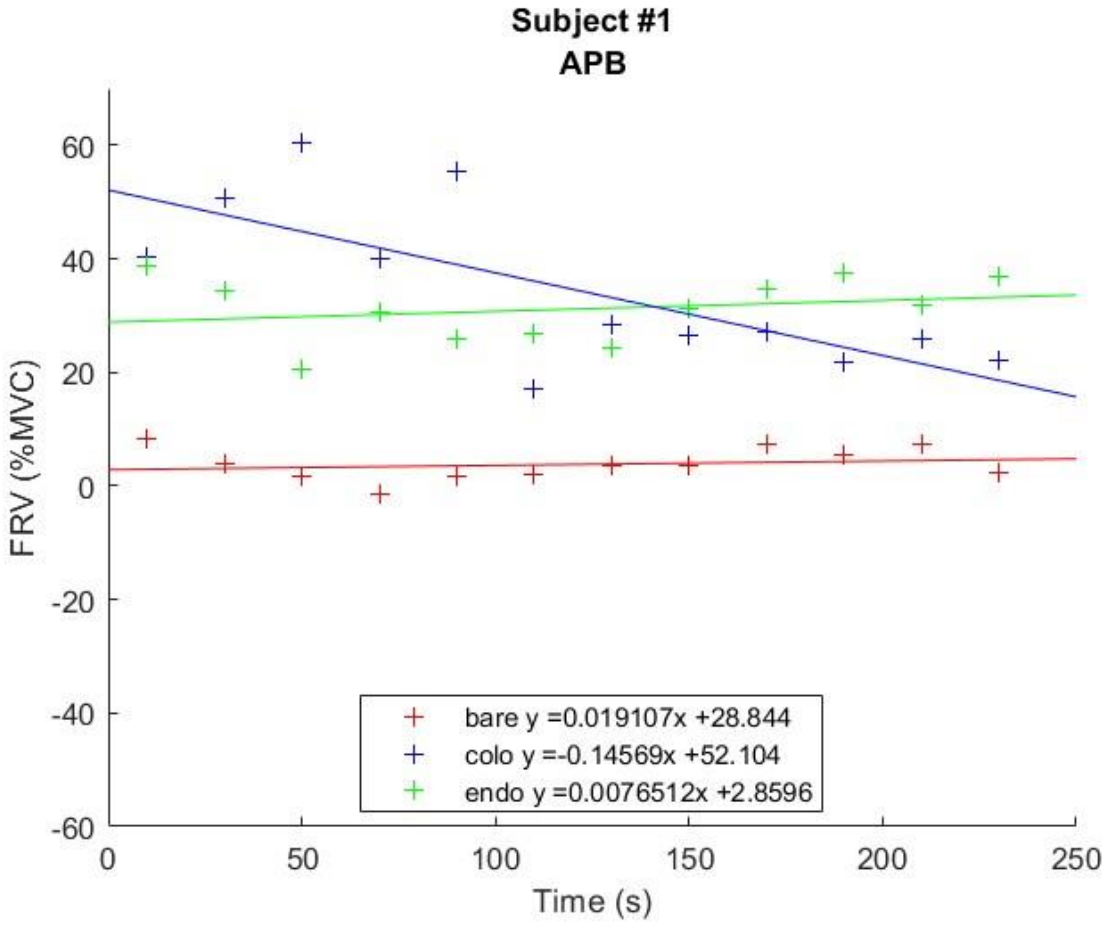

Figure 54: Linear models of change in FRV over time for APB in subject 1 (red – barehand, blue – competitor grip, green – EndoGrip)

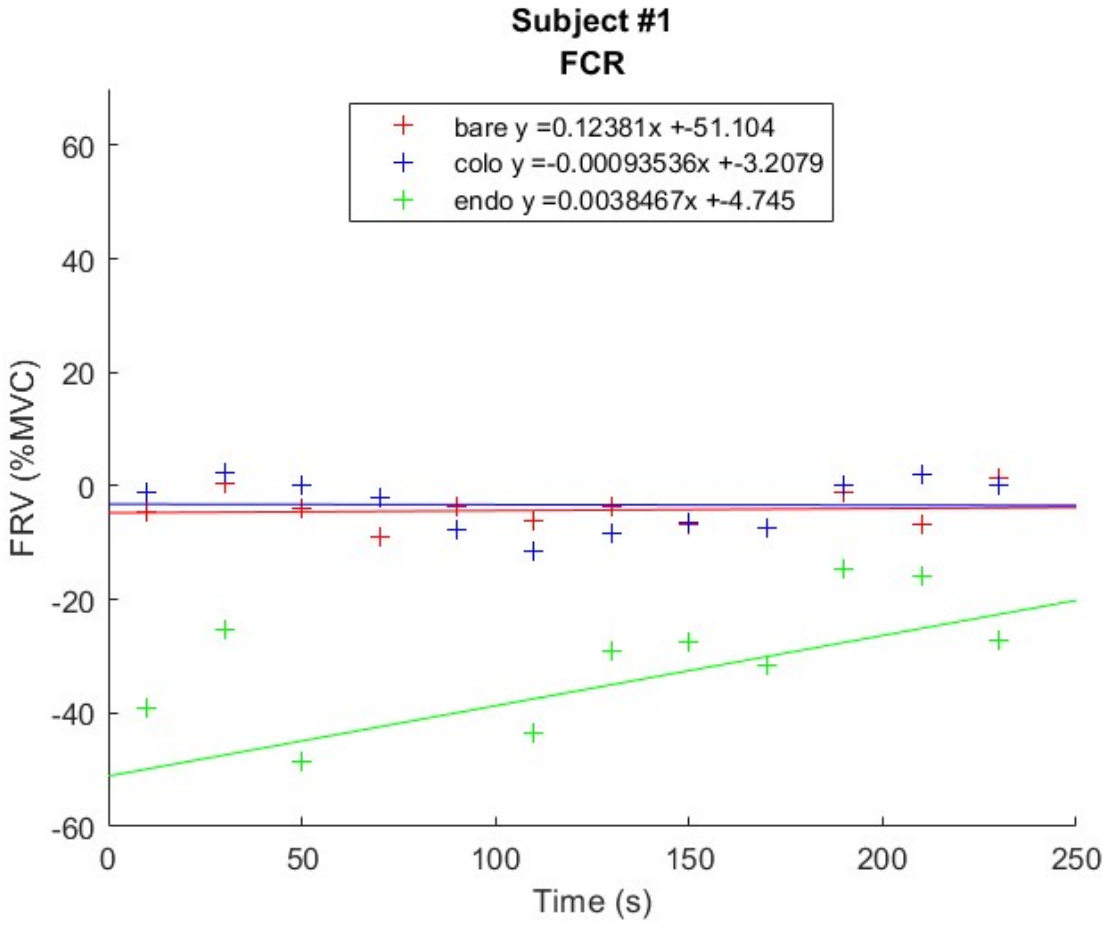

Figure 55: Linear models of change in FRV over time for FCR in subject 1 (red – barehand, blue – competitor grip, green – EndoGrip)

Subject 2:

The rate of FRV for the FDI was not significantly different for both the competitor grip and the EndoGrip when compared to the baseline.

The rate of FRV for the APB was significantly different for both the competitor grip and the EndoGrip when compared to the baseline. The competitor grip's rate of FRV differed in the intercept ($p=1.06 \times 10^{-5}$) whereas the EndoGrip's rate of FRV differed in both the intercept ($p=1.20 \times 10^{-9}$) and the slope ($p=0.000547$).

The rate of FRV for the FCR was significantly different for only the EndoGrip when compared to the baseline. The EndoGrip's rate of FRV differed in only the intercept ($p=0.0318$).

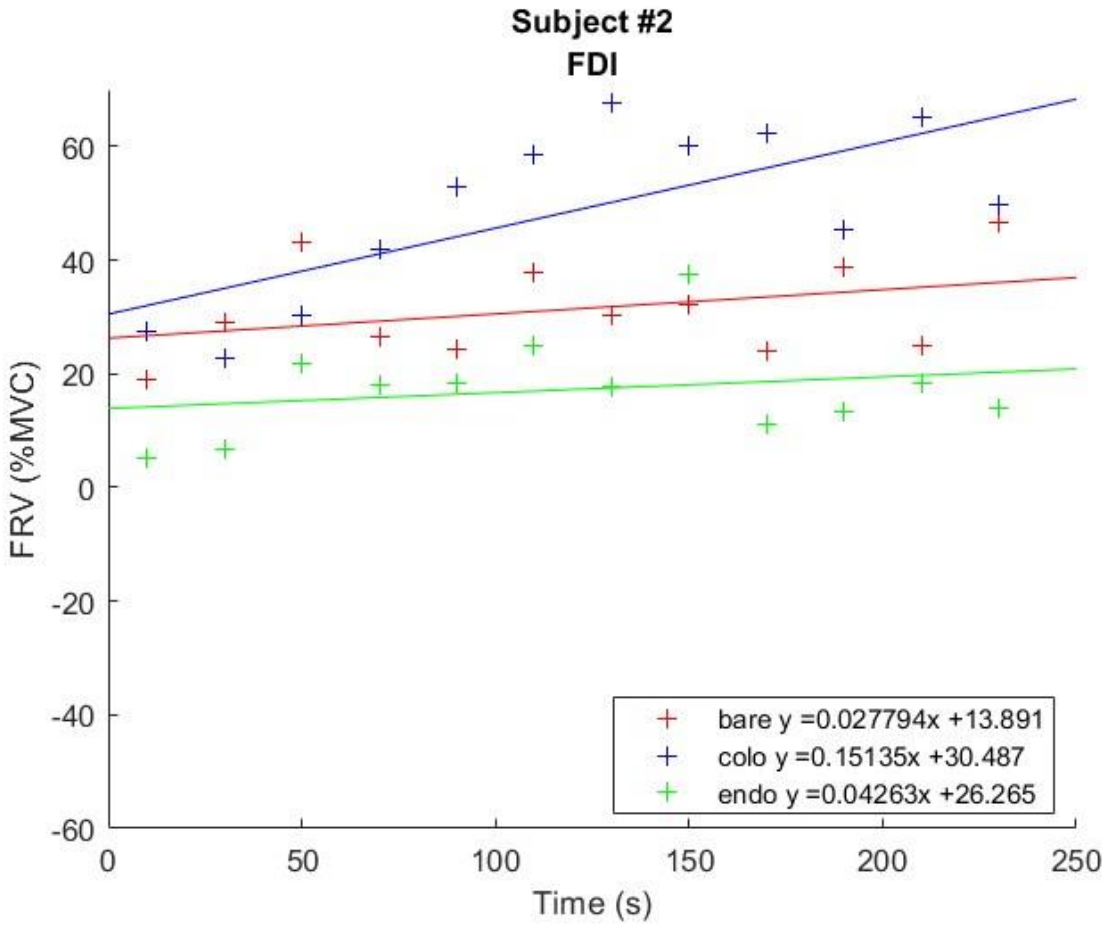

Figure 56: Linear models of change in FRV over time for FDI in subject 2 (red – barehand, blue – competitor grip, green – EndoGrip)

