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Evaluation of artistic gymnastics vault board design

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by

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The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this thesis. The Graduate College will ensure this thesis is globally accessible and will not permit alterations after a degree is conferred.

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LIST OF TERMS

Front entry: A type of vault entry style where the gymnast runs, hurdles, and strikes the vault board resulting in a forward-facing direction of the vault table. Vaults of this entry style include handsprings and Tsukahara.

Back entry: A type of vault entry style where the gymnast runs, hurdles, completes a round-off, and strikes the vault board resulting in a backward-facing direction of the vault table. Vaults of this entry style are called a Yurchenko.

Pre-flight: Anything that occurs before the gymnast contacts the vault table.

Post-flight: Anything that occurs after the gymnast contact the vault table. Normally includes a flip off the vault table.

Vault timer: Consists of the completion of the pre-flight phase of the vault without performing the post-flight (or flip) off the vault table. Commonly used as a warmup or practice before completing a full vault.

Sweet spot: Optimal area on the vault board for the gymnast to strike.

ABSTRACT

Ever since its introduction at the 1896 Athens Olympics, artistic gymnastics has continued to evolve into the sport it is today. Over the years, the physical demands placed on the gymnast have increased as gymnasts continue to increase their skill level, difficulty, and intensity of training. Gymnastics equipment has continued to evolve with the sport with major improvement such as the spring floor, vaulting table, and protective matting since its creation in 1896. The present study aims to shift current research in the sport of gymnastics from optimizing the gymnast's performance to identifying ways gymnastics equipment manufacturers can design better equipment. The study analyzes how the gymnast interacts with different vault boards by using qualitative and quantitative analysis methods related to human impact, performance, and product design and testing. It was identified that some aspects of a vault board design have a significant effect on the gymnast's interaction between the vault board while some factors have no effect. In summary, this study determined that gymnasts do not change how they interact when using various types of vault boards.

CHAPTER 1. INTRODUCTION

Artistic gymnastics is a sport that embraces the essence of grace, beauty, power, endurance, flexibility, and strength. The conceptual idea of gymnastics began with the ancient Greeks as they perfected the symmetry between the mind and body (Olympics Sport History). In the early 1800s, the term "artistic gymnastics" was established to identify a free-flowing style technique used in military training. In 1896, artistic gymnastics was introduced at the Athens Olympic Games and has been present ever since. Since the 1896 Athens Olympics, to the 2016 Rio Olympics, artistic gymnastics has become the sport it is today because gymnastics equipment has evolved as gymnasts continue to push the limits and reach new skill levels.

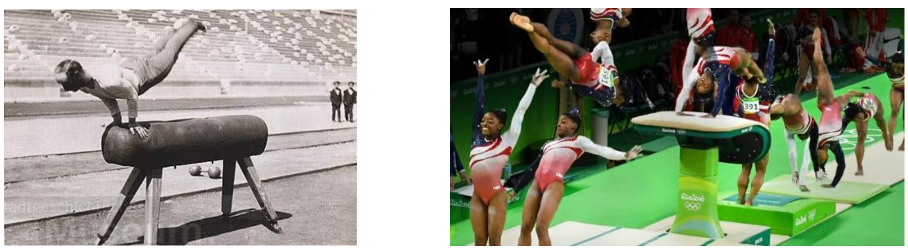

Figure 1. Gymnast performing a vault during the 1896 Athens Olympics and 2016 Rio Olympics

Women's artistic gymnastics consist of four events: vault, uneven bars, balance beam, and the floor exercise. Men's artistic gymnastics consist of six events: vault, high bar, parallel bars, rings, pommel horse, and the floor exercise. For this research study, the focus was placed on women's artistic gymnastics and how the gymnast interacts with the vault board during the vaulting event. Although the vault board is mainly used for the vaulting event, it is also used to mount the balance beam, uneven bars, and parallel bars.

The Federation Internatinale de Gymnastique (FIG) is the governing body for gymnastics worldwide. FIG establishes rules and regulations for the apparatus used in artistic gymnastics. The purpose of the Apparatus Norms is to ensure the quality of the equipment is standardized at all FIG sanctioned competitions. FIG also performs standardized testing on the equipment to ensure the functional properties of the equipment conforms to their standards. By enforcing these standards, it minimizes any differences in the training and competition equipment for gymnasts. The vault board regulations include the form and measurements, functional properties, and color of the vault board (FIG). The standardized vault board testing procedures includes a drop test to analyze the deflection of the impactor, the height of rebound of the impactor, and maximum value of force measured during the impact (FIG).

Table 1: Figures for the "hard" Vaulting Boards
See Figure 1 for an illustration of the impact sites. X represents the overall mean value of the measured variable.

	Deflection (mm)	*Height of rebound (mm)*	*F_{max} (N))*
Mean value across impact sites 1 to 5	$55 \le x \le 68$	$340 \le x \le 400$	$x \le 4000$
Difference between highest and lowest mean value on impact sites 1 to 5	≤ 15	≤ 100	
Difference between mean value on impact sites 6 and 7	≤ 4	≤ 25	≤ 150

Figure 1: Impact Locations for Vaulting Boards
(Dimensions in cm)

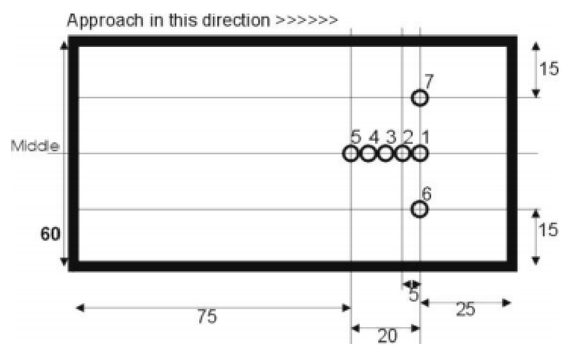

Figure 2. Example of standardized testing specifications and drop test impact locations

The vaulting event in artistic gymnastic has been divided into seven phases: run, hurdle, take-off, pre-flight, support, post-flight, and landing (Orlofsky and Gault, 1985: Whitlock *et al.*, 1990; Prassas, 2002, Coventry *et al.*, 2006). During this study, we focused on how the gymnast interacts with the vault board which includes the take-off and pre-flight phases. Figure 3 explains the three distinct phases of vault board contact. Although the gymnast's interaction with the vault board is less than one second, it provides them with the foundation upon which their vaulting routine is built. From a previous study, it was identified that the total board contact time for a round-off entry vault was on average 0.15 seconds with a compression and repulsion time average of 0.08 seconds each (Bradshaw, 2004). This study also identified that the vault board contact position was not a critical requirement for a successful Yurchenko entry vaulting performance (Bradshaw, 2004). While vault board contact position might not be critical, it is crucial to have a successful entry and take-off on the vault board in order to ensure a successful performance in the event. The ideal vault board contact position has been deemed the term sweet spot. It was created by the coach's belied that a gymnast could optimize their performance by hitting a specific location on the vault board (Taylor et al. 1972). However, there has been no research to date that addresses the sweet spot or optimal foot location on the vault board.

Figure 3: Distinct phases during the gymnast's interaction with the vault board
(Left to Right: Initial Contact, Maximum Compression, Take-off)

Artistic gymnastics is a physically demanding sport and it is known to be of high-risk. During competition, gymansts are evaluated by a judging panel and are given a score based on their performance and exection of the routine. The natural evolution of the sport demands that gymnasts continuously increase their skill level, difficulty, and intensity. This can lead to an increased risk of injury because of the additional physical and mental demands placed on the gymnast. Risk factors for gymnastics include intrinsic and extrinsic factors (Bradshaw & Partia, 2012; Fu, 2001; Vanderlei et al., 2007; Wadley & Albright, 1993). Intrinsic factors include the athlete's anthropometric measurements, muscle stiffness and strength, and hormonal and neuromuscular function where extrinsic factors include the repetitive nature of the sport, the equipment, training for practice and competition, and coaching techniques (Bradshaw & Partia, 2012). These extrinisc factors can all influence how the gymnast performs and how they interact with the equipment. FIG's goals for standardizing appartus for artitisc gymnastics focuses on decreasing the amount of extrinsic risk involved in gymnastics.

American Athletic, Inc. (AAI) in Jefferson, Iowa manufactures world class-sports equipment, such as gymnastics equipment. AAI's gymnastic equipment can be found in both club and collegiate gyms across the United States and was the official equipment supplier of the 2008 Olympic Trials, the 2018 U.S. Gymnastics Championships, and the NCAA Gymnastics Championships. With the recent launch of their EVO-line, the Evo-Board was introduced by AAI to the gymnastics world. Traditionally, vault boards are composed of up to eight conical compression springs placed inside the springboard. However, the Evo-Board is composed of leaf springs within the vault board. Below are relevant points of the product description for AAI's Evo-Board (AAI):

- Evo-Boards have a larger sweet spot allowing for variations in entry position.
- Softer and less jarring feel allows for more repetition with anti-fatigue matting providing a unique softer feel on hands or feet.
- Predictable and consistent rebound action giving maximum return of energy input.

It is hypothesized that the Evo-Board due to its leaf spring design has a larger sweet spot area allowing for a greater variation of vault board contact positions. The second hypothesis is that the gymnasts will prefer anti-fatigue top surface of the Evo-Board in comparison to others. Thirdly, it is hypothesized that the gymnast's interaction between the Evo-Board will not change or effect their performance. The overarching goal of this project is to evaluate how the vault board impacts and effects the gymnast's performance, and specifically how AAI equipment compares to alternative brands. The advanced techniques used relate to human impact, performance, and product design and testing. This project consists of a preliminary study that observed and analyzed NCAA women's artistic gymnasts as they performed their competition vault during a NCAA gymnastics meet. It was then followed by a study where NCAA, and USAG club level women's artistic gymnasts, performed warmup vault timers with five different types of vault boards.