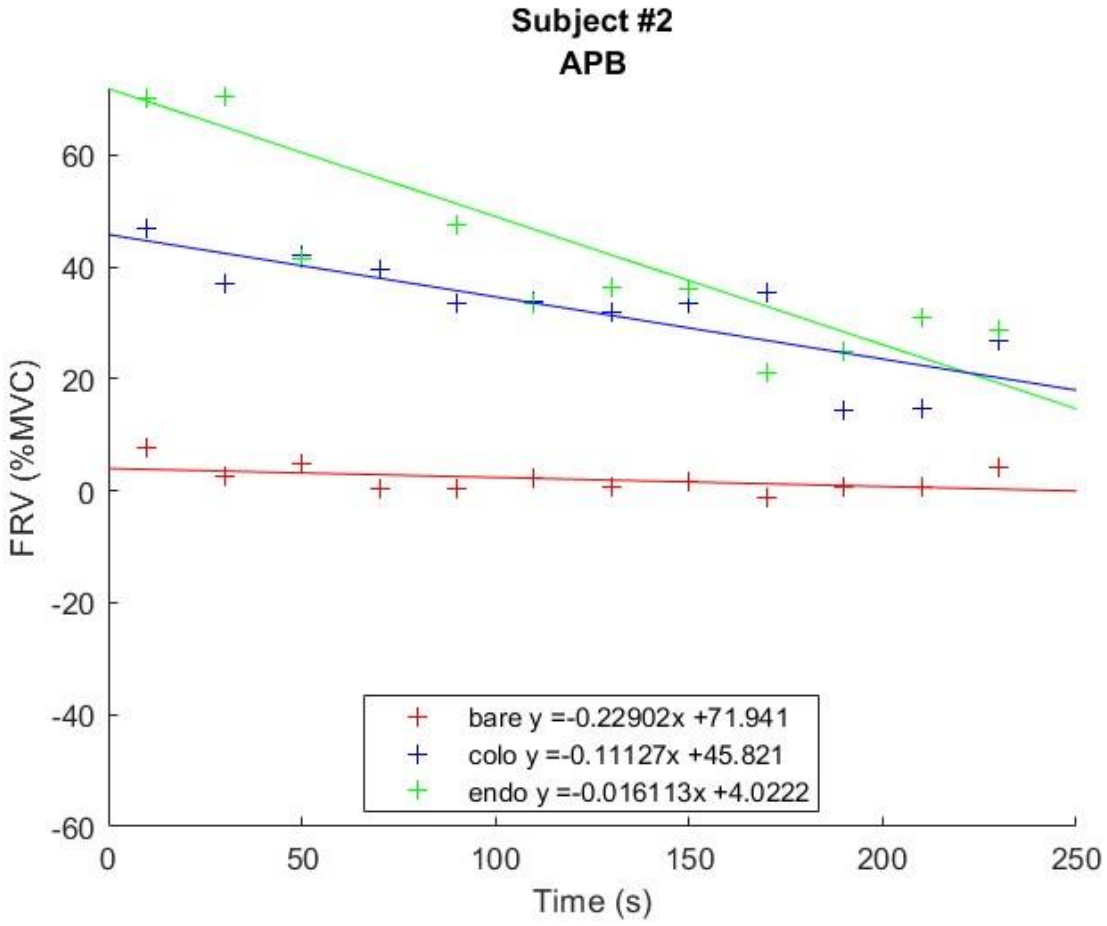

Figure 57: Linear models of change in FRV over time for APB in subject 2 (red – barehand, blue – competitor grip, green – EndoGrip)

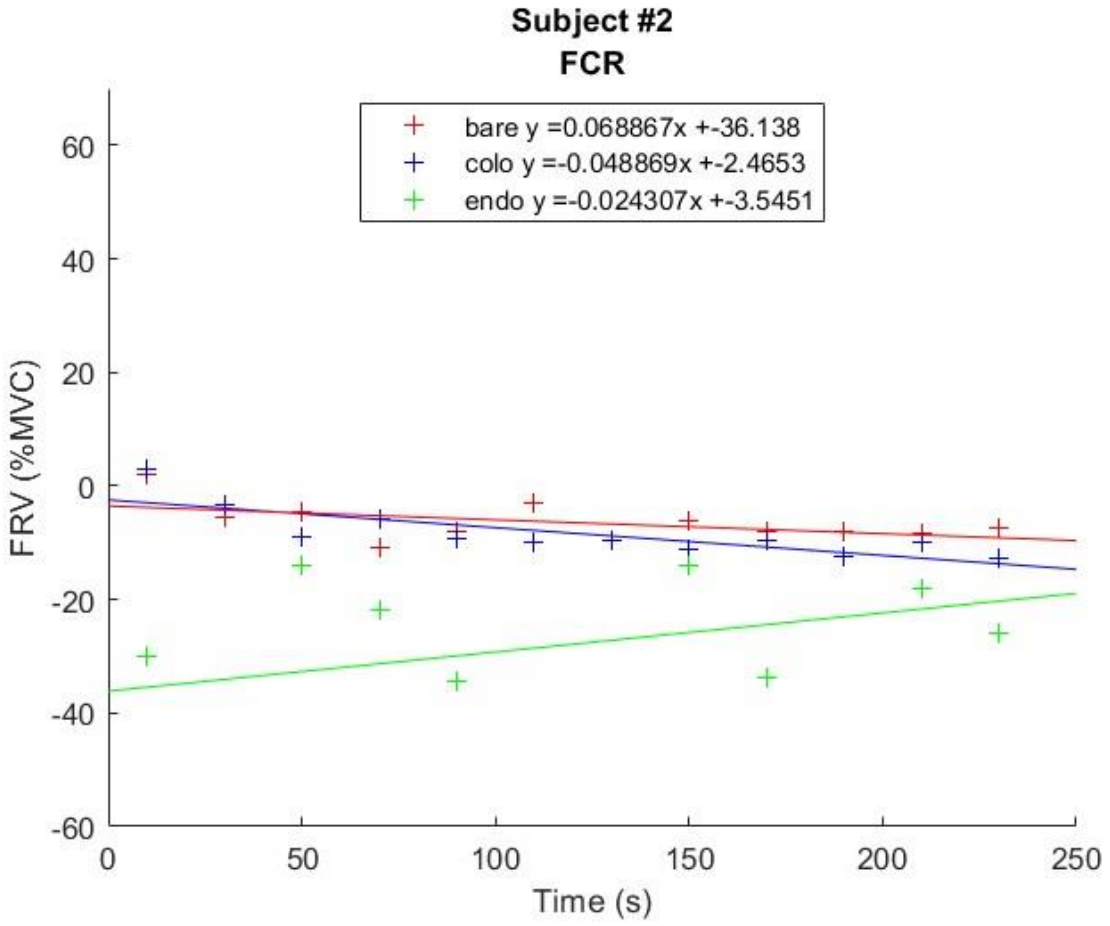

Figure 58: Linear models of change in FRV over time for FCR in subject 2 (red – barehand, blue – competitor grip, green – EndoGrip)

Subject 3:

The rate of FRV for the FDI was significantly different for only the competitor grip when compared to the baseline. The competitor grip's rate of FRV differed in only the slope ($p=0.000383$).

The rate of FRV for the APB was significantly different for only the competitor grip when compared to the baseline. The competitor grip's rate of FRV differed in only the intercept ($p=3.36 \times 10^{-5}$).

The rate of FRV for the FCR was significantly different for only the EndoGrip when compared to the baseline. The EndoGrip's rate of FRV differed in only the intercept ($p=0.0141$).

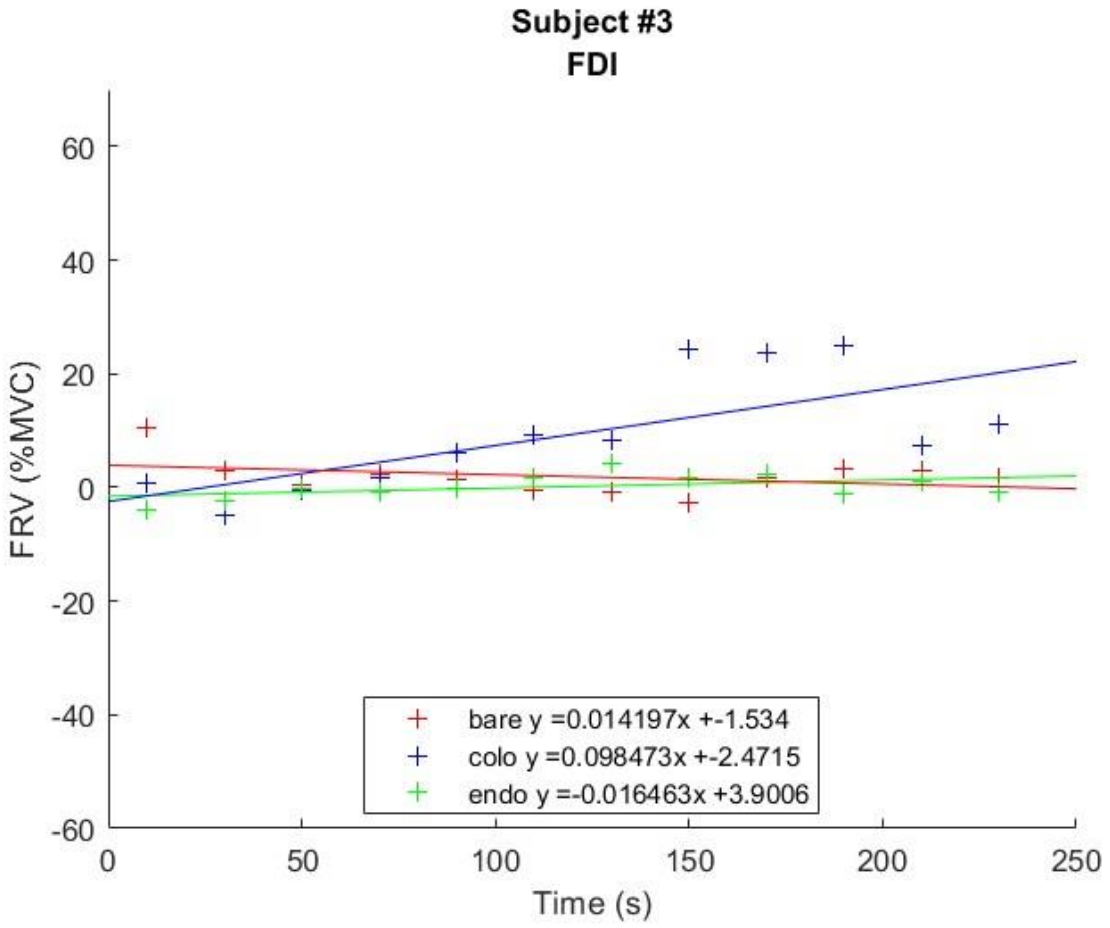

Figure 59: Linear models of change in FRV over time for FDI in subject 3 (red – barehand, blue – competitor grip, green – EndoGrip)