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CHAPTER 2. GYMNASTICS VAULT BOARD DESIGN: A COMPARISON OF SPRING CONFIGURATION AND STYLE OF SPRING – PRELIMINARY STUDY

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Modified from a conference paper approved by HFES

Abstract

The goal of this study is to analyze the gymnastics vault board spring configuration to provide insight for a follow-up study to compare a traditional conical compression vault board with a new leaf spring vault board design. For the vaulting apparatus, gymnasts use a vault board to propel themselves onto the vaulting table to perform their vault. However, a new innovative leaf spring design has been produced and little research has been done to evaluate the performance of this vault board. Video recordings were taking during a NCAA Division I gymnastics competition. The video captured the gymnast's interaction with the vault board during their competition vaults. During the gymnastics competition, two vault entry styles were performed, three spring configurations were used, and the number of conical springs inside the board were either seven or eight. With the current data, there is no significant evidence that correlates the spring configuration with the performance score of the athlete. It was identified that the maximum amount of compression achieved on the vault board varies from gymnasts, as well as the number of conical springs and the spring configuration varies. Further research should be conducted to investigate the effects of spring configuration and the amount of compression achieved during the vaulting apparatus with two different vault boards: the conical vault board design and the leaf spring vault board design.

Introduction

Artistic gymnastics continues to evolve as athletes push the limits and reach new skill levels. Gymnastics is a sport of perfection and perfection is achieved by repetition. During competition, gymnasts are evaluated by a judging panel and are given a score based on their performance and execution of the routine. During the vaulting event, the gymnast's performance has been divided into seven phases: run, hurdle, take-off, pre-flight, support, post-flight, and landing (Orlofsky and Gault, 1985: Whitlock *et al.*, 1990; Prassas, 2002, Coventry *et al.*, 2006). The run is the basis of energy production for the vault. The gymnast will then hurdle onto the vault board to gain additional forces and to change momentum direction, which then propels the gymnast's hands onto the vaulting table and ultimately into the air to perform the vault. Traditionally, vault boards are composed of up to eight removable conical compression springs placed inside the vault board. However, with the introduction of new leaf spring design, the Evo-Board can now provide a "larger sweet spot allowing for variations in entry position and a softer and less jarring feel" based on the manufacturer's product description (AAI). A previous study identified that there is no statistical significance between take-offs from the rear of the vault board and those from the middle when observing handspring vault drills (Coventry *et al.*, 2006). Coventry also concluded that modern vault boards have a larger sweet spot area, which allows the gymnast a larger margin of error when contacting with the vault board.

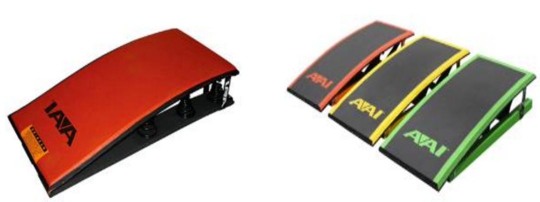

Figure 4. TAC/10 Vault Board (left) and Evo-Boards (right)

In NCAA Collegiate Gymnastics and USA Gymnastics Level 1-10 sanctioned competitions, gymnasts can add or remove springs in the vault board in order to optimize their performance. Interviews conducted with club and collegiate gymnasts and coaches have indicated that the configuration and number of springs is determined by the gymnasts' perceived "feel" on the vault board and their ability to compress the vault board. Figure 3 explains the three distinct phases during the gymnasts' interaction with the vault board. The gymnasts' interaction with the springboard provides them with the foundation upon which their vaulting routine is built. It is crucial to have a successful entry and take-off on the vault board in order to ensure a successful performance on the event.

Figure 5. Distinct phases during the gymnast's interaction with the vault board
(Left to Right: Initial Contact, Maximum Compression, Take-off)

Previous studies have created methods for measuring the reaction force of the vault board (BRF) to improve take-off techniques and have developed an apparatus for measuring vault board actions which was designed to determine optimal vault board parameters, repeatability of jumps, and optimal training techniques (Cuk, 2011; Sano, 2007). Both studies identified how gymnasts could optimize their performance on the apparatus, but they did not include correlations with spring configuration and number of springs in their studies. The aim of this study was to analyze spring configuration and the number of springs within the vault board, the gymnasts' contact location on the vault board, and the performance score for each gymnast during their competition vault.

Methods

Participants

NCAA Division I female gymnasts (n=12, aged 18-22 years) participated in this study. Gymnasts in this study represented two different collegiate women's gymnastics programs and both teams were ranked in the top 25 nationally. Participation in this study occurred as a natural sequence of their competition and the performance of the athletes was not interfered by data collection.

Procedures

Gymnasts performed their competitive vault during competition. Two judges then rated the gymnasts' performance on a scale from 0 – 10, with a score of 10 indicating perfect execution. The two scores are then averaged and given to the gymnasts. Gymnasts could change the vault board spring configuration to meet their desired "feel" on the vault board.

Equipment

The vault board used was a TAC/10 Vault Board manufactured by AAI, Inc. (American Athletic Inc., Jefferson, IA). The TAC/10 Vault Board meets NCAA competition specifications and is composed of eight conical removable springs.

Data Collection

A Go Pro Hero 7 camera was mounted next to the vaulting apparatus. Researchers were granted video and camera access during the meet. The video frame was focused directly on the vault board. Through video analysis, screenshots were captured to identify three phases: initial contact location, maximum compression, and take-off on the vault board.

Results

Out of the twelve gymnasts, eleven performed a round-off entry style vault and one performed a front handspring entry style vault (Figure 6). Round-off entry style vaults and front handspring entry style vaults differ in two ways. During a round-off entry style vault, gymnasts contact the vault board with their back facing the vaulting table and tend to contact towards the back end of the vault board. For front handspring entry style vaults, gymnasts are facing the vaulting table and tend to contact the front end of the vault board. The focus was on analyzing the round-off entry style because the majority of the gymnasts competed this entry style vault. Further research should be performed to analyze front handspring entry style vaults.

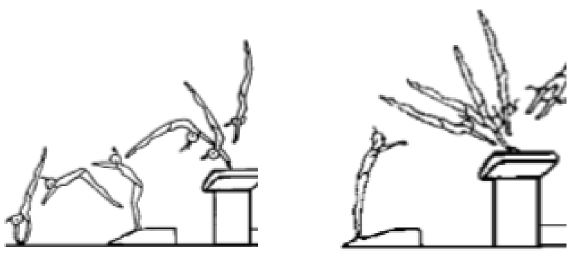

Figure 6. Round-off entry (left) vs. front handspring entry (right)

Three spring configurations were identified in this study. The number of springs placed inside the vault board ranged from seven to eight springs. Figures 7-9 illustrate the three spring configurations. The average performance score with seven springs and eight springs respectively, 9.813 ± 0.088 and 9.838 ± 0.047. Due to a small variation in the performance score with seven springs and eight springs present, there is no evidence that spring configurations can negatively affect the performance of the gymnast. Although the gymnast’s interaction with the vault board is crucial to the success of vault, it was observed that performance scores reflected more from post-flight off the vault table and the execution of landing. It is evident that maximum compression of the vault board was greater when seven springs were used in comparison to eight but no correlations can be made due to a lack of anthropometric data of the gymnasts.

x	x	x	
x	x		
x	x	x	

Back End Front End

Figure 7. Eight Springs

x	x	x	
x			
x	x	x	

Back End Front End

Figure 8. Seven Springs (a)

x	x	x	
	x		
x	x	x	

Back End Front End

Figure 9. Seven Springs (b)

A 6x4 grid system was created in order to map out the location of the gymnasts' contact position on the vault board (Figure 10). Position was determined by the initial toe contact point on the vault board. Figure 11 identifies the areas on the board where initial toe contact occurs most frequently.

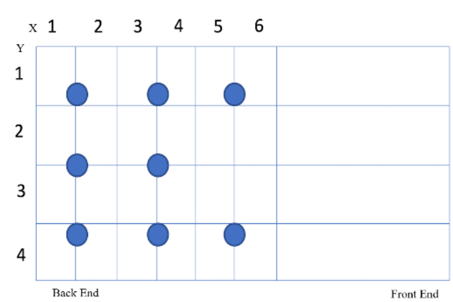

Figure 10. 6x4 grid system used to identify contact position

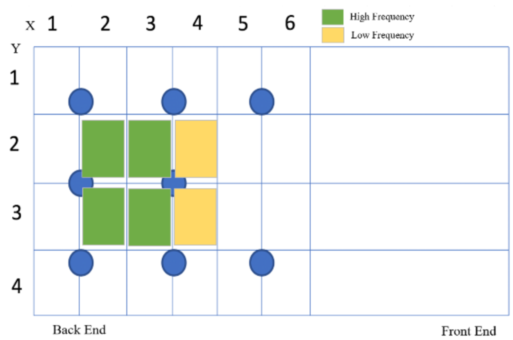

Figure 11. Frequency of contact

Discussion

This preliminary study provided valuable information regarding how the gymnast interacts with the vault board. As mentioned previously, gymnasts can change the number of springs and spring configuration in the vault board during collegiate or club competitions. Gymnasts must self-determine the number of springs and the spring configuration of the vault board to optimize their performance and achieve their desired “feel” on the vault board. Currently, the new leaf spring vault board design are not capable of spring customization but are sold in three different strengthens: soft, medium, and firm. With the current data, there is no significant evidence that correlates the spring configuration with the performance score of the athlete. However, the maximum amount of compression achieved on the vault board varies from gymnast, the number of springs, and the spring configuration.

Limitations

During this preliminary study, gymnast’s anthropometric data was not collected. Without this data, correlations between spring configuration and maximum compression could not be analyzed. Since only one of the twelve gymnasts competed a front handspring vault entry, limited analysis could be performed, and further research should be conducted to identify vault board characteristics for front handspring vault entries.

Conclusion

In conclusion, this preliminary study provides enough information to investigate further the effects of spring configuration and the amount of compression achieved during the vaulting event. Further research will include the new leaf spring Evo-Board in order to create a comparison of maximum compression achieved when using both a traditional compression vault board and a leaf spring vault board.

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CHAPTER 3. EVALUATION OF ARTISTIC GYMNASTICS VAULT BOARD DESIGN

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Abstract

The purpose of this study was to compare how gymnasts interact with different types of vault boards, specifically how the Evo-Board leaf spring design compares to a traditional conical spring vault board design. Fourteen female gymnasts performed five Yurchenko timers on five vault boards. Performances were measured via participant surveys, high-speed video, kinematics (knee angle at three vault board contact phases), vault board contact position, electromyography of four lower extremity muscles, and the amount of compression achieved by the gymnast on the vault board. In result, the Evo-Board leaf spring designed increases the sweet spot area by 37% in comparison to traditional conical spring vault boards. Survey results showed that participants preferred the anti-fatigue top surface of the Evo-Board more than the carpeted top surface. No significant differences were identified for the knee angle and muscle activation profiles across the five vault boards. The muscle activation for the biceps femoris showed the highest level of activation compared to the rectus femoris, tibialis anterior, and gastrocnemius medialis. In conclusion, it was identified that the gymnast does not change how they interact among different vault boards and their performance remains consistent. The Evo-Board design does present additional benefits to the gymnast and its perceived value is ranked the highest among the other vault boards.

Introduction

In 2003, the USA Gymnastics program transitioned the official vaulting apparatus from a horse to the vaulting table (Rand). Since then, there has been minor changes in the gymnastics equipment besides additional protective matting to reduce the risk of injury during practice and competition events. With the introduction of AAI's new leaf spring Evo-Board, there has been no research that analyzes how the leaf spring design affects the gymnast. The product overview for the Evo-Board states that the vault board has a larger sweet spot, a softer and less jarring feel, and a predictable and consistent rebound (AAI).

Previous studies have analyzed and characterized the gymnast's interaction with the vault board. For example, Coventry's study identified that there is no statistical significance between take-offs from the rear of the board to those from the middle when observing handspring vault drills, and concluded that modern vault boards have a larger sweet spot area (Coventry *et al.*, 2010). While Coventry's study investigated vaulting characteristic behaviors during a handspring drill take-off, this study investigates those of a Yurchenko drill. Bradshaw conducted a study with five elite female gymnasts and concluded that vault board contact position was not a critical requirement for a successful Yurchenko entry vaulting performance (Bradshaw, 2004).

The term sweet spot has been created by coach's belief that a gymnast can optimize their performance while executing their vault by striking a specific location on the vault board (Taylor et al. 1972). Some gymnastics equipment manufacturers have included visuals on the vault board to represent a target area and coaches have also applied tape lines to highlight the target area on the vault board. However, there has been no research to date that addresses the sweet spot or optimal foot location on the vault board.

Other studies have used miniature Micro-Electro-Mechanical (MEMS) type accelerometer(s) and force plates to measure vaulting characteristics during the gymnast's interaction with the vault board (Križaj and Čuk; Čuk, 2011; Sano, 2007). The purpose of these studies was to analyze vaulting characteristics to identify ways the gymnast can improve and optimize their vaulting techniques. Some gymnastics facilities have video monitoring systems that allow gymnasts to review their vaults to identify improvements. Currently, there is no 'smart' vault board on the market that provides the gymnast and coaches direct feedback.

Human performance can be measured in various ways. Qualitative methods, such as a survey, can be used to measure the participants perceived performance or how confident they felt when performing a skill. Quantitative methods, such as electromyography (EMG) and kinematics, can be used to measure the amount of muscle activation during a skill and analysis the motion of the gymnast. One study examined the muscle activation characteristics of lower extremity muscles during tumbling take-offs and identified that muscle activation characteristics in the pre-activation and impact phases differed between tumbling series (McNeal, Sands, Shultz, 2007).

The purpose of this study is to quantitatively and qualitatively determine the significance of the Evo-Board and its leaf spring design. To do so, human subject testing was performed to compare the Evo-Board with other types of vault boards that have a conical spring design.

Methods

Participants

Two groups of women artistic gymnasts participated in this study. Group 1 consisted of five National Collegiate Athletic Association (NCAA) Division I female gymnasts who attend Iowa State University. Within Group 1, participates ranged in age from 18 to 22 years old with experience in the sport ranging from 11 to 19 years. One gymnast had previously competed at the Elite Level, which is the highest competitive level in gymnastics. The remaining four have competed at the NCAA Division I level. Due to the high frequency of injury within the sport, all participants had previously experienced an injury, but these injuries did not inhibit them from participating in the study.

Group 2 consisted of nine club level female gymnasts. Within Group 2, participants ranged in age from 12 to 17 years old with experience in the sport ranging from 8 to 12 years. Competition levels within the group included gymnasts who had competed at Level 8, 9, or 10. Four out of the nine gymnasts did not report any incidence of injury.

All participates have used vault boards similar to or the same one as the vault boards tested in the experiment. Group 1 athletes would be classified as elite or experts and Group 2 athletes would be classified as intermediate to advance in gymnastics.

Equipment

This study used a variety of gymnastics vault boards which were provided by AAI (American Athletic Inc., Jefferson, IA). The vault boards varied in three aspects: manufacturer, top surface of the vault board, and spring type (Table 1).

Table 1. Vault boards included in research study

	Manufacturer	**Top Surface**	**Spring Type**
Stratum® Vault Board	AAI	Carpet	Compression
Evo-Boards	AAI	Anti-fatigue	Leaf
Evo-Silver	AAI	Anti-fatigue	Compression
INTERNATIONAL Springboard (HARD)	Speith	Carpet	Compression
COMPETITION Performance Series Acceleration Board	Speith	Carpet	Compression

Stratum® Vault Board (Figure 12) - This vault board is manufactured by AAI. It is approved by the Federation Internatinale de Gymnastics (FIG) approved and meets USAG, NCAA, NFHS and AAU competition specifications. Eight removable conical spring are placed within the vault board. For FIG sanctioned meets, a hard (eight spring) and soft (six spring) version are used and springs cannot be removed. The top surface will be described as carpet on top of foam. The total weight of the vault board is 60 pounds.

Evo-Boards (Figure 13) - This vault board is manufactured by AAI. The Evo-Board uses the next evolution in leaf springs design to provide a larger sweet spot and a softer and less jarring feel allowing for more repetition for the gymnast (AAI). A soft, medium, and firm vault board option are available because the leaf springs are non-removable. The top surface of the vault board is an anti-fatigue mat. The total weight of the vault board ranges from 49 to 57 pounds dependent on the number of leaf springs within the vault board.

Evo-Board Silver (Figure 14) - This vault board is manufactured by AAI. The vault board consists of eight to nine removable conical springs and has an anti-fatigue mat for the top surface. It could be described as a combination of the Stratum® Vault Board and Evo-Board. The total weight of the vault board is 55 pounds.

INTERNATIONAL Springboard (Hard) (Figure 15) - This vault board is manufactured by Speith. FIG approved, this vault board consist of eight non-removable conical springs and the top surface is designed with curved multi-ply timber and carbon fiber covered in carpet (Speith). The total weight of the vault board is 56 pounds.

COMPETITION Performance Series Acceleration Board (Figure 16) - This vault board is manufactured by Speith. This vault board consists of seven removable conical springs, four hard and three soft springs placed in a strategic configuration (Speith). The top surface is carpeted with three white lines for visual reference. The total weight of the vault board is 51 pounds.

Figure 12. Stratum® Vault Board

Figure 13. Evo-Board (soft, medium, hard)

Figure 14. Evo-Board Silver

Figure 15. INTERNATIONAL Springboard (Hard)

Figure 16. COMPETITION Performance Series Acceleration Board

Data Collection Equipment

The EMG signals were gathered using ProComp encoders and recorded by BioGraph Infiniti system with a sampling rate of 2048 HZ. Four Pro Sensors were used to measure muscle activity during the vaulting performance and were placed on the following muscles: biceps femoris, rectus femoris, tibialis anterior, and the gastrocnemius medialis. These muscles were selected because they are the main muscles for the upper and lower legs. The biceps femoris and rectus femoris muscles allow gymnasts to produce speed for the vault run and power during the take-off from the vault board. Gymnasts use the tibialis anterior and gastrocnemius medialis for pointing and flexing the foot and for jumping.