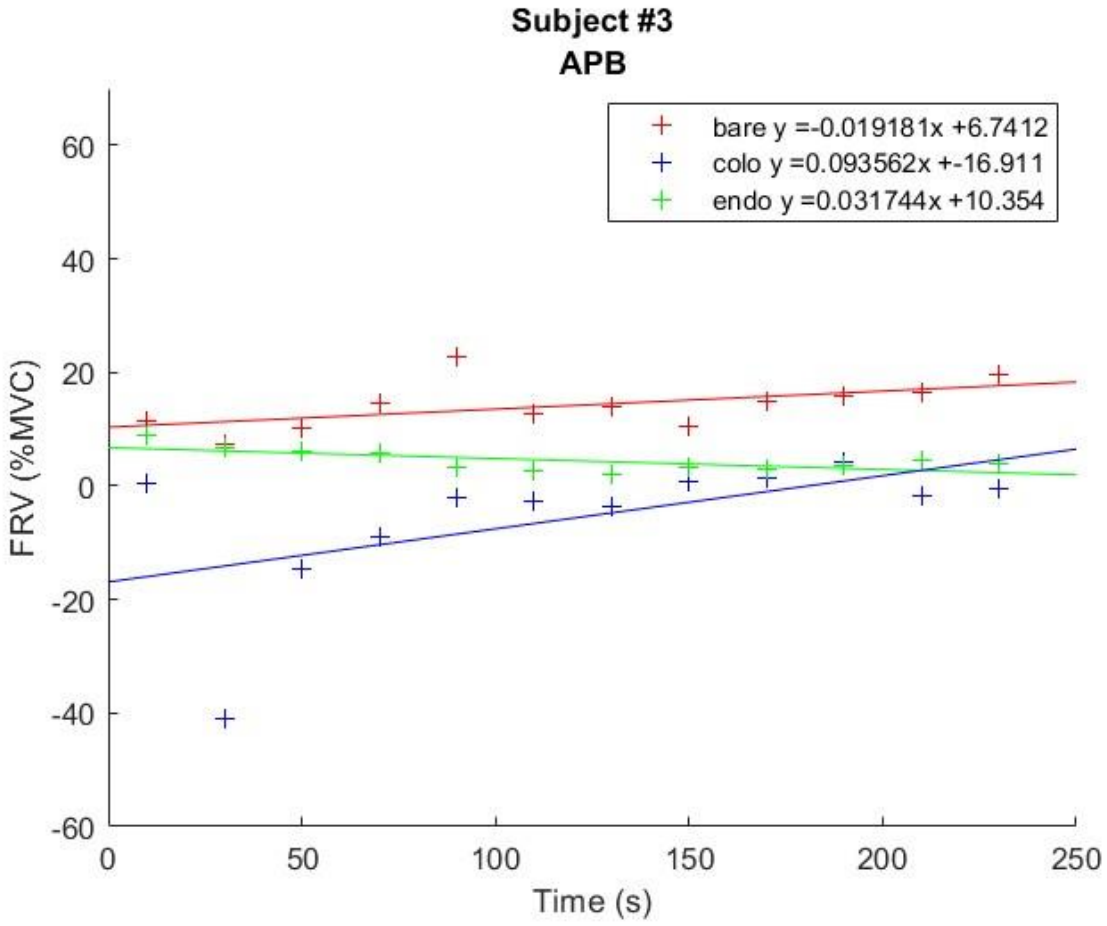

Figure 60: Linear models of change in FRV over time for APB in subject 3 (red – barehand, blue – competitor grip, green – EndoGrip)

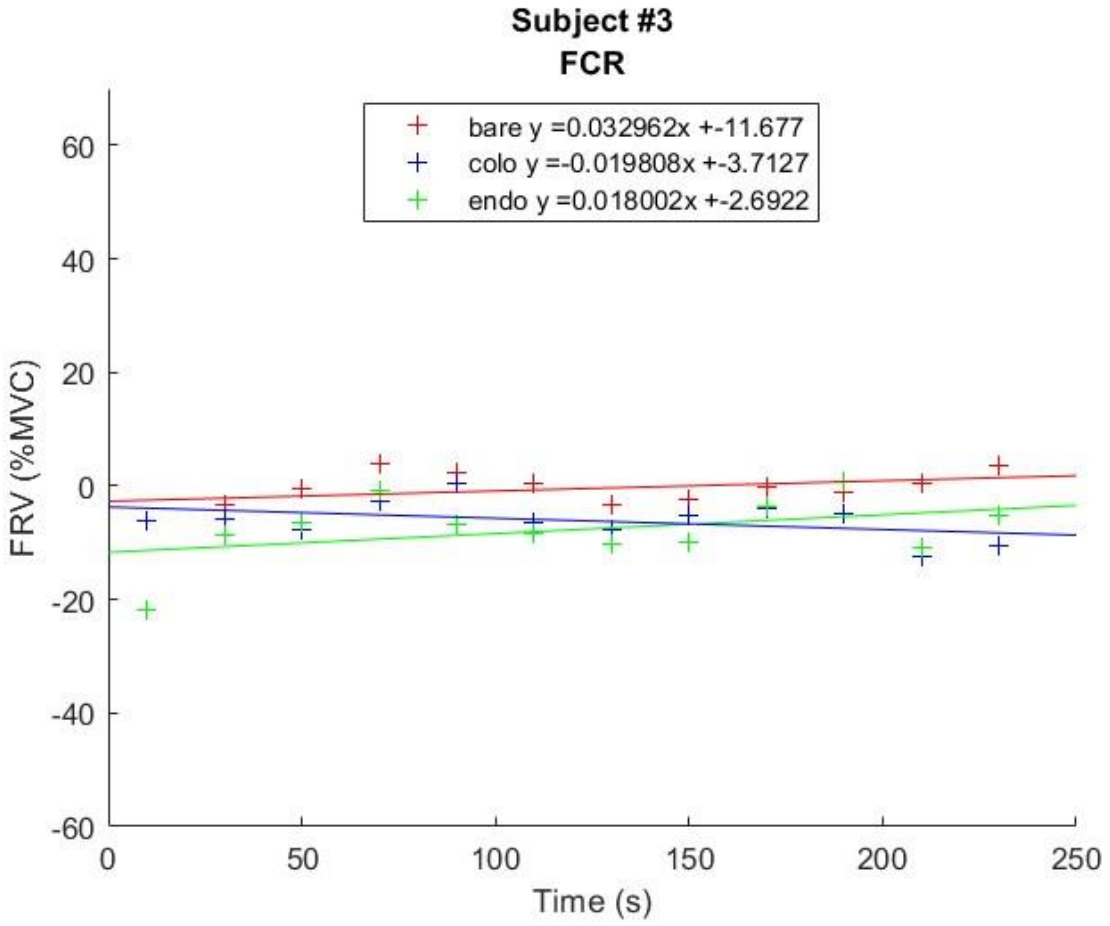

Figure 61: Linear models of change in FRV over time for FCR in subject 3 (red – barehand, blue – competitor grip, green – EndoGrip)

Subject 4:

The rate of FRV for the FDI was significantly different for both the competitor grip and the EndoGrip when compared to the baseline. The competitor grip's rate of FRV differed in only the slope ($p=0.0288$) whereas the EndoGrip's rate of FRV differed in only the intercept ($p=0.0328$).

The rate of FRV for the APB was significantly different for only the competitor grip when compared to the baseline. The competitor grip's rate of FRV differed in both the intercept ($p=1.66 \times 10^{-6}$) and the slope ($p=0.0106$).

The rate of FRV for the FCR was significantly different for both the competitor grip and the EndoGrip when compared to the baseline. The competitor grip's rate of FRV differed in only the intercept ($p=1.44 \times 10^{-5}$) while the EndoGrip's rate of FRV also differed in only the intercept ($p=0.000163$).

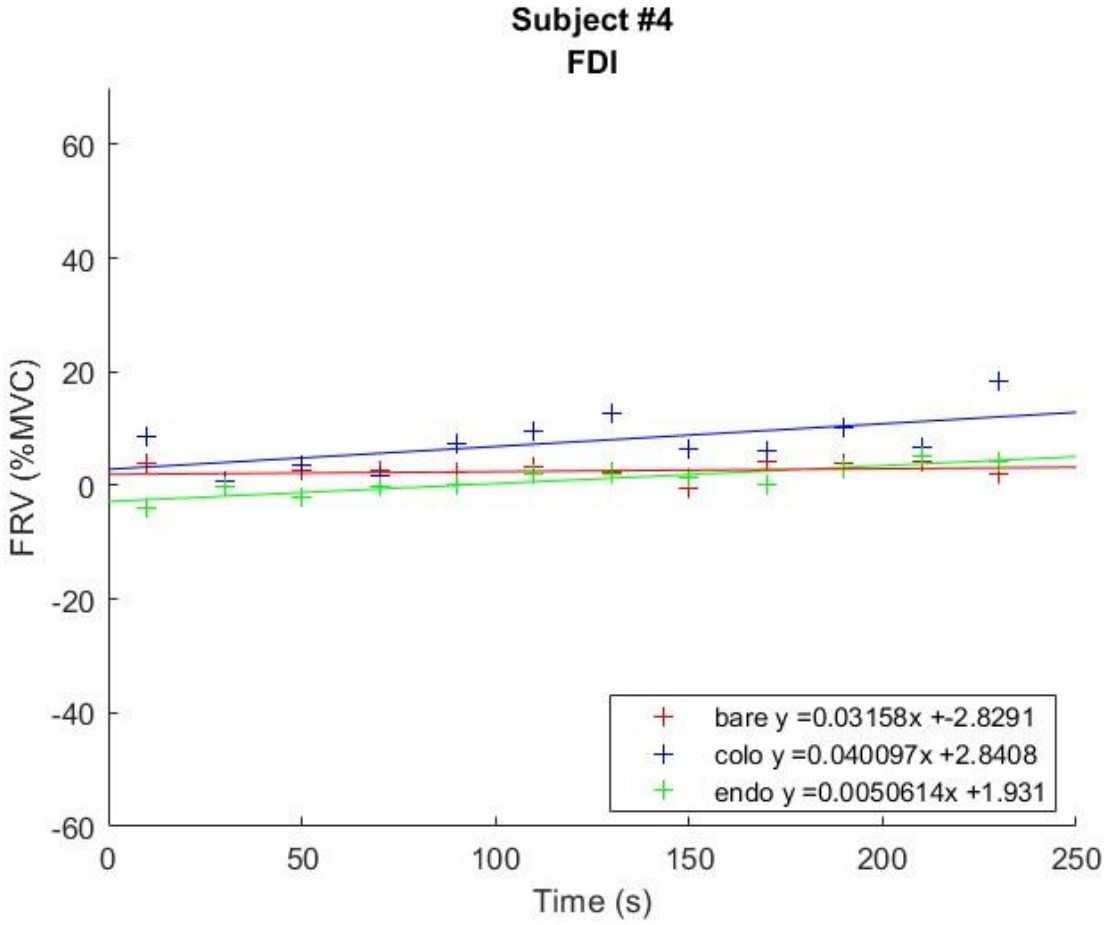

Figure 62: Linear models of change in FRV over time for FDI in subject 4 (red – barehand, blue – competitor grip, green – EndoGrip)

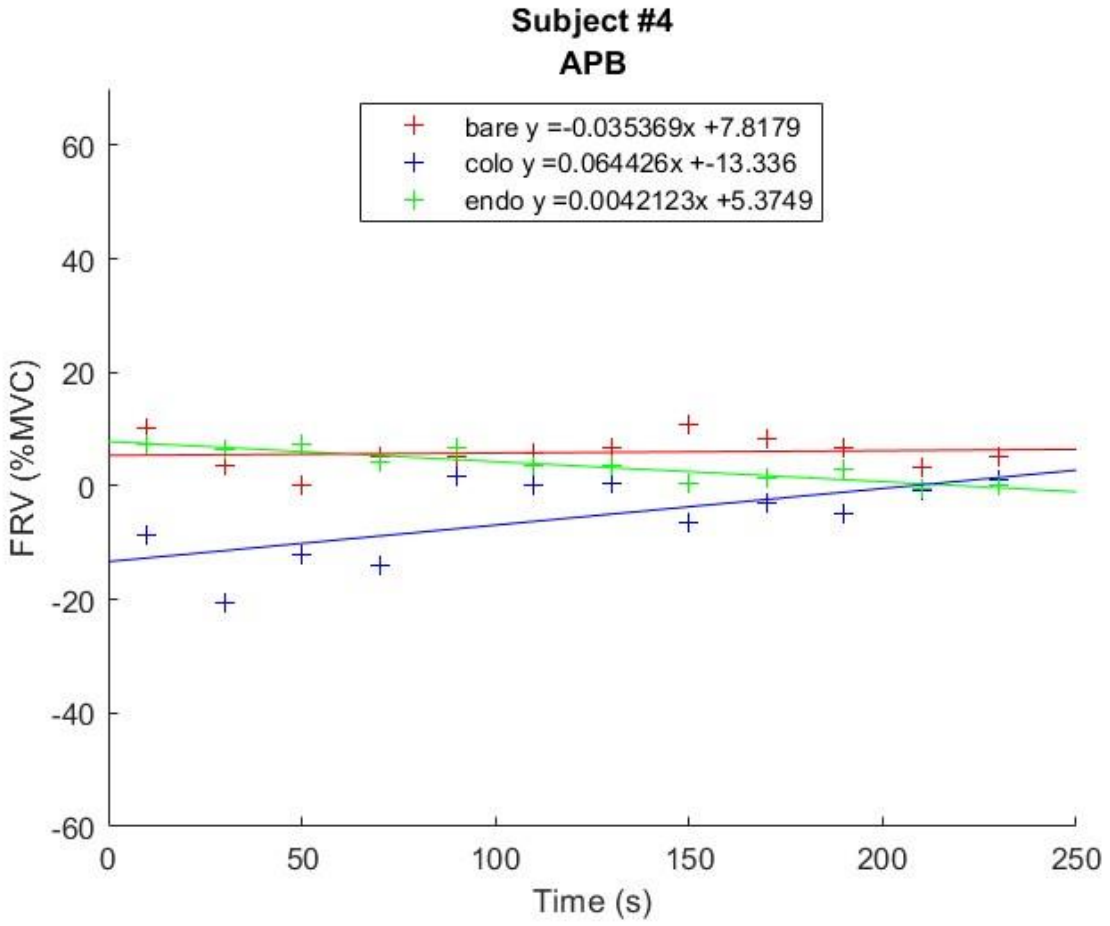

Figure 63: Linear models of change in FRV over time for APB in subject 4 (red – barehand, blue – competitor grip, green – EndoGrip)

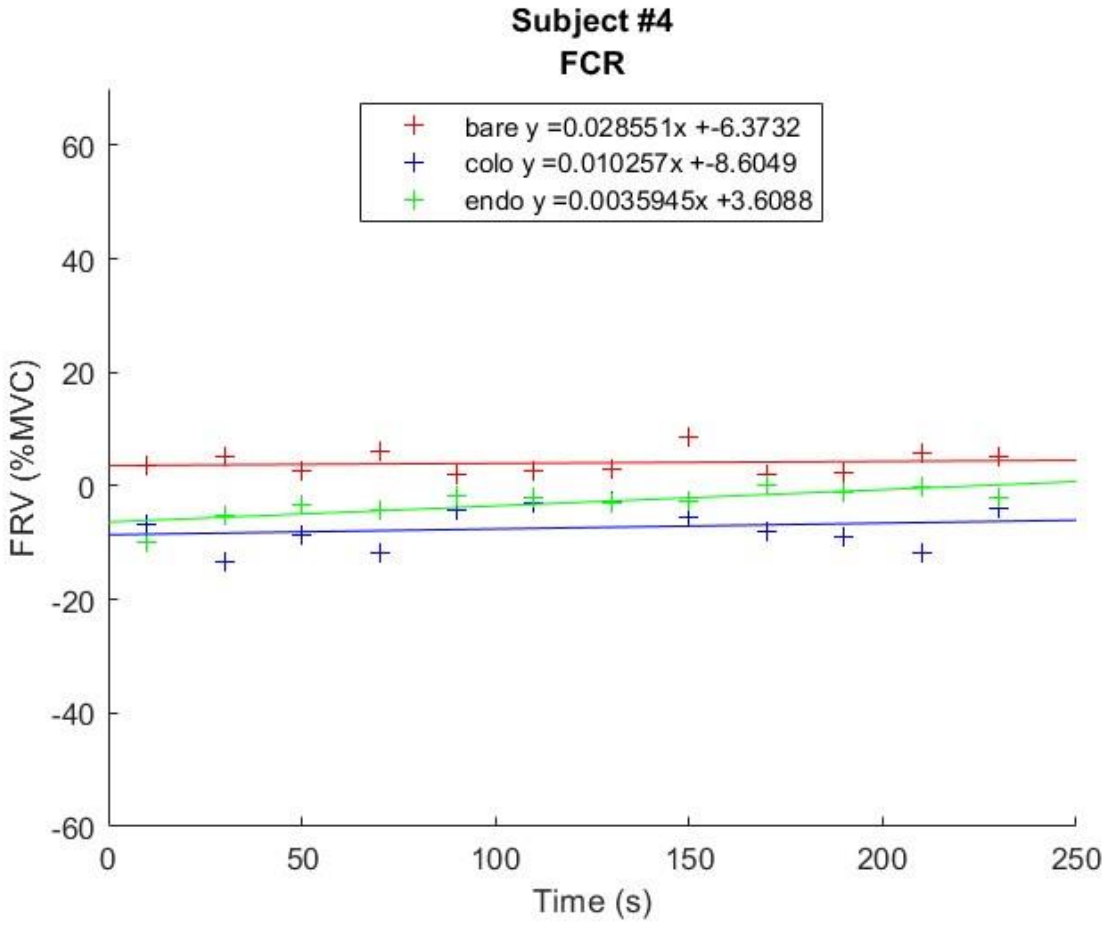

Figure 64: Linear models of change in FRV over time for FCR in subject 4 (red – barehand, blue – competitor grip, green – EndoGrip)

Subject 5:

The rate of FRV for the FDI was not significantly different for both the competitor grip and the EndoGrip when compared to the baseline.

The rate of FRV for the APB was significantly different for both the competitor grip and the EndoGrip when compared to the baseline. The competitor grip's rate of FRV differed in both the intercept ($p=1.11 \times 10^{-6}$) and the slope ($p=0.00803$) whereas the EndoGrip's rate of FRV differed in only the intercept ($p=0.000134$).

The rate of FRV for the FCR was significantly different for both the competitor grip and the EndoGrip when compared to the baseline. The competitor grip's rate of FRV differed in both the intercept ($p=3.16 \times 10^{-6}$) and the slope ($p=0.00164$) while the EndoGrip's rate of FRV also differed in both the intercept ($p=2.73 \times 10^{-6}$) and the slope ($p=5.31 \times 10^{-6}$).

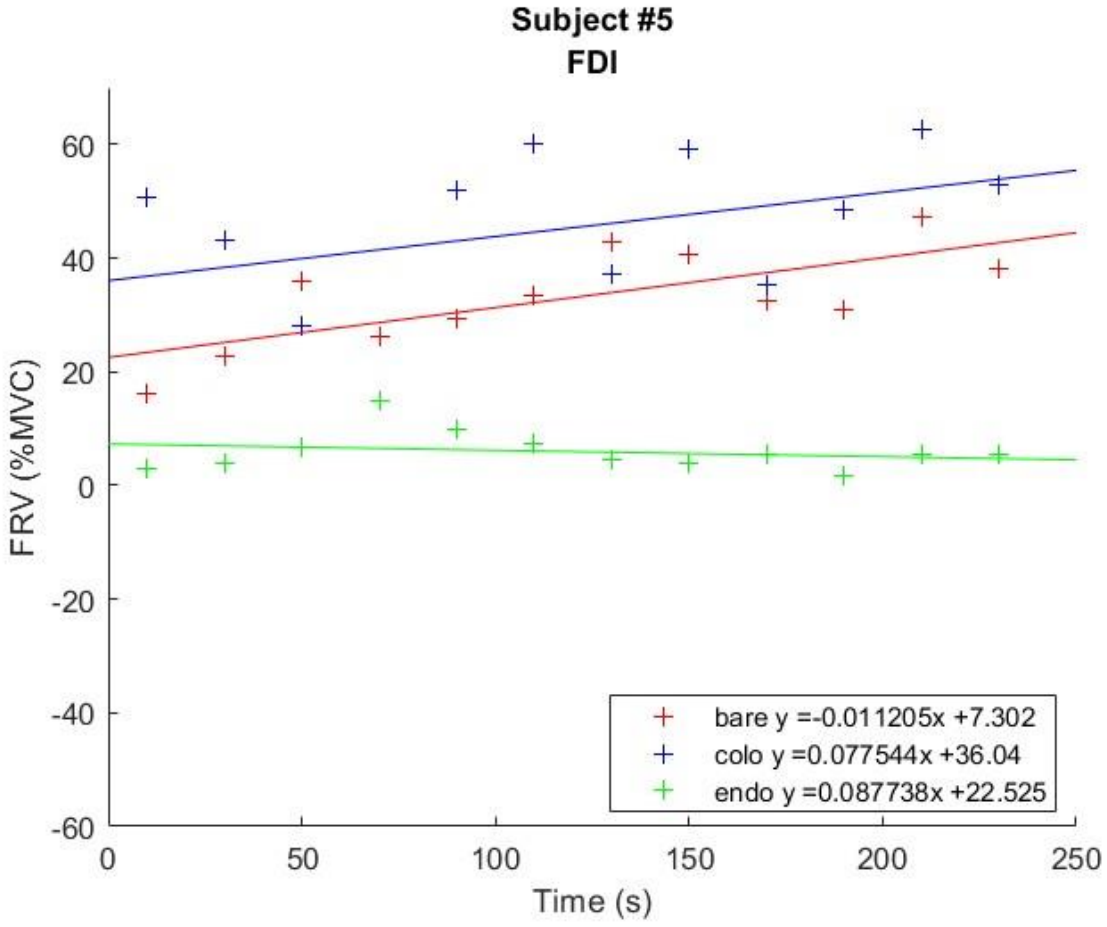

Figure 65: Linear models of change in FRV over time for FDI in subject 5 (red – barehand, blue – competitor grip, green – EndoGrip)

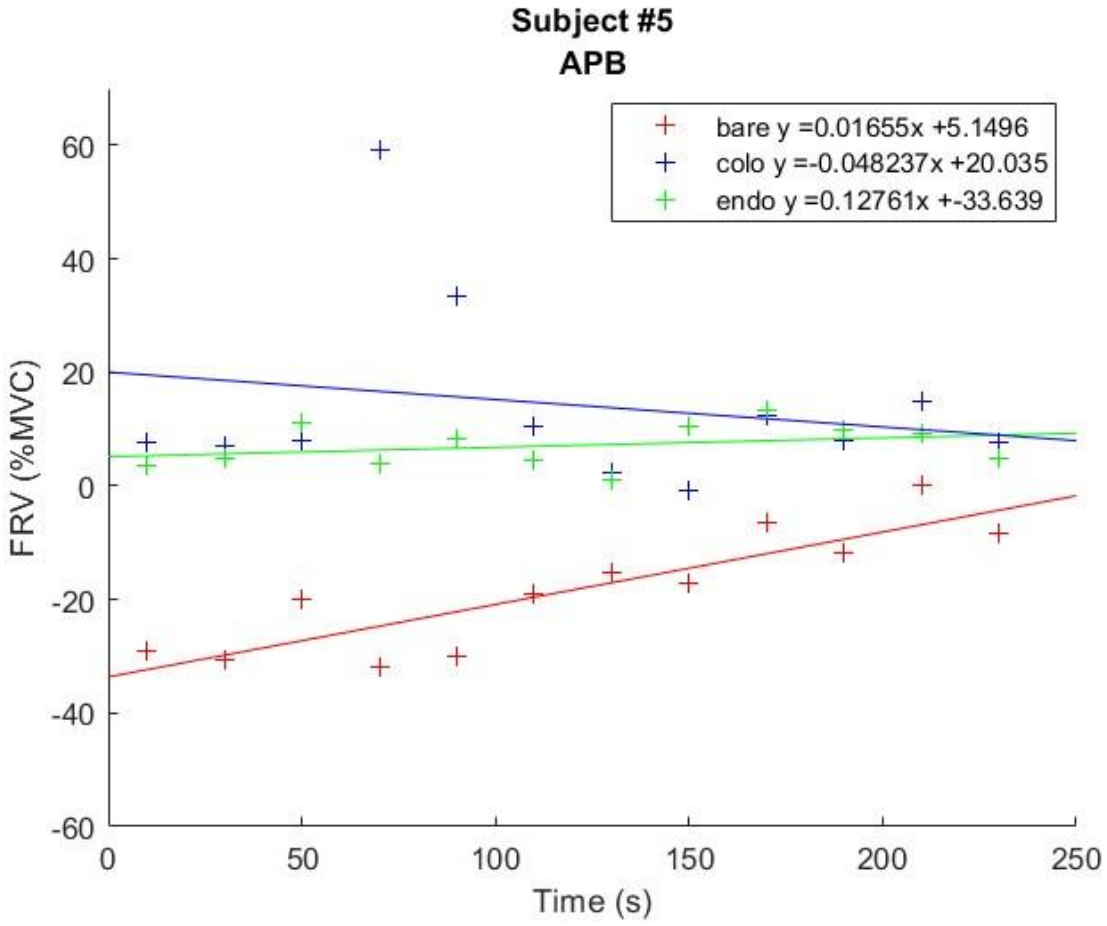

Figure 66: Linear models of change in FRV over time for APB in subject 5 (red – barehand, blue – competitor grip, green – EndoGrip)