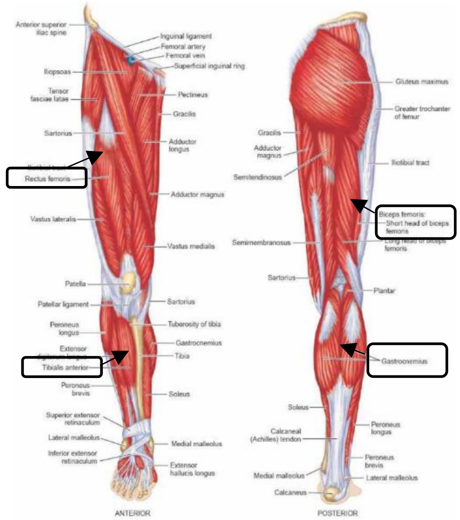


Figure 17. Target muscles collected during EMG

Three Go Pro cameras were used to record the gymnast while they performed their vaults and to collect two-dimensional kinematic data. One Go Pro captured the overall/wide view, the second focused on the lateral side of the vault board, and the third angled down onto the top/front surface of the vault board. The Go Pro cameras captured video with a resolution of 1080p at 120 frames per second. The research team decided to use Go Pro cameras because it allowed us to collect video during the experiment without having to use additional bright lighting that traditional high-speed cameras use. This eliminated the risk of distracting the gymnasts during their performance.

A Garmin 735XT was placed on the wrist of the gymnasts to monitor heart rate throughout the experiment. The Garmin 735XT was only used to monitor the athlete as they performed the study and the data collected was not used for analysis.

A Vault Board Sensor was designed for this experiment using an Arduino Uno and three Sharp GP2Y0A41SKOF Analog Distance Sensors 4-30cm. The three distance sensors were placed on the underside of the vault board (Figure 18). These distance sensors were connected to an Arduino Uno which was powered by a computer. The Arduino code written for this study and utilized for the Vault Board Sensor can be seen in Appendix B.

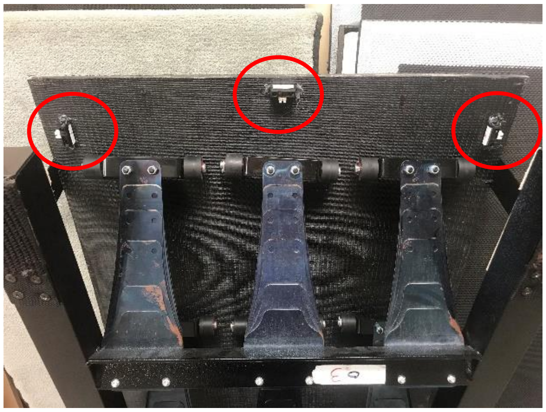


Figure 18. Location of three distance sensors on vault board

The data collected during the experiment was the change in compression and the maximum compression achieved on the vault board. The Vault Board Sensor was created for this research study to measure the maximum compression achieved on the vault board and its values were compared to the those identified through video analysis.

A Vault Safety Zone (Figure 19) was used to ensure the safety of the gymnast during their vault performance. Video grid lines were placed on the inner portion of the mat to measure the amount of compression during each vault by ±.25 inch. With the safety of the gymnast being of high importance during this study, we believe that ±.25 inches was the minimum tolerance we could accept for our video analysis without compromising their safety.

Figure 19. Vault Safety Zone

Experimental Procedures

This study was approved by the Institutional Review Board (IRB), which can be found in the Appendix A. Upon arrival, the participants were given an informed consent form that provided a general overview of the research study. The study consisted of three sessions. During Session One, participants read, reviewed, and signed the informed consent document. Participants were then given a pre-study survey to complete which included basic information regarding their gymnastics career, injury history, and current preferences in gymnastics equipment. Upon completion, participants were given a five minute warmup period in order to collect an accurate reading when taking maximum voluntary contraction measurements. After the warmup, the electromyography (EMG) system was placed on the participant. Four sensors were placed on the following muscles: biceps femoris, rectus femoris, tibialis anterior, and the gastrocnemius medialis. The maximum voluntary contractions (MVC) were then collected by conducting standardized strength tests that targeted the specific muscles. To ensure proper placement of the surface electrodes and the correct strength test exercises, SENIAM recommendations for sensor locations and clinical tests were used (SENIAM).

During Sessions Two and Three, participants performed five vault timers on five different types of vault boards and completed a post-study survey after each session. The order of the five vault boards were randomized. Participants completed five vault timers on three of the vault boards during Session Two and completed five vault timers on the remaining two vault boards during Session Three. The EMG system was placed on the participant, along with the Garmin 735XT watch during these sessions. Before beginning the experiment with a vault board, the EMG system, Garmin 735XT, and Go Pro cameras were all turned on to record the five vault timers. Participants were provided a three minute warmup period for every vault board, seven minutes to complete the five vault times, and three minutes of rest between vault boards. The warmup period was given to allow the participant a practice round with each vault board to ensure an accurate representation of their vault timer on the first trail. Rest was given between each vault to prevent fatigue.

Data Analysis

The independent variables in the study were the five vault boards (Stratum ® Vault Board, Evo-Board, Evo-Board Silver, INTERNATIONAL Springboard (HARD), and COMPETITION Performance Series Acceleration Board). The dependent variables included the amount of compression achieved on the vault board, the knee angle during the contact phases (initial contact, maximum compression, and take-off), the amount of muscle activity, and the qualitative rating for overall performance, top surface, and bounce of the vault board.

The Vault Board Sensor was placed on the Stratum® Vault Board (control) and the Evo-Board (experimental) during Group 2's vault timers. The VBS was manually switched on once the participant began running for their vault timer and it collected the change in compression of the vault board as the participant punched the vault board. The maximum compression was then calculated by taking the initial starting distance and subtracting the minimum distance collected during the participants interaction with the vault board. A two-way (factorial) ANOVA was used test effects of the amount of compression measured by the two measurement methods, the Vault Board Sensor and through video analysis.

Video analysis software was used to analyze the gymnast's contact position on the vault board and the two-dimensional kinematic data was used to assess the gymnast's knee angle during the three phases of interaction with the vault board: initial contact, maximum compression, and take-off (Kinevoa). The vault board surface was divided into a 6x4 grid system to determine the frequency of the gymnast's contact position on the vault board with the black dots representing the spring placement on the vault board (Figure 20). The gymnast's contact position was determined by the location of the lateral malleolus on vault board contact, a method previously used by *Coventry et al*. (2010). The lateral view Go Pro camera was used to determine the gymnast's X-location and the top view Go Pro camera was used for the Y-location on the vault board.

Three body landmarks were used to collect the angle of the knee and full extension of the knee joint was defined at 180°. The knee angle was extracted from the kinematic data and was analyzed via 5 vault boards x3 vault board contact phases (initial contact, compression, and take-off) x14 participants for a within-factor repeated measure ANOVA ($p < .05$).

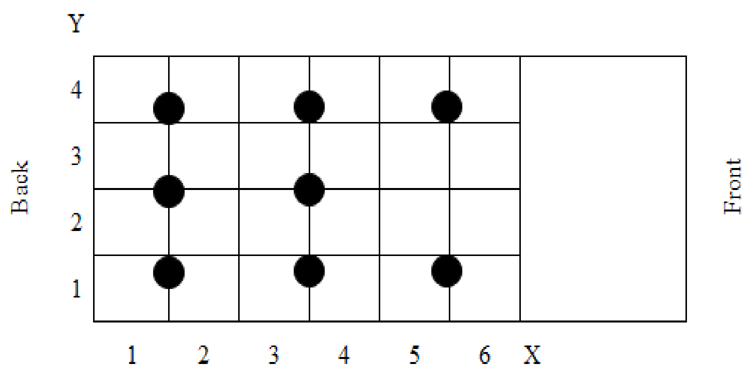


Figure 20: 6x4 grid system for the vault board

For each vault board, participants completed five vault timers. The average muscle activation peak high was taken across the five vault timers for the four muscles being measured. The raw EMG data was fully rectified and smoothed using a Butterworth's filter. Muscle activations were then normalized by the participants maximum voluntary contraction to analyze the percentage of the maximum value obtained for each muscle (Mirka, 1991). To assess the significance between EMG signals for the five vault boards, a one-way repeated measure analysis of variance was used to assess the differences in muscle activation for each vault board.

The factors analyzed were four muscles (biceps femoris, rectus femoris, gastrocnemius medialis, and tibialis anterior) and five vault boards.

Results

Survey Results & Comments

Pre-Study

All participants completed a pre-study survey during Session 1. The survey asked participants information regarding their gymnastics experience, injury history, and anthropometric measurements. It also included questions about what their vault board preference is, how many springs they use in the vault board, and their perceived performance on the vaulting apparatus.

Table 2 shows the participants ranges for age, anthropometric measurements, and years in gymnastics for Groups 1 and 2. All five participants in Group 1 have competed at the NCAA Division I level and one participant had previously competed at an Elite Level before becoming a collegiate gymnast. Group 2 consisted of four Level 8's, one Level 9, and four Level 10 gymnasts. The average reported performance rating based on the participants own perception was 8.09 out of 10 among both groups. Level 8 was the minimum required level to have competed because the Yurchenko vault timers required to perform are trained and competed from Level 8's up to the Elite Level. That being said, the Level 8's included in the study would be 'beginners' to this skill.

Table 2. Description of participants for Group 1 and 2

		Age (years)	Height (inches)	Weight (lbs)	Years in Gymnastics
Group 1	Average	19.60	62.05	120.80	16.00
	Min	18.00	59.00	109.00	11.00
	Max	22.00	64.00	135.00	19.00
	SD	1.82	2.29	10.26	3.08
Group 2	Average	14.56	62.00	109.50	10.00
	Min	12.00	56.00	70.00	8.00
	Max	17.00	66.00	138.00	12.00
	SD	1.74	3.20	21.97	1.41

From the survey, we identified that 71% of the participants included in this study had previously experienced an injury from gymnastics. Injury sites reported included ankle/foot (46%), hand/wrist (23%), back (23%), achilles (8%), and elbow (8%). With safety as our highest priority, we ensured that participants were not currently suffering from any injuries, and that they were physically able to perform the skills required of them. The four athletes that reported no injuries were among the youngest participants in Group 2.