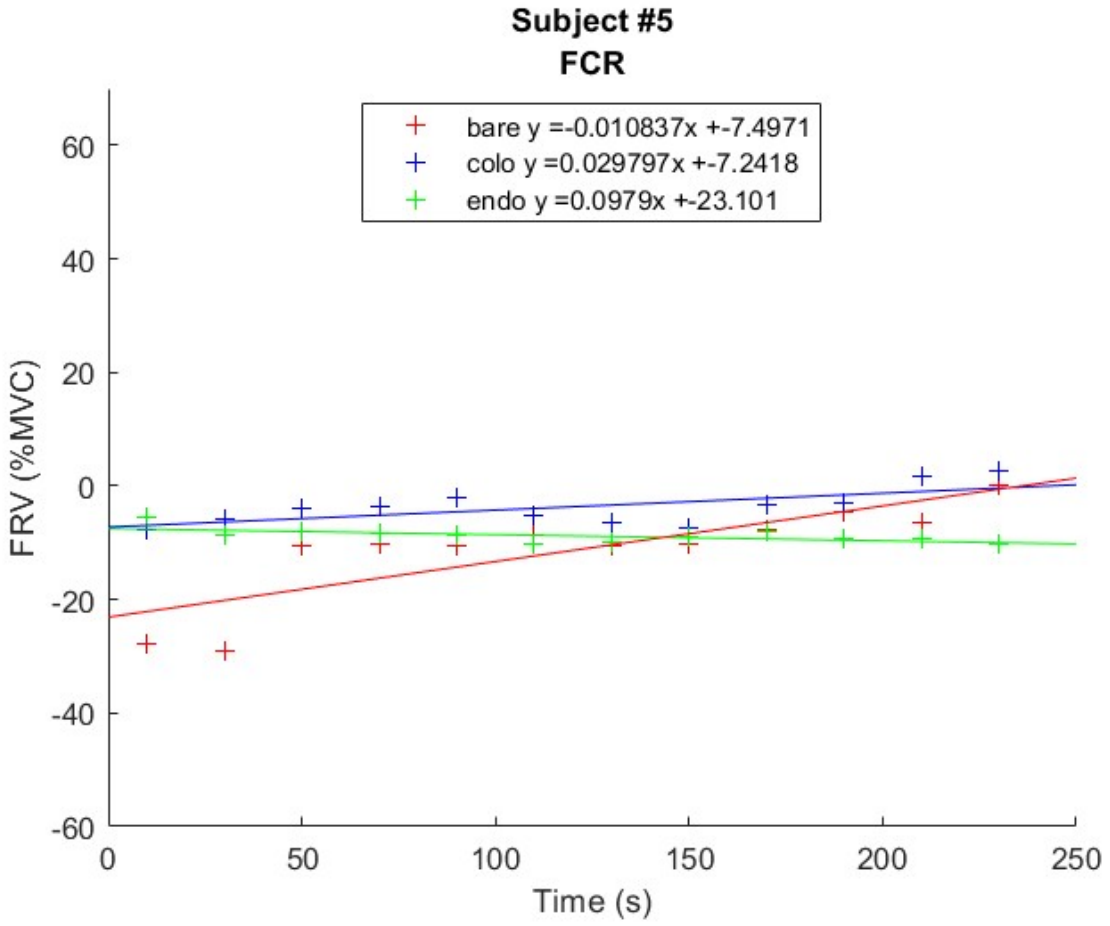

Figure 67: Linear models of change in FRV over time for FCR in subject 5 (red – barehand, blue – competitor grip, green – EndoGrip)

Subject 6:

The rate of FRV for the FDI was significantly different for both the competitor grip and the EndoGrip when compared to the baseline. The competitor grip's rate of FRV differed in only the intercept ($p=0.00200$) whereas the EndoGrip's rate of FRV differed in both the intercept ($p=5.56 \times 10^{-11}$) and the slope ($p=0.00794$).

The rate of FRV for the APB was significantly different for only the EndoGrip when compared to the baseline. The EndoGrip's rate of FRV differed in only the intercept ($p=9.88 \times 10^{-7}$).

The rate of FRV for the FCR was significantly different for only the competitor grip when compared to the baseline. The competitor grip's rate of FRV differed in only the intercept (p=0.000199).

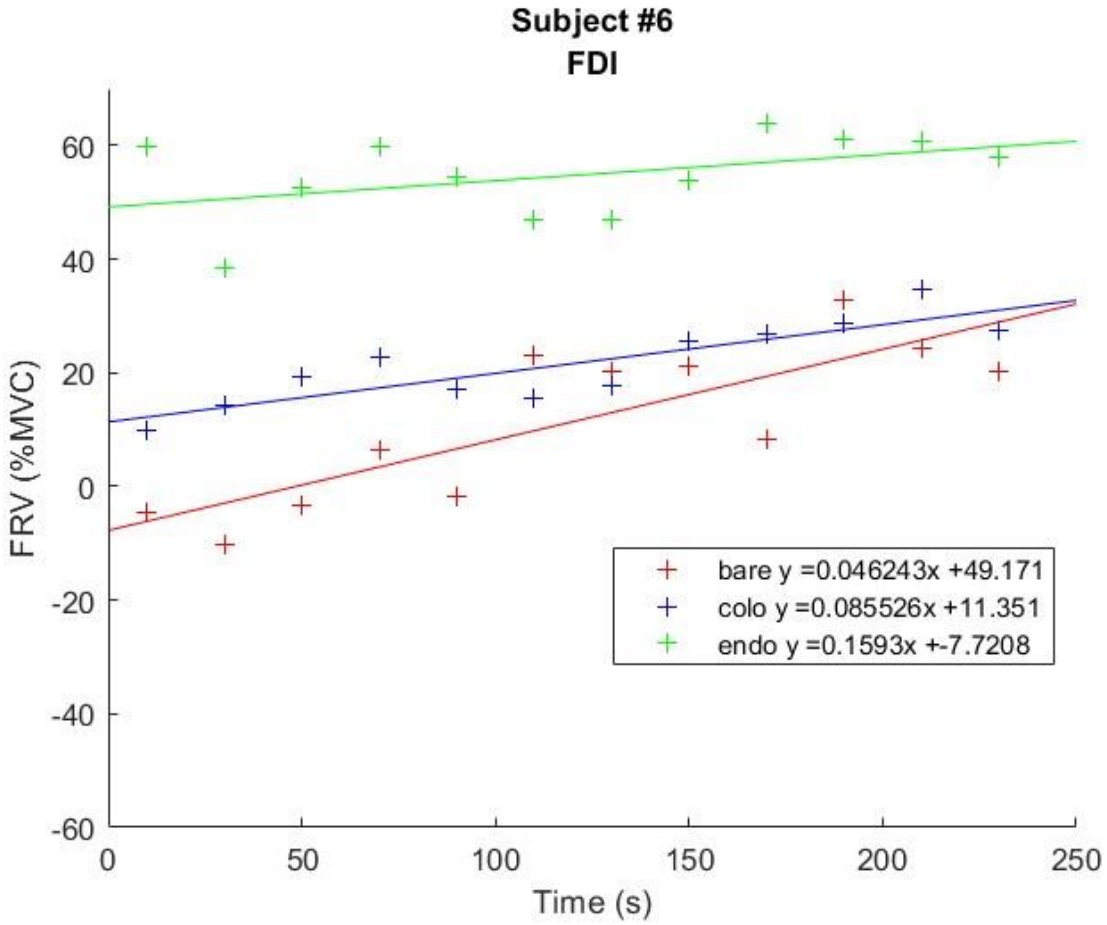

Figure 68: Linear models of change in FRV over time for FDI in subject 6 (red – barehand, blue – competitor grip, green – EndoGrip)

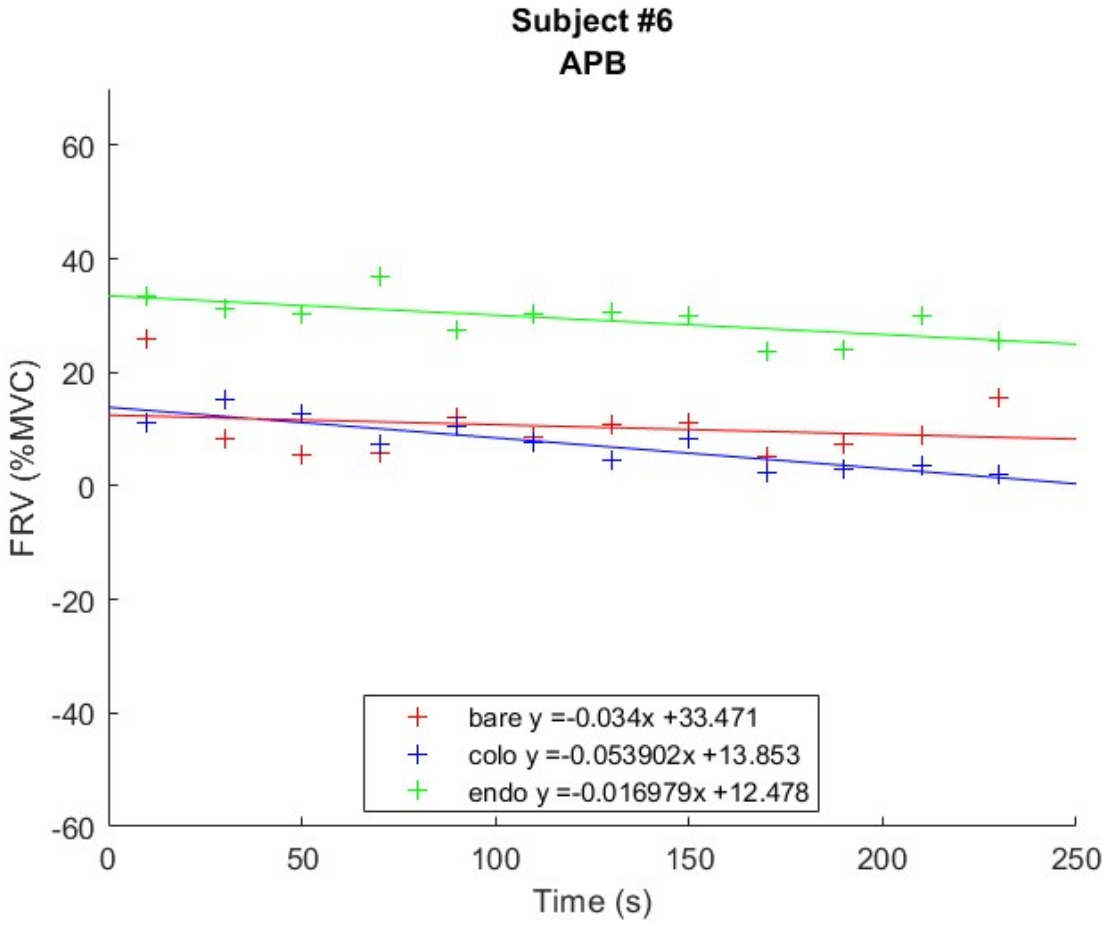

Figure 69: Linear models of change in FRV over time for APB in subject 6 (red – barehand, blue – competitor grip, green – EndoGrip)

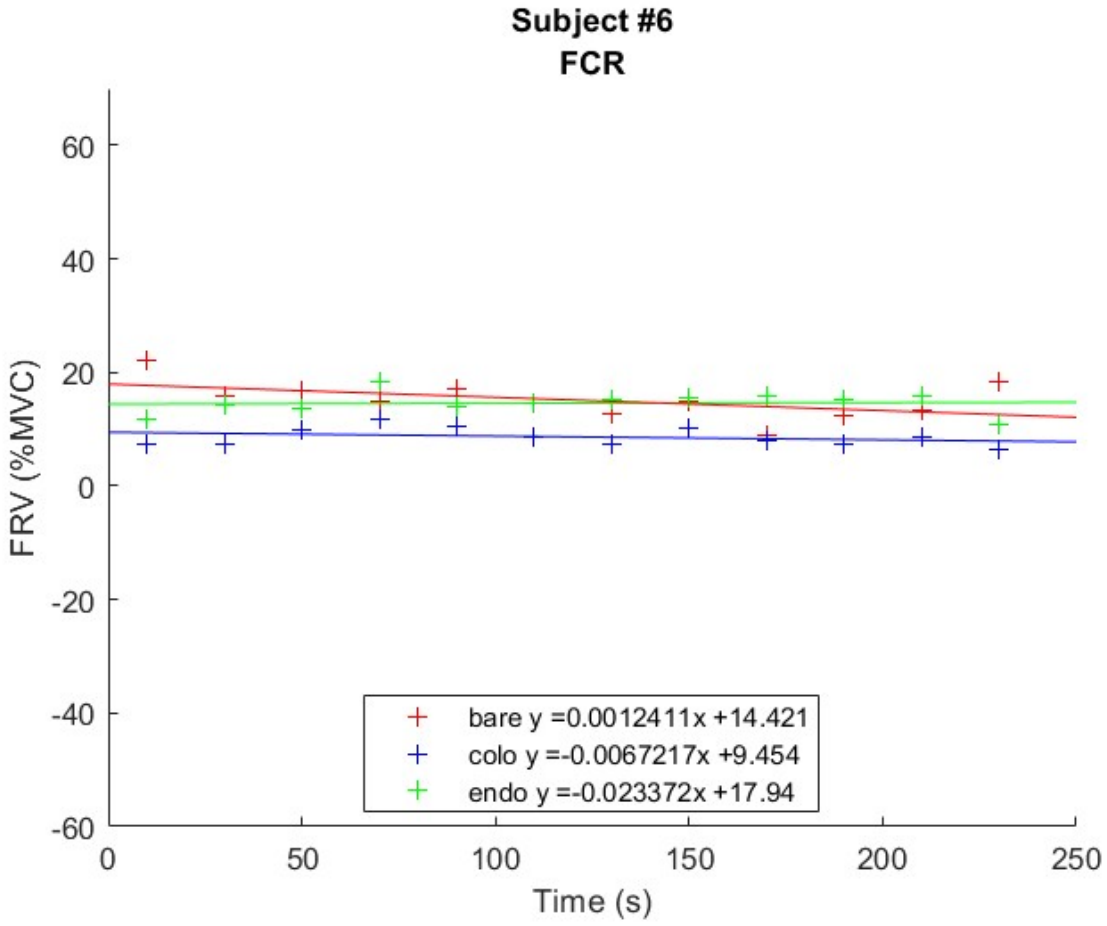

Figure 70: Linear models of change in FRV over time for FCR in subject 6 (red – barehand, blue – competitor grip, green – EndoGrip)

Subject 7:

The rate of FRV for the FDI was significantly different for both the competitor grip and the EndoGrip when compared to the baseline. The competitor grip's rate of FRV differed in only the slope ($p=0.00331$) whereas the EndoGrip's rate of FRV also differed in only the intercept ($p=0.00892$).

The rate of FRV for the APB was significantly different for both the competitor grip and the EndoGrip when compared to the baseline. The competitor grip's rate of FRV differed in both

the intercept ($p=4.06 \times 10^{-6}$) and the slope ($p=0.000789$) while the EndoGrip's rate of FRV also differed in both the intercept ($p=6.18 \times 10^{-16}$) and the slope ($p=0.000994$).

The rate of FRV for the FCR was not significantly different for both the competitor grip and the EndoGrip when compared to the baseline.

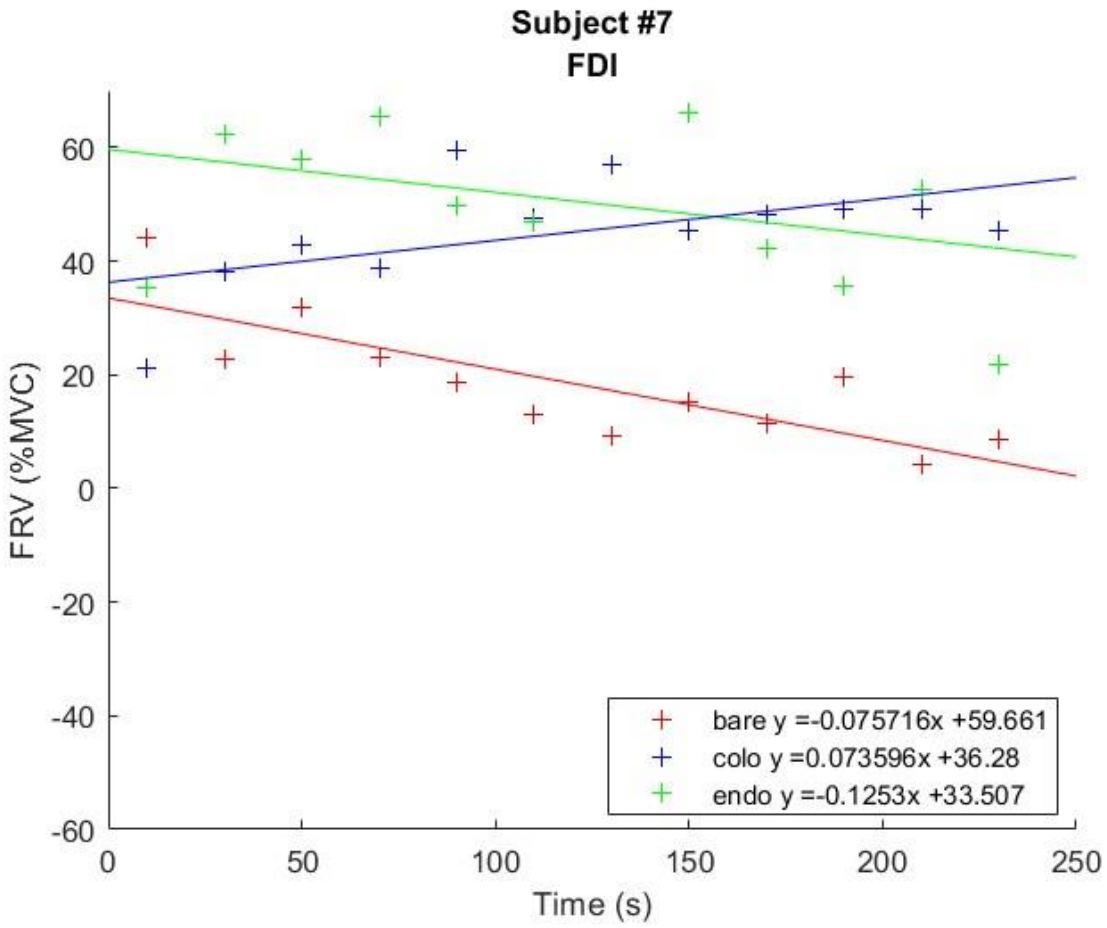

Figure 71: Linear models of change in FRV over time for FDI in subject 7 (red – barehand, blue – competitor grip, green – EndoGrip)

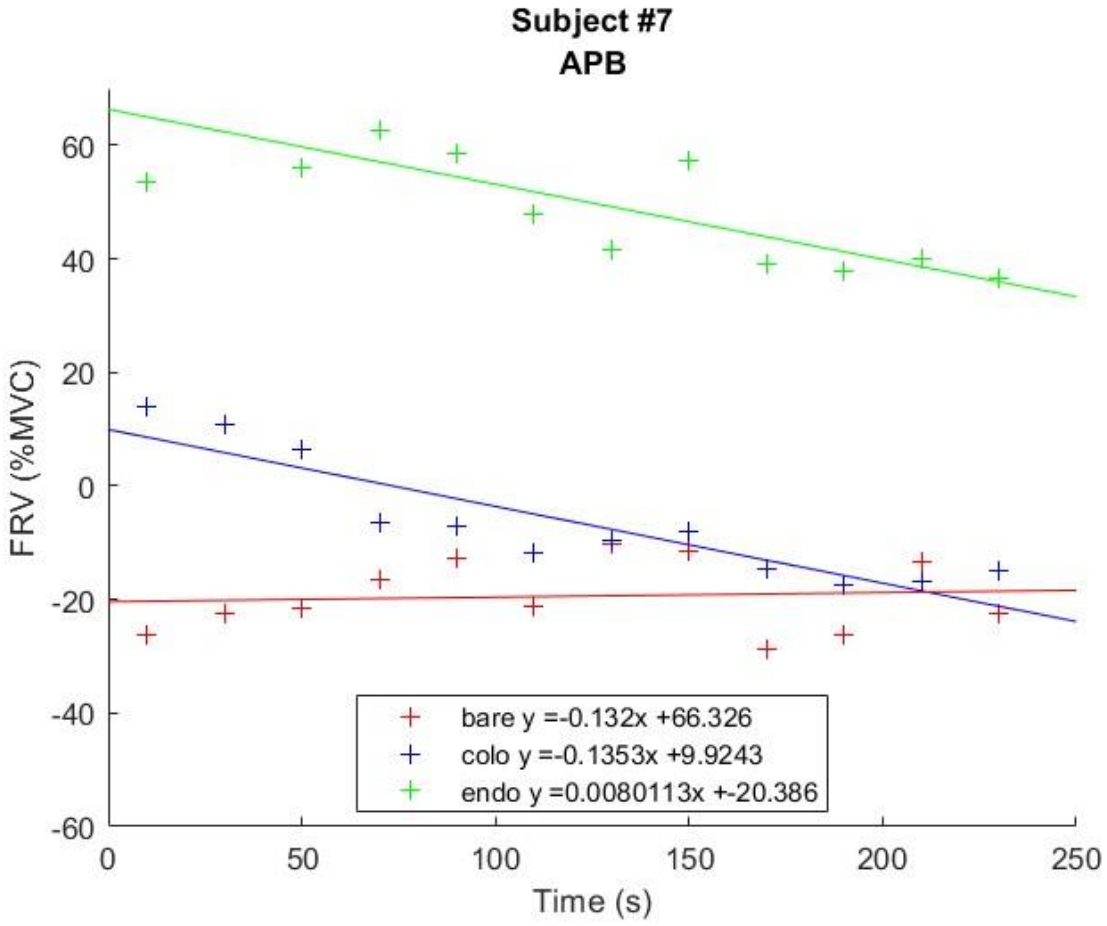

Figure 72: Linear models of change in FRV over time for APB in subject 7 (red – barehand, blue – competitor grip, green – EndoGrip)