When asked what vault board the participants used or preferred, all responded with the AAI TAC/10 Vault Board and the Elite gymnast also included a Gymnova vault board. Some of the reasons why they use or prefer this vault board included: “it is provided by our gym”, “it is what I am used to”, “it is bouncy, not slippery, and easy to make adjustments”, and “it is what I practice on”. The TAC/10 Vault Board is one of the most common vault boards used by club and collegiate gymnasts. It is the official vault board of the NCAA® Women’s Gymnastics Championship and it meets USAG competition specifications (AAI). This vault board has eight conical springs that can be removed based on the gymnast’s preference. The participants reported the following spring configurations (Figure 21-25). The amount of variation in spring configurations is because gymnasts base their vault board setting from their perceived “feel” on the vault board. Some other factors that are considered is the weight of the gymnast, the amount of “spring” desired, and the tightness on the vault board.

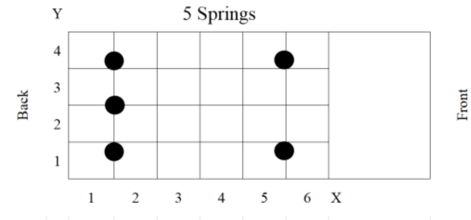


Figure 21. Five Springs

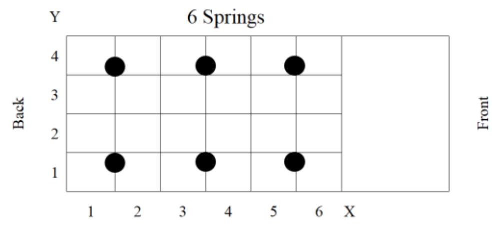


Figure 22. Six Springs

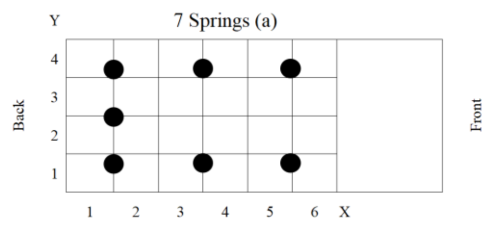


Figure 23. Seven Springs (a)

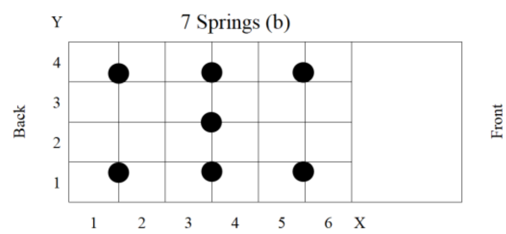


Figure 24. Seven Springs (b)

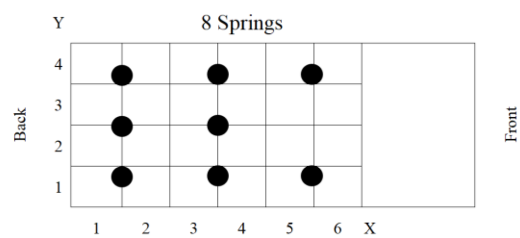


Figure 25. Eight Springs

Post-Study

After Session Two and Three, participants completed a post-study survey. Participants were asked to describe their interaction after every vault boards. For example, the general "feel" of the vault board, whether or not they liked the top surface of the vault board, and how they felt they were able to perform while using the vault board. They were also asked to rate each vault board on a scale from 1 to 10, with 1 meaning they would not use the vault board again, 5 they would possibly use it, and 10 meaning they would use the vault board again.

In result, the average rating score was calculated from the participants responses and the Evo-Boards received the highest rating score at a 7.5. The Evo-Board Silver board came in second with a rating score of 6.33, followed by the COMPETITION Performance Series Acceleration Board (6.08), Stratum® Vault Board (5.92), and INTERNATIONAL Springboard (Hard) (5.46).

Table 3. Ranking of Vault Boards

	Average	Max	Min	SD
Evo-Boards	7.5	9.00	4.00	1.29
Evo-Board Silver	6.33	10.00	2.00	2.31
COMPETITION Performance Series Acceleration Board	6.08	10.00	3.00	1.98
Stratum® Vault Board	5.92	8.00	4.00	1.68
INTERNATIONAL Springboard (Hard)	5.46	9.00	4.00	1.45

From the written survey results, a verbal protocol analysis was used to examine and quantify the responses (Trickett and Trafton, 2009). The results were broken up into three categories: overall description, top surface, and bounce of the vault board. Participants comments were identified as favorable, neutral, and unfavorable and given a corresponding score of 1, 0.5, 0 respectively. Table 4 demonstrates some key words used to identify and rate the interactions.

Table 4. Key words used to assess verbal analysis

	Favorable	Neutral	Unfavorable
Top Surface	Not slippery, soft, not too hard, nice texture, my favorite	A little slippery, did not mind/matter, okay	Slippery, hard, loud
Bounce	Not too stiff or bouncy, sturdy, softer	A little too stiff or hard, decent bounce, okay	Stiff, hard to get enough punch/power

After the verbal protocol analysis was perform, a percentage was calculated by summing up the total value from all the participants responses for each vault board. The sum was then divided by the number of responses evaluated. In result, the Evo-Board received the highest percentage score for the two categories, Top Surface (86%) and Bounce (75%). Table 5 shows the results for all the vault boards. The Evo-Board Silver was second in rating both for Top Surface (77%) and Bounce (58%). Both the Evo-Board and Evo-Board Silver have an anti-fatigue mat as the top surface for the vault board. INTERNATIONAL Springboard (Hard), COMPETITION Performance Series Acceleration Board, and the Stratum® Vault Board have a foam surface with carpet material covering it which is traditionally seen. As we see from the result, the participants preferred the anti-fatigue top surface over the traditional carpet surface.

Table 5. Verbal protocol results for Top Surface and Bounce of the vault boards

	Top Surface
Evo-Boards	86%
Evo-Board Silver	77%
INTERNATIONAL Springboard (Hard)	75%
Stratum® Vault Board	75%
COMPETITION Performance Series Acceleration Board	64%

	Bounce
Evo-Boards	75%
Evo-Board Silver	58%
INTERNATIONAL Springboard (Hard)	50%
COMPETITION Performance Series Acceleration Board	50%
Stratum® Vault Board	40%

Vault Board Sensor (VBS)

During the experiment, 61 vaults were recorded using the VBS and 48 samples had usable data. The maximum compression values collected from the VBS for the Stratum® Vault Board (mean = 3.36 inches, SD = 0.479) and the Evo-Board (mean = 3.84 inches, SD = 0.430) were compared against the maximum compression values collected through video analysis (VA). Significant differences were observed in the amount of compression achieved between the vault boards ($p = 0.002$) but no significant differences were seen by the type of measuring method used to identify the amount of compression. Similar to the video analysis data, the amount of compression achieved by the participants was greater on the Evo-Board compared to the Stratum® Vault Board.

Some explanations in measurement variation could be from the sensitivity of the distance sensors. Previous studies have identified that the total board contact time for a round-off entry vault was on average 0.15 seconds with a compression and repulsion time average of 0.08 seconds each (Bradshaw, 2004). For the Arduino code written for this application, the delay parameter was set to a delay (5) meaning there was a 5 millisecond pause between every reading. Theoretically, this parameter should collect a very accurate reading, but other factors play a role. For example, the amount of light underneath the vault board, the color of reflective surface, and the quality of the distance sensor itself.

Video Analysis

Sweet Spot

The total number of foot contacts for each area in the grid was collected. The percentage of contact hits was then calculated by dividing the number of contacts in each area of the grid by the total number of contacts for a single vault board. Based on the percentages, a heat map was created to visually represent the area on the vault board where the gymnasts hit. Figures 26-35 show the contact percentages for Vault Boards 1 - 5 for Groups 1 and 2. All vault boards are the same in size (length and width) but varied in spring configuration, spring type, and top surface.

Table 6. Vault Board Key

Vault Board	
1	Stratum® Vault Board
2	Evo-Board Silver
3	Evo-Boards
4	INTERNATIONAL Springboard (Hard)
5	COMPETITION Performance Series Acceleration Board