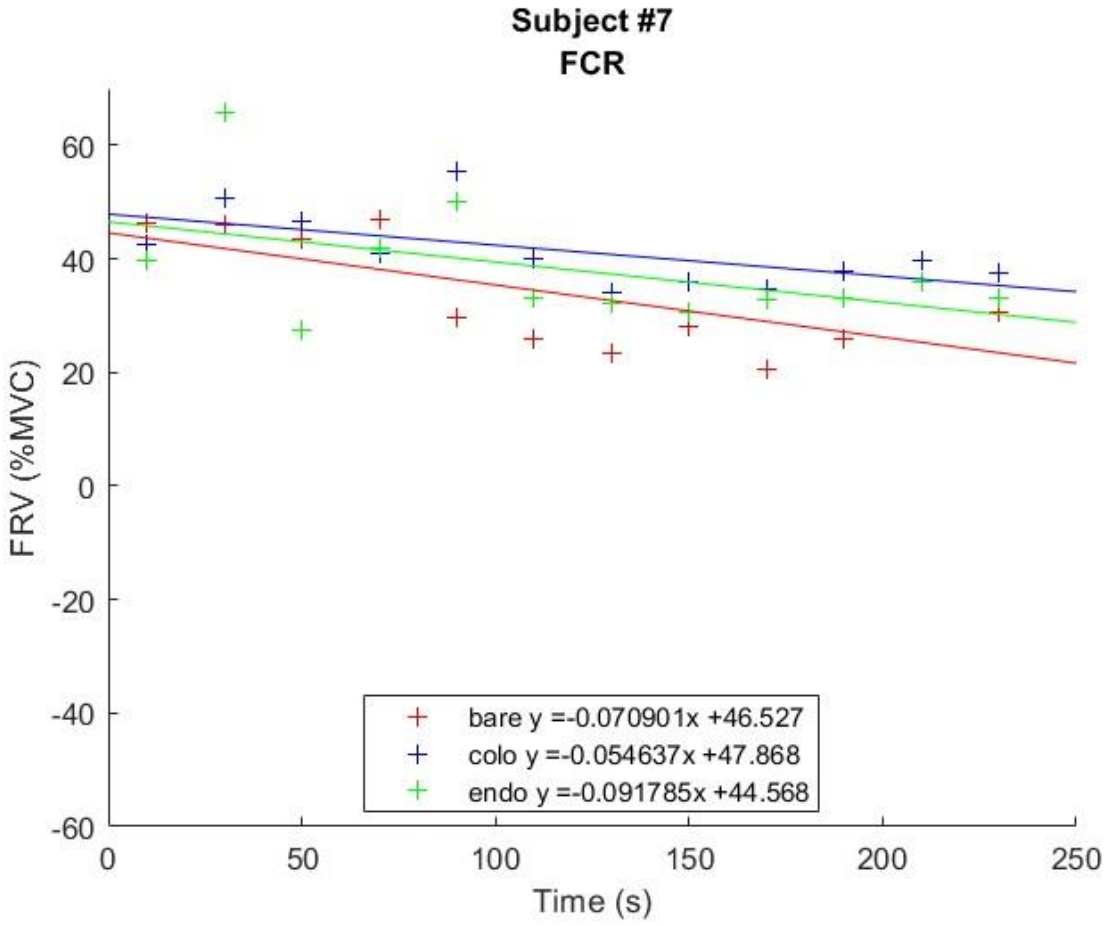

Figure 73: Linear models of change in FRV over time for FCR in subject 7 (red – barehand, blue – competitor grip, green – EndoGrip)

Table 4: Summary of p-values for coefficients from multiple linear regression (b2 = change in intercept due to competitor grip, b3 = change in intercept due to EndoGrip, b4 = change in slope due to competitor grip, b5 = change in slope due to EndoGrip)

Subject		**FDI**		**APB**		**FCR**	
1	Competitor	**P_{b2}=2.28x10^{-10}**	**P_{b4}=8.48 x 10^{-5}**	**P_{b2}=3.20 x 10^{-9}**	**P_{b4}=0.000933**	P_{b2}=0.901	P_{b4}=0.956
	EndoGrip	**P_{b3}=0.0155**	P_{b5}=0.691	**P_{b3}=0.000215**	P_{b5}=0.786	**P_{b3}=7.24 x 10^{-5}**	P_{b5}=0.0620
2	Competitor	P_{b2}=0.709	P_{b4}=0.0643	**P_{b2}=1.06 x 10^{-5}**	P_{b4}=0.0941	P_{b2}=0.940	P_{b4}=0.837
	EndoGrip	P_{b3}=0.152	P_{b5}=0.795	**P_{b3}=1.20 x 10 $^{-}$**	**P_{b5}=0.000547**	**P_{b3}=0.0318**	P_{b5}=0.967
3	Competitor	P_{b2}=0.0856	**P_{b4}=0.000383**	**P_{b2}=3.36 x 10^{-5}**	P_{b4}=0.0122	P_{b2}=0.856	P_{b4}=0.123
	EndoGrip	P_{b3}=0.185	P_{b5}=0.295	P_{b3}=0.592	P_{b5}=0.200	**P_{b3}=0.0141**	P_{b5}=0.535
4	Competitor	P_{b2}=0.805	**P_{b4}=0.0288**	**P_{b2}=1.66 x 10^{-6}**	**P_{b4}=0.0106**	**P_{b2}=1.44 x 10^{-5}**	P_{b4}=0.863
	EndoGrip	**P_{b3}=0.0328**	P_{b5}=0.0924	P_{b3}=0.390	P_{b5}=0.833	**P_{b3}=0.000163**	P_{b5}=0.132
5	Competitor	P_{b2}=0.0933	P_{b4}=0.850	**P_{b2}=1.11 x 10^{-6}**	**P_{b4}=0.00803**	**P_{b2}=3.16 x 10^{-6}**	**P_{b4}=0.00164**
	EndoGrip	P_{b3}=0.0801	P_{b5}=0.0736	**P_{b3}=0.000134**	P_{b5}=0.0830	**P_{b3}=2.73 x 10^{-6}**	**P_{b5}=5.31 x 10^{-6}**
6	Competitor	**P_{b2}=0.00200**	P_{b4}=0.0733	P_{b2}=0.617	P_{b4}=0.126	**P_{b2}=0.000199**	P_{b4}=0.240
	EndoGrip	**P_{b3}=5.56 x 10^{-}**	**P_{b5}=0.00794**	**P_{b3}=9.88 x 10^{-7}**	P_{b5}=0.474	P_{b3}=0.0752	P_{b5}=0.0863
7	Competitor	P_{b2}=0.932	**P_{b4}=0.00331**	**P_{b2}=4.06 x 10^{-6}**	**P_{b4}=0.000789**	P_{b2}=0.669	P_{b4}=0.427
	EndoGrip	**P_{b3}=0.00892**	P_{b5}=0.433	**P_{b3}=6.18 x 10^{-}**	**P_{b5}=0.000994**	P_{b3}=0.798	P_{b5}=0.654

4.4 Discussion

Differences in intercepts can be interpreted as the initial impact of the grip types on the amplitude of FRV, whereas the differences in slopes can be interpreted as the impact of the grip types on the rate of FRV.

When comparing the regression lines of FRV over time for the EndoGrip and competitor trials to the barehand trials, we observed similar trends appearing in the male and female subject groups as we did in Chapter 3, where we evaluated just the single mean FRV for each muscle for a given subject and grip type.

That is, when using the EndoGrip, 40% of male subjects showed improvements (i.e., reduction) in the intercept of their regression lines for FDI while the slopes were not significantly different. The rest of the male subjects still showed a non-significant trend of initial FRV reduction. This initial improvement in the FRV, along with the rate of FRV not being different from that of the barehand trial, point to an overall reduction of FRV over the entire duration of a task. The proportion of male subjects that showed significant reduction in the intercept of their regression lines for FDI did not match the proportion of male subjects that showed significant reduction in the mean FRV for FDI. This is due to the latter being an average of the 12 individual FRV used in the regression line.

Similarly, 80% of male subjects showed improvements in the intercept of their regression lines for FCR while the slopes were not significantly different. This initial improvement in the FRV, along with the rate of FRV not being different from that of the barehand trial, point to an overall reduction of FRV over the entire duration of a task.

In contrast, all female subjects showed negative initial impacts on the FRV for FDI when comparing the barehand trial to the EndoGrip trial. Also, all female subjects showed no changes in the FRV for FCR under the same comparison.

Lastly, 60% of male subjects and all female subjects showed negative initial impacts on the FRV for APB when comparing the barehand trial to the EndoGrip trial.

Therefore, we can conclude that using the EndoGrip reduces the average muscle fatigue but does not necessarily reduce the rate at which fatigue builds up for FDI and FCR, under the pretense that the EndoGrip is appropriately sized for the user. Additionally, using the EndoGrip results in a higher average muscle fatigue for APB, regardless of hand size.

LIMITATIONS

This study design had several limitations. First, we could only secure 7 volunteer subjects for the experiments, due to time constraints brought on by EMG equipment shipment delays, extensive preliminary testing, and the high level of commitment required from the subjects in order to complete a full set of trials (around 2 hours total per subject). Another limitation was that the gripping and torquing forces enacted onto the rigid mock endoscope was not directly measured. Doing so could have allowed more insight into the impact of different grip types on the generation of forces pertinent to endoscopy.

For future studies expanding upon the concepts covered in this thesis, along with an increased sample size and direct measurement of forces, other muscle groups should be added, such as the shoulder, neck, and lower back muscles, since these are also commonly reported areas of pain and injury. The experimental task could also be altered to be a longer duration with lower intensity, to assess the longer-term effects of the different grip types. The experimental task could also be performed on an electronic endoscopy simulator to better assess the impacts of the different grips under conditions similar to those of performing endoscopy in the operating room.

CONCLUSION

In this thesis, we evaluated the efficacy of a novel endoscope grip adaptor (i.e., the EndoGrip) in its ability to improve physician ergonomics during a statically simulated colonoscopy by using surface electromyography and the Threshold Limit Value to measure the muscle fatigue and risk of injury. Three muscles were selected based on criteria discussed in chapter 1: first dorsal interosseous (FDI), abductor pollicis brevis (APB), and flexor carpi radialis (FCR). We observed that using the EndoGrip significantly reduced the mean fatigue risk value (FRV) for the FDI and FCR in most male subjects when compared to using the barehand. Using the EndoGrip did not, however, affect the rate of FRV (approximated by the slope of the regression line fitted to scatterplot of FRV vs time) in those muscles. As for the female subjects, we observed that using the EndoGrip significantly increased the mean FRV for the FDI only. The mean FRV for APB was significantly increased for most male subjects and all female subjects. Finally, the EndoGrip outperformed the competitor grip in reducing the mean FRV for the FDI for all male subjects and for the FCR in most male subjects.

The positive impact of the EndoGrip on the physician ergonomics was most prevalent in male subjects for the FDI and FCR. In contrast, for female subjects, these muscles pointed towards a negative impact of the EndoGrip. Additionally, the mean FRV for the APB was negatively impacted for most males and all females. These inconsistencies between the groups are attributed to the differences in their hand sizes. Gripping strength in the power grip position is strongest when the thumb just barely touches the index finger, with the strength decreasing as the thumb and index finger get farther apart. The EndoGrip's outer diameter is too large relative to the female subjects' hand sizes and pushes the thumb away from the fingers in the power grip position, resulting in

weaker grip strength. Since they had to perform the same task as male subjects, who in general benefitted from the EndoGrip, the female subjects showed an increase in their muscle fatigue.

A fully developed and manufactured device holds major implications for gastroenterologists everywhere. It could reduce the amount of muscle pain and number of musculoskeletal injuries in physicians, extending the length of their career as well as increasing the volume of cases. Ultimately, this device could prevent harm to physicians and increase the pool of practicing physicians in the face of increasing demand for endoscopists due to a growing aging population and expanding disease screening criteria.

APPENDICES

Appendix A – MATLAB Code for data acquisition

```
function [dc,emg] = getdata(sr,subject,muscle,width)
    % 1 = FDI
    % 2 = ABP
    % 3 = Flex

    minutes = 4;

    %generate filename
    filename = strcat(width,'_trial_1');

    %generate path
    Path = strcat('subject_',int2str(subject),'/',filename);
    File = strcat(filename,'.csv');

    %Grab data
    data = table2array(readtable(strcat(Path,'/',File),'NumHeaderLines',6));

    %truncate data after time runs out
    data = data((3*sr):((3+((minutes)*60))*sr),:);

    %notch filter
    notchfilt = designfilt('bandstopiir','FilterOrder',2, ...
                    'HalfPowerFrequency1',59,'HalfPowerFrequency2',61, ...
                    'DesignMethod','butter','SampleRate',sr);
    den = filtfilt(notchfilt,data(:,muscle));

    %Bandpass filter
    fp = [20 400];
    bp_data = bandpass(den,fp,sr);

    %Full-wave rectification
    rect_data = abs(bp_data);

    %low pass filter for envelope
    fpass = 10;
    env_data = lowpass(rect_data,fpass,sr);

    %moving window average for MVC value
    windowlength = 1; %seconds
    wrange = round(sr * windowlength);

    mean_data= movmean(env_data,wrange);

    plot(mean_data)

    %Grab MVC

    if (muscle == 3) || (muscle ==4)
        width = 0;
```

```
    end
    averageMVC = avgMVC(sr,subject,muscle,width);

    %normalize data to MVC
    norm = mean_data/averageMVC;

    %Duty Cycle calculation
    height = length(data);
    dc_count = 0;
    dcmark = 0;

    for i = 1:height
        if norm(i) > 0.05
            dcmark = dcmark + norm(i);
            dc_count = dc_count + 1;
        end
    end

    dc = dc_count/height;
    emg = dcmark/dc_count;
end
```

Appendix B – MATLAB Code for MVC calculation

```
function meanMVC = avgMVC(sr,subject,muscle,width)

    %width = str ('bare', 'colo', 'endo',0)

    % muscles = int (1,2,3)
    % 1 = FDI
    % 2 = ABP
    % 3 = FCR

    %determine motion
    motions = {'hand','flex'};

    if (muscle == 1) || (muscle == 2)
        motionUsed = 1;
    elseif muscle == 3
        motionUsed = 2;
    end

    % Grab the EMG data
    %Raw EMG plots
    for i =1:3
        %Read Data
        prefix = strcat('subject_',int2str(subject),'/');
        if width == 0
            Folder = strcat(string(motions(motionUsed)),'_mvc_trial_',int2str(i));
            Path =
strcat(string(motions(motionUsed)),'_mvc_trial_',int2str(i),'.csv');
        else
            Folder = strcat(width,'_mvc_trial_',int2str(i));
            Path = strcat(width,'_mvc_trial_',int2str(i),'.csv');
        end

        MVCdata =
table2array(readtable(strcat(prefix,Folder,'/',Path),'NumHeaderLines',6));

        %Notch Filter
        notchfilt = designfilt('bandstopiir','FilterOrder',2,...
            'HalfPowerFrequency1',59,'HalfPowerFrequency2',61,...
            'DesignMethod','butter','SampleRate',sr);

        den = filtfilt(notchfilt,MVCdata(:,muscle));

        %Bandpass filter
        fp = [20 400];
        bp_MVCdata = bandpass(den,fp,sr);

        %Full-wave rectification
        rect_MVCdata = abs(bp_MVCdata);

        %low pass filter for envelope
        fpass = 10;
        env_MVCdata = lowpass(rect_MVCdata,fpass,sr);
```

```
        %moving window average for MVC value
        windowlength = 1; %seconds
        wrange = round(sr * windowlength);

        mean_MVCdata= movmean(env_MVCdata,wrange);

        %Find Max window
        MVCdata=max(mean_MVCdata);
        MVCs(i)=MVCdata;
    end
    meanMVC = mean(MVCs);
end
```

Appendix C – MATLAB Code for TLV generation

```
clc
clear

% muscles = int (1,2,3)
% 1 = FDI
% 2 = APB
% 3 = FCR

muscles = {'FDI','APB','FCR'};

for muscle=1:length(muscles)
    %subject
    subject = 7;

    %set number of points per trial
    numSlices = 12;

    %trials;
    trials = {'bare','colo','endo'};

    %sr
    sr=2148;

    %minutes
    minutes = 4;

    %prep figure
    figure(muscle)
    hold on
    xlim([0,100])
    ylim([0,100])
    title({strcat('Subject #',int2str(subject)),char(muscles(muscle))})
    xlabel('Duty Cycle (%)')
    ylabel('% MVC')

    %Prep reference curve
    DC = linspace(0,1,1000);
    TLV = 100*(-.143*log(DC)+.066);
    plot(DC*100,TLV)

    dcs = zeros(length(trials),numSlices);
    emgs = zeros(length(trials),numSlices);

    for trial=1:length(trials)

        width = char(trials(trial));

        %generate filename
        filename = strcat(width,'_trial_1');

        %generate path
        Path = strcat('subject_',int2str(subject),'/',filename);
        File = strcat(filename,'.csv');
```

```
%Grab data
data = table2array(readtable(strcat(Path,'/',File),'NumHeaderLines',6));

%truncate data after time runs out
data = data((3*sr):((3+((minutes)*60))*sr),:);

slicelength = round(length(data)/numSlices);

%get MVC prior to loop

%width = str ('bare', 'colo', 'endo',0)
% muscles = int (1,2,3)
% 1 = FDI
% 2 = ABP
% 3 = Flex

if (muscle == 3)
    width = 0;
end
averageMVC = avgMVC(muscle,width,sr,subject);

for i=0:(numSlices-1)
    curSlice = data(((slicelength*i)+1):(i+1)*slicelength,:);

    %notch filter
    notchfilt = designfilt('bandstopiir','FilterOrder',2, ...
                    'HalfPowerFrequency1',59,'HalfPowerFrequency2',61, ...
                    'DesignMethod','butter','SampleRate',sr);
    den = filtfilt(notchfilt,curSlice(:,muscle));

    %Bandpass filter
    fp = [20 400];
    bp_data = bandpass(den,fp,sr);

    %Full-wave rectification
    rect_data = abs(bp_data);

    %low pass filter for envelope
    fpass = 10;
    env_data = lowpass(rect_data,fpass,sr);

    %moving window average
    windowlength = 1; %seconds
    wrange = round(sr * windowlength);

    mean_data= movmean(env_data,wrange);

    %normalize data to MVC
    norm = mean_data/averageMVC;

    %Duty Cycle calculation
    height = length(norm);
    dc_count = 0;
    dcmark = 0;
```

```
            for j = 1:height
                if norm(j) > 0.05
                    dcmark = dcmark + norm(j);
                    dc_count = dc_count + 1;
                end
            end

            dc = dc_count/height;
            emg = dcmark/dc_count;

            dcs(trial,i+1) = dc*100;
            emgs(trial,i+1) = emg*100;

        end

        if trial== 1
            color = 'r';
        elseif trial == 2
            color = 'b';
        else
            color = 'g';
        end

        style = '.';
        plot(dcs(trial,:),emgs(trial,:),strcat(color,style));
    end

    hold off
end
```

Appendix D – MATLAB Code for mean and rate of FRV assessment

```
clc
clear

% muscles = int (1,2,3)
% 1 = FDI
% 2 = APB
% 3 = FCR

muscles = {'FDI','APB','FCR'};

for muscle=1:length(muscles)
    %subject
    subject = 1;

    %set number of points per trial
    numSlices = 12;

    %trials;
    trials = {'bare','colo','endo'};

    %sr
    sr=1037;

    %minutes
    minutes = 4;

    %prep figure
    figure(muscle)
    hold on
    ylim([-60,70])
    title({strcat('Subject #',int2str(subject)),char(muscles(muscle))})
    xlabel('Time (s)')
    ylabel('FRV (%MVC)')

    dcs = zeros(length(trials),numSlices);
    emgs = zeros(length(trials),numSlices);

    for trial=1:length(trials)
        width = char(trials(trial));

        %generate filename
        filename = strcat(width,'_trial_1');

        %generate path
        Path = strcat('subject_',int2str(subject),'/',filename);
        File = strcat(filename,'.csv');

        %Grab data
        data = table2array(readtable(strcat(Path,'/',File),'NumHeaderLines',6));

        %width = str ('bare', 'colo', 'endo',0)
        % muscles = int (1,2,3)
        % 1 = FDI
```

```
% 2 = ABP
% 3 = Flex

if (muscle == 3)
    width = 0;
end

%truncate data after time runs out
data = data((3*sr):((3+((minutes)*60))*sr),:);

slicelength = round(length(data)/numSlices);

%get MVC prior to loop
averageMVC = avgMVC(sr,subject,muscle,width);

for i=0:(numSlices-1)
    curSlice = data(((slicelength*i)+1):(i+1)*slicelength,:);

    %notch filter
    notchfilt = designfilt('bandstopiir','FilterOrder',2, ...
                    'HalfPowerFrequency1',59,'HalfPowerFrequency2',61, ...
                    'DesignMethod','butter','SampleRate',sr);
    den = filtfilt(notchfilt,curSlice(:,muscle));

    %Bandpass filter
    fp = [20 400];
    bp_data = bandpass(den,fp,sr);

    %Full-wave rectification
    rect_data = abs(bp_data);

    %low pass filter for envelope
    fpass = 10;
    env_data = lowpass(rect_data,fpass,sr);

    %moving window average for MVC value
    windowlength = 1; %seconds
    wrange = round(sr * windowlength);

    mean_data= movmean(env_data,wrange);

    %normalize data to MVC
    norm = mean_data/averageMVC;

    %Duty Cycle calculation
    height = length(norm);
    dc_count = 0;
    dcmark = 0;

    for j = 1:height
        if norm(j) > 0.05
            dcmark = dcmark + norm(j);
            dc_count = dc_count + 1;
        end
    end
```

```
            dc = dc_count/height;
            emg = dcmark/dc_count;

            FRVs(trial,i+1) = 100*(emg-(-.143*log(dc)+.066));
            times(trial,i+1) = round((minutes*60)/numSlices*(i+1/2));
        end

        if trial== 1
            color = 'r';
        elseif trial == 2
            color = 'b';
        else
            color = 'g';
        end
        style = '+';
        plot(times(trial,:),FRVs(trial,:),strcat(color,style));

        TF = isnan(FRVs(trial,:));
        FRVs(trial,TF) = -95;

    end

    mean_b = mean(FRVs(1,:))
    std_b = std(FRVs(1,:))
    mean_c = mean(FRVs(2,:))
    std2_c = std(FRVs(2,:))
    mean3_e = mean(FRVs(3,:))
    std3_e = std(FRVs(3,:))
    [h_a,p_a] = ttest(FRVs(1,:),FRVs(2,:))
    [h_b,p_b] = ttest(FRVs(2,:),FRVs(3,:))
    [h_c,p_c] = ttest(FRVs(1,:),FRVs(3,:))

    h = lsline;

    for k = 1:numel(h)
        B = polyfit(h(k).XData, h(k).YData,1);
        slope(k) = B(1);
        intercept(k) = B(2);
    end
    for entry=1:length(trials)
        key{entry} = strcat(char(trials(entry)),' y =',...
            num2str(slope(entry),5),'x + ',num2str(intercept(entry),5));
    end
    legend(char(key(1)),char(key(2)),char(key(3)),'location','best');
    hold off

    if muscle == 1
        FRVlist_FDI = FRVs;
    elseif muscle == 2
        FRVlist_APB = FRVs;
    else
        FRVlist_FCR = FRVs;
    end
end
```

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