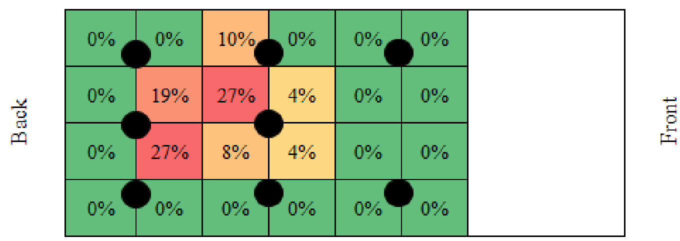


Figure 26. Vault Board 1 – Group 1

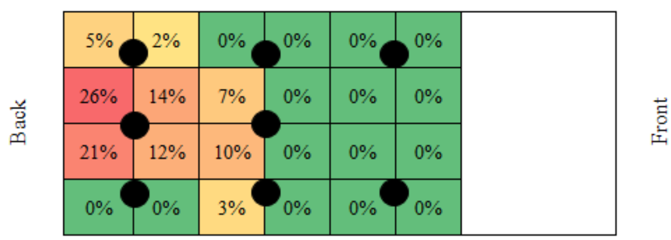


Figure 27. Vault Board 1 – Group 2

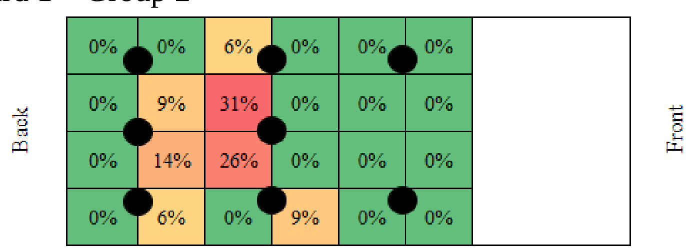


Figure 28. Vault Board 2 – Group 1

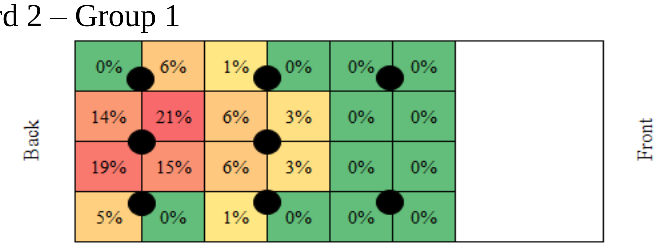


Figure 29. Vault Board 2 – Group 2

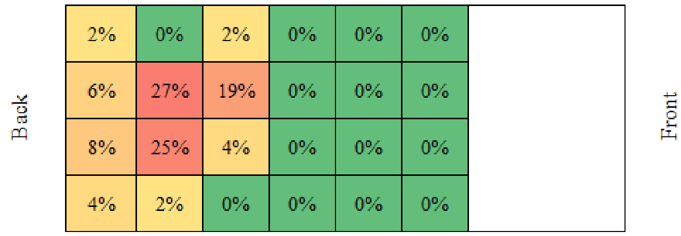


Figure 30. Vault Board 3 – Group 1

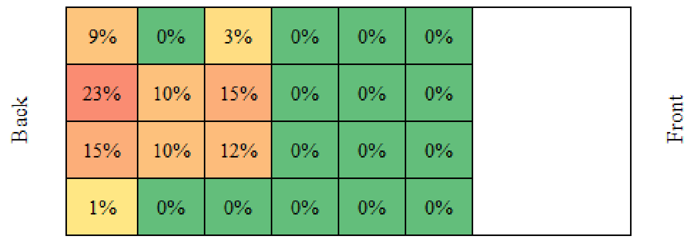


Figure 31. Vault Board 3 – Group 2

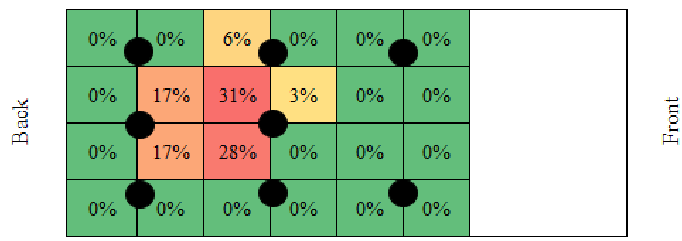


Figure 32. Vault Board 4 – Group 1

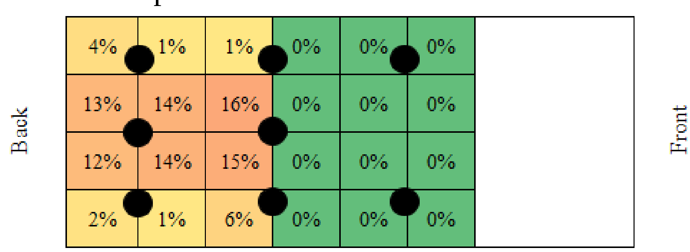


Figure 33. Vault Board 4 – Group 2

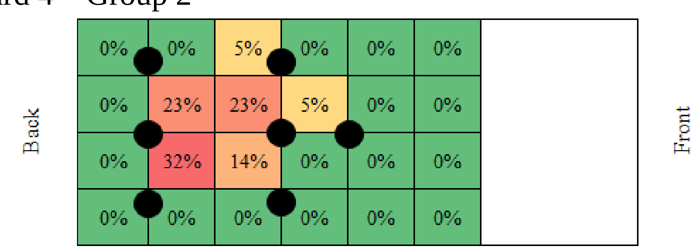


Figure 34. Vault Board 5 – Group 1

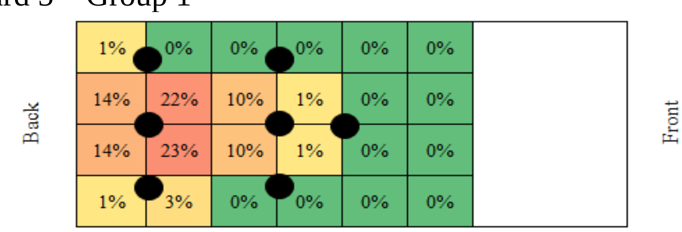
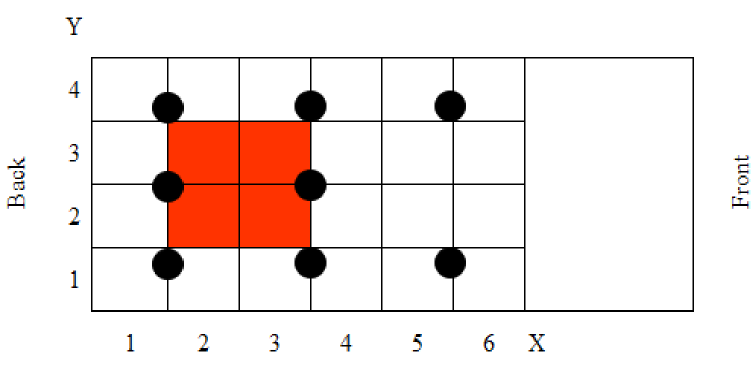


Figure 35. Vault Board 5 – Group 2

Although the sweet spot on a vault board is not scientifically defined, we have defined the sweet spot as the four-grid area shown in Figure 36. Group 1 consistently hits this defined sweet spot on average 84% between all 5 vault boards. We have assumed this sweet spot based on the data collected because Group 1 consists of expert gymnasts which have proven a high level of performance by competing at the NCAA Division I or Elite Level. By defining the sweet spot of the vault board, it allows us to compare and evaluate the gymnast's interactions between the vault boards.



Sweet Spot Hit Percentage		
	Group 1	**Group 2**
VB1	81%	43%
VB2	80%	49%
VB3	75%	48%
VB4	92%	60%
VB5	91%	65%
Average	84%	53%

Figure 36. Defined 'sweet spot' and hit percentages within the 'sweet spot'

When comparing the percentages of hitting the 'sweet spot', Group 1 had an average of 84% compared to Group 2 whose average was 53%. One reasoning behind this is the experience difference of the gymnasts between groups. On average, Group 1 participants had six more years of experience in the sport. Gymnastics is a sport of repetition to attain perfection. The goal is to make every skill consistent to allow the gymnast to execute the skill the same way on any given turn. Another factor is that Group 2 participants are either new to Yurchenko vaults or have only trained and competed it for one to three years. Whereas at the NCAA Division I or Elite Level, these gymnasts have been performing Yurchenko vaults for five plus years.

As we see with the Vault Board 3 (Evo-Board), there is a greater variation from the defined sweet spot where Group 1 and 2 had a hit percentage of 75% and 48% respectively. Although with a lower hit percentage than average and a larger hit area, we did not see an effect on the maximum compression amount the gymnast achieved on the vault board. With Group 1 and 2 combined, the average amount of maximum compression was 3.836 inches with a standard deviation of 0.789 on Vault Board 3. This standard deviation value was the second lowest when comparing the five vault boards. The lowest standard deviation value was from Vault Board 5 at 0.562 with an average maximum compression of 4.078 inches. When comparing the 'sweet spot' hit percentages, Vault Board 5 was among the top two for both Group 1 and 2. Unlike all the other vault boards, Vault Board 5 was the only board to have a visual represented on the top surface of the vault board. This could be one conclusion as to why the gymnasts were more consistent hitting this vault board compared to the others.

Figure 37. Vault Board 5

Compression

The amount of maximum compression achieved on each vault board showed a statistical difference ($f = 72.43$, $p < 0.0001$). Vault Board 5 exhibited the largest value for maximum compression at 4.078 inches ($SD = 0.562$) and Vault Board 3 with the second largest value at 3.836 inches ($SD = 0.789$). Both Vault Board 3 and 5 varied in spring configuration compared to Vault Boards 1, 2, and 4. Vault Board 5 had seven removable conical springs, four hard and three soft springs that were place in different design configuration than traditional vault boards.

Figure 38 shows the spring configuration in comparison to the other vault boards. Vault Board 3 consisted of eight leaf springs, which is the only vault board with the leaf spring design.

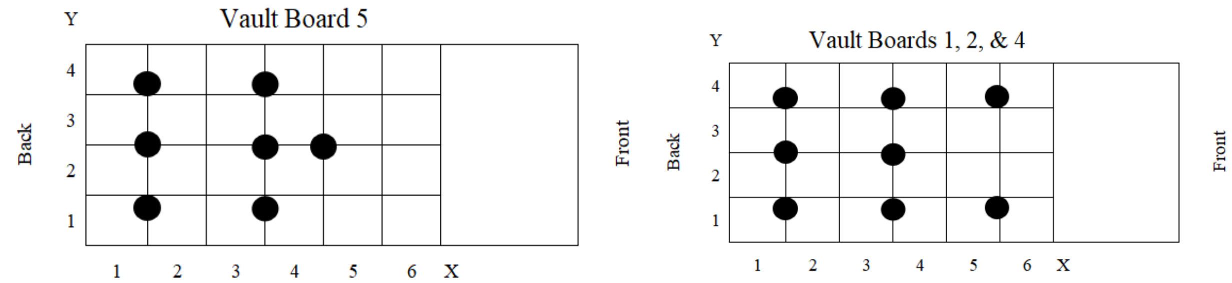


Figure 38. Difference in spring configuration for Vault Board 5 compared to Vault Boards 1, 2, & 4

Table 7. Maximum compression achieved on each vault board

Maximum Compression (in.)		
Vault Board	Mean	Std Dev
1	2.773	0.844
2	3.066	0.954
3	3.836	0.789
4	2.629	0.898
5	4.078	0.562

Knee Angular Positions

The type of vault board did not show a statistical main effect on the gymnast's kinematic reaction for the knee angle (f = 2.06, p = 0.0883). The knee angle phase showed a statistical difference (f = 299.27, p < 0.001). The two-factor interaction with phase x vault board did not have a statistical difference. The three-factor interaction with phase x vault board x participant identified some detectable effects but the magnitude of these effects are not large enough to discuss further. On average, the participants knee angle during the board contact phases was 148^{o} for initial contact, 140^{o} for maximum compression, and 166^{o} during take-off. These values compare with a previous study that identified knee angle position during the three vault board contact phases (Penitente, 2014). Only a three-degree difference was observed between the vault board contact phases. There is no surprise that the knee angle during the board contact phases are different. When the gymnast first hits the vault board, there should be some amount of flexion in the knee because the gymnast is preparing to contact the vault board. As the gymnasts progresses to the maximum compression phase, we see greater flexion in the knee as they use their momentum and length strength to compress the vault board. At the take-off phase, the gymnast extends their legs in order to achieve the maximum amount of rebound from the vault board. From this analysis, we can conclude that the gymnast's kinematic performance is not affected by the type of vault board they use. Their interaction during the initial contact, maximum compression, and take-off phase remain consistent across all the board.

Figure 39. Knee angle at initial contact, maximum compression, and take-off

Electromyography (EMG) Analysis

The peak height for muscle activation was taken for each of the five vault timers and averaged. The analysis of variance performed on the EMG muscle data did not show significant difference across vault boards for each muscle ($p > .05$). A statistically significant difference was evident across the muscles analyzed ($p < .0001$). Figure 29 shows the average percentage of maximum voluntary contraction for each muscle across the five vault boards. The biceps femoris was on average 20% higher across all vault boards compared to the other muscles analyzed. The second muscle that exhibited more activation was the gastrocnemius medialis.

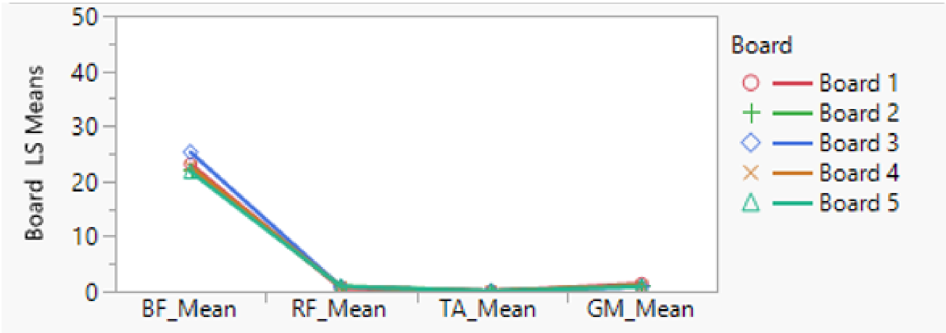


Figure 40. Mean values for muscles across the five vault boards

Table 8. Percent of MVC – mean value of each muscle

	Biceps Femoris	Rectus Femoris	Tibialis Anterior	Gastrocnemius Medialis
Vault Board 1	23.11	0.56	0.03	1.41
Vault Board 2	22.15	0.99	0.05	1.11
Vault Board 3	25.27	082	0.06	0.82
Vault Board 4	22.65	0.81	0.05	1.01
Vault Board 5	21.69	0.89	0.04	0.86

The muscle activation profiles can be seen in Appendix E. The smoothed EMG data was plotted in a table with the percentage of maximum voluntary contraction being on the y-axis and time being on the x-axis. For each vault board, five peaks are evident in the graphs which can be identified as when the gymnast strikes the vault board. The signal from the biceps femoris is always the strongest in comparison to the other muscles. The biceps femoris helps perform knee flexion. As discussed previously, the gymnast achieves the greatest amount of knee flexion at the maximum compression phases on the vault board. The peak in muscle activation for the biceps femoris is evidence of the gymnast's knee flexion during the vault board contact. Figure 30 is an example of the muscle activation profile seen for a given board.

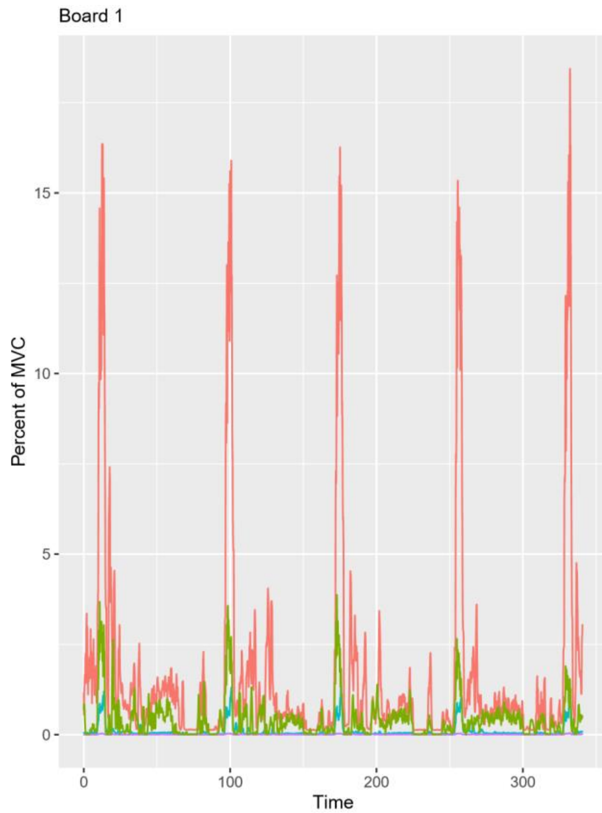


Figure 41. Muscle activation profile for Participant 11, Vault Board 1

Discussion

The main purpose of this study was to assess how the gymnast interaction with different types of vault boards, specifically the Evo-Board. By using techniques related to human impact and performance and product design and testing, we were able to better understand how the gymnast interacts with the vault boards. Quantitative and qualitative analysis methods were used to determine the significance of the leaf spring design of the Evo-Board.

The primary result of this study indicates that the Evo-Board did not negatively impact or affect how the gymnast interacted with the vault board. There were statistically significant differences in the amount of maximum compression achieved among the vault boards. On average, the gymnasts achieved the second highest maximum compression value on the Evo-Board and it received the highest rating score by the gymnasts. This vault board also presented to have a larger sweet spot or acceptable contact area without negatively affecting the gymnast's amount of compression on the vault board. With a defined 'sweet spot' area of 25%, the acceptable contact area for this vault board increased by 37%. This allows for a greater variation in contact position when the gymnast hits the vault board. While consistency is key, this also allows for gymnast to train new skills on the vaulting event and still achieve an optimal compression on the vault board.

The Vault Board Sensor could be used to analyze the gymnast's performance on the vault board for training or competition purposes. As mentioned before, gymnastics is a sport of perfection and to achieve this, gymnasts must consistently do the same thing repeatedly. To reduce the amount of variation during a gymnast's vault, one might want to know how much they compressed the vault board during their vault. The Vault Board Sensor would allow gymnasts and coaches to monitor the amount of compression and to maintain consist readings during both practice and competition vaults.

The kinematic results indicated that there are statistical differences in the knee angle for the three contact phases: initial contact, maximum compression, and take-off. More importantly, the results showed that the knee angle during the phases are not statistically different across vault boards. The gymnasts knee angles remained consistent regardless of the vault board they used. Although the knee angle changed between phases, this was to be expected.

The findings from the EMG showed a spike in muscle activation as the gymnast interacted with the vault board. The normalized EMG data result showed that there was no statistical difference in the muscle activation profile across the vault board. There was a statistical difference in the amount of muscle activation for each muscle. The biceps femoris had the highest level of muscles activation during the gymnast's interaction with the vault board.

This makes sense in the case that the biceps femoris main function is to aid in flexion of the knee. As the gymnast transitions through the vault board contact phases, there is an increase in knee flexion with the maximum flexion achieved during maximum compression phase on the vault board.

Conclusion

In conclusion, this project seeks to shift current research in the sport of gymnastics from optimizing the gymnast's performance to identifying ways gymnastics equipment manufacturers can better design equipment to fit the gymnast. AAI claims that the Evo-Boards have a "larger sweet spot allowing for variations in entry position" is a valid statement. AAI should consider placing a visual on their vault board to provide the gymnast a visual target area aiding them on where they should hit the vault board. Participants also preferred the anti-fatigue top surface of the Evo-Board and Evo-Board Silver in comparison to the carpeted surface. The Evo-Board leaf spring design does not allow for variation in spring configurations which traditional conical spring vault boards have. With both studies, we saw a variation in spring configuration among participants. Future work should include designing an Evo-Board that allows for a variation in spring configurations. The research also validates that AAI should consider expanding their product line to include new monitoring sensors to the vault boards to help coaches measure the athlete's ability to consistently optimize their vaults. AAI's creation of a "smart" vaulting board would also help increase future demand and revenue from this type of equipment. This type of advancement in the vault board design could help increase vaulting consistency and reduce variations resulting in improved safety for the gymnasts.

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APPENDIX A: IRB APPROVAL

IOWA STATE UNIVERSITY
OF SCIENCE AND TECHNOLOGY

Institutional Review Board
Office for Responsible Research
Vice President for Research
2420 Lincoln Way, Suite 202
Ames, Iowa 50014
515 294-4566

Date: 04/18/2019

To: Courtney Middelkoop   Richard T Stone

From: Office for Responsible Research

Title: **Evaluation and Analysis of Artistic Gymnastics Equipment**

IRB ID: **19-107**

Submission Type: Initial Submission   **Review Type**: Full Committee

Approval Date: 04/16/2019   **Approval Expiration Date: N/A**

The project referenced above has received approval from the Institutional Review Board (IRB) at Iowa State University according to the dates shown above. Please refer to the IRB ID number shown above in all correspondence regarding this study.

To ensure compliance with federal regulations (45 CFR 46 & 21 CFR 56), please be sure to:

- **Use only the approved study materials** in your research, including the **recruitment materials and informed consent documents that have the IRB approval stamp**.
- **Retain signed informed consent documents for 3 years after the close of the study,** when documented consent is required**.**
- **Obtain IRB approval prior to implementing any changes** to the study or study materials.
- **Promptly inform the IRB of any addition of or change in federal funding for this study.** Approval of the protocol referenced above applies only to funding sources that are specifically identified in the corresponding IRB application.
- **Inform the IRB if the Principal Investigator and/or Supervising Investigator end their role or involvement with the project** with sufficient time to allow an alternate PI/Supervising Investigator to assume oversight responsibility. Projects must have an eligible PI to remain open.
- **Immediately inform the IRB of** (1) **all serious and/or unexpected** adverse experiences involving risks to subjects or others; and (2) **any other** unanticipated problems **involving risks** to subjects or others.
- IRB approval means that you have met the requirements of federal regulations and ISU policies governing human subjects research. **Approval from other entities may also be needed.** For example, access to data from private records (e.g., student, medical, or employment records, etc.) that are protected by FERPA, HIPAA, or other confidentiality policies requires permission from the holders of

IRB 01/2019

IOWA STATE UNIVERSITY
OF SCIENCE AND TECHNOLOGY

Institutional Review Board
Office for Responsible Research
Vice President for Research
2420 Lincoln Way, Suite 202
Ames, Iowa 50014
515 294-4566

Date: 05/15/2019

To: Courtney Middelkoop   Richard T Stone

From: Office for Responsible Research

Title: **Evaluation and Analysis of Artistic Gymnastics Equipment**

IRB ID: **19-108**

Submission Type: Initial Submission   **Review Type**: Full Committee

Approval Date: 05/15/2019   **Approval Expiration Date: 05/14/2020**

The project referenced above has received approval from the Institutional Review Board (IRB) at Iowa State University according to the dates shown above. Please refer to the IRB ID number shown above in all correspondence regarding this study.

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- **Immediately inform the IRB of** (1) **all serious and/or unexpected** adverse experiences involving risks to subjects or others; and (2) **any other** unanticipated problems **involving risks** to subjects or others.
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APPENDIX B: VAULT BOARD SENSOR (VBS)

SharpSensorCm_MultipleN §

```
#include <SharpIR.h>

#define IR1 A0 //define signal pin
#define IR2 A1 //define signal pin
#define IR3 A2 //define signal pin

#define model1 430
#define model2 430
#define model3 430

// 4 to 30 cm GP2Y0A1SK0F use 430

SharpIR SharpIR1(IR1, model1);
SharpIR SharpIR2(IR2, model2);
SharpIR SharpIR3(IR3, model3);

void setup() {
  // Multiple Sharp IR Distance sensor code:
   Serial.begin(9600);
   Serial.begin(9600);
   Serial.println("CLEARSHEET");
   Serial.println("CLEARDATA");
   Serial.println("LABEL,Date,Time,Dis_cm,Dis2_cm,Dis3_cm");

  //extra pin for 5V if needed
  pinMode(2, OUTPUT);
  digitalWrite(2,HIGH);

  pinMode(4, OUTPUT);
  digitalWrite(4,HIGH);

}

void loop() {
  //time between samples (ms)
  delay(5);

  unsigned long startTime=millis();  // takes the time before the loop on the library begins

  int dis1=SharpIR1.distance();  // this returns the distance to the object you're measuring
  int dis2=SharpIR2.distance();
  int dis3=SharpIR3.distance();

  Serial.println( (String) "," + dis1 + "," + dis2 + "," + dis3); // dis1, dis2, dis3

}
```

Figure 1B. Arduino code for VBS

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
Board	1	1	20.18	12.2882	0.0022*
Method	1	1	17.16	1.3041	0.2692
Method*Board	1	1	17.18	1.2931	0.2711

Random Effect Predictions

Term	BLUP	Std Error	DFDen	t Ratio	Prob>|t|
Participant[P16]	-0.166305	0.166022	4.964	-1.00	0.3628
Participant[P18]	0.0184401	0.162888	5.215	0.11	0.9141
Participant[P19]	0.0141262	0.182365	3.807	0.08	0.9422
Participant[P20]	0.1502881	0.1633	5.186	0.92	0.3982
Participant[P21]	0.1567294	0.163912	5.141	0.96	0.3817
Participant[P22]	-0.282656	0.163912	5.141	-1.72	0.1436
Participant[P23]	0.0355255	0.18327	3.739	0.19	0.8564
Participant[P25]	0.0738524	0.18327	3.739	0.40	0.7089
Method[VA]*Board[1]*Participant[P16]	-0.316314	0.243558	17.11	-1.30	0.2113
Method[VA]*Board[1]*Participant[P18]	-0.103418	0.242801	16.91	-0.43	0.6755
Method[VA]*Board[1]*Participant[P20]	0.0776685	0.242927	16.95	0.32	0.7531
Method[VA]*Board[1]*Participant[P21]	0.1070843	0.243116	17	0.44	0.6651
Method[VA]*Board[1]*Participant[P22]	0.2349791	0.243116	17	0.97	0.3473
Method[VA]*Board[3]*Participant[P16]	0.0110112	0.234267	20.89	0.05	0.9630
Method[VA]*Board[3]*Participant[P18]	0.0888441	0.233261	20.64	0.38	0.7072
Method[VA]*Board[3]*Participant[P19]	-0.144602	0.239745	19.95	-0.60	0.5532
Method[VA]*Board[3]*Participant[P20]	0.3712278	0.233393	20.68	1.59	0.1269
Method[VA]*Board[3]*Participant[P21]	-0.072076	0.233588	20.73	-0.31	0.7607
Method[VA]*Board[3]*Participant[P22]	-0.788323	0.233588	20.73	-3.37	0.0029*
Method[VA]*Board[3]*Participant[P23]	0.2123689	0.240059	19.99	0.88	0.3869
Method[VA]*Board[3]*Participant[P25]	0.3215489	0.240059	19.99	1.34	0.1955
Method[VBS]*Board[1]*Participant[P16]	-0.103963	0.25071	16.53	-0.41	0.6837
Method[VBS]*Board[1]*Participant[P18]	-0.064347	0.245316	16.75	-0.26	0.7963
Method[VBS]*Board[1]*Participant[P20]	0.0671544	0.250196	16.41	0.27	0.7917
Method[VBS]*Board[1]*Participant[P21]	0.0743236	0.257291	15.78	0.29	0.7764
Method[VBS]*Board[1]*Participant[P22]	0.0268316	0.257291	15.78	0.10	0.9183
Method[VBS]*Board[3]*Participant[P16]	0.0393961	0.263576	16.3	0.15	0.8830
Method[VBS]*Board[3]*Participant[P18]	0.1199321	0.234223	20.5	0.51	0.6141
Method[VBS]*Board[3]*Participant[P19]	0.1760196	0.240534	19.87	0.73	0.4728
Method[VBS]*Board[3]*Participant[P20]	-0.181804	0.23435	20.54	-0.78	0.4467
Method[VBS]*Board[3]*Participant[P21]	0.2392406	0.234539	20.58	1.02	0.3195
Method[VBS]*Board[3]*Participant[P22]	-0.102128	0.234539	20.58	-0.44	0.6678
Method[VBS]*Board[3]*Participant[P23]	-0.133359	0.246246	19.48	-0.54	0.5943
Method[VBS]*Board[3]*Participant[P25]	-0.157298	0.246246	19.48	-0.64	0.5304

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	Std Error	95% Lower	95% Upper	Pct of Total
Participant	0.1870373	0.0496111	0.0533388	-0.054931	0.1541533	11.668
Method*Board*Participant	0.4159786	0.110337	0.0586416	-0.004599	0.2252725	25.950
Residual		0.2652469	0.038654	0.2032268	0.3608846	62.382
Total		0.4251949	0.0748512	0.3095962	0.6205534	100.000

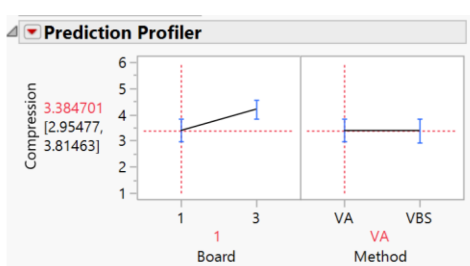


Figure 2B. JMP Analysis – Two-way within subject repeated measure analysis of variance (2 measuring methods x 2 vault boards x 8 participants)

APPENDIX C: COMPRESSION ANALYSIS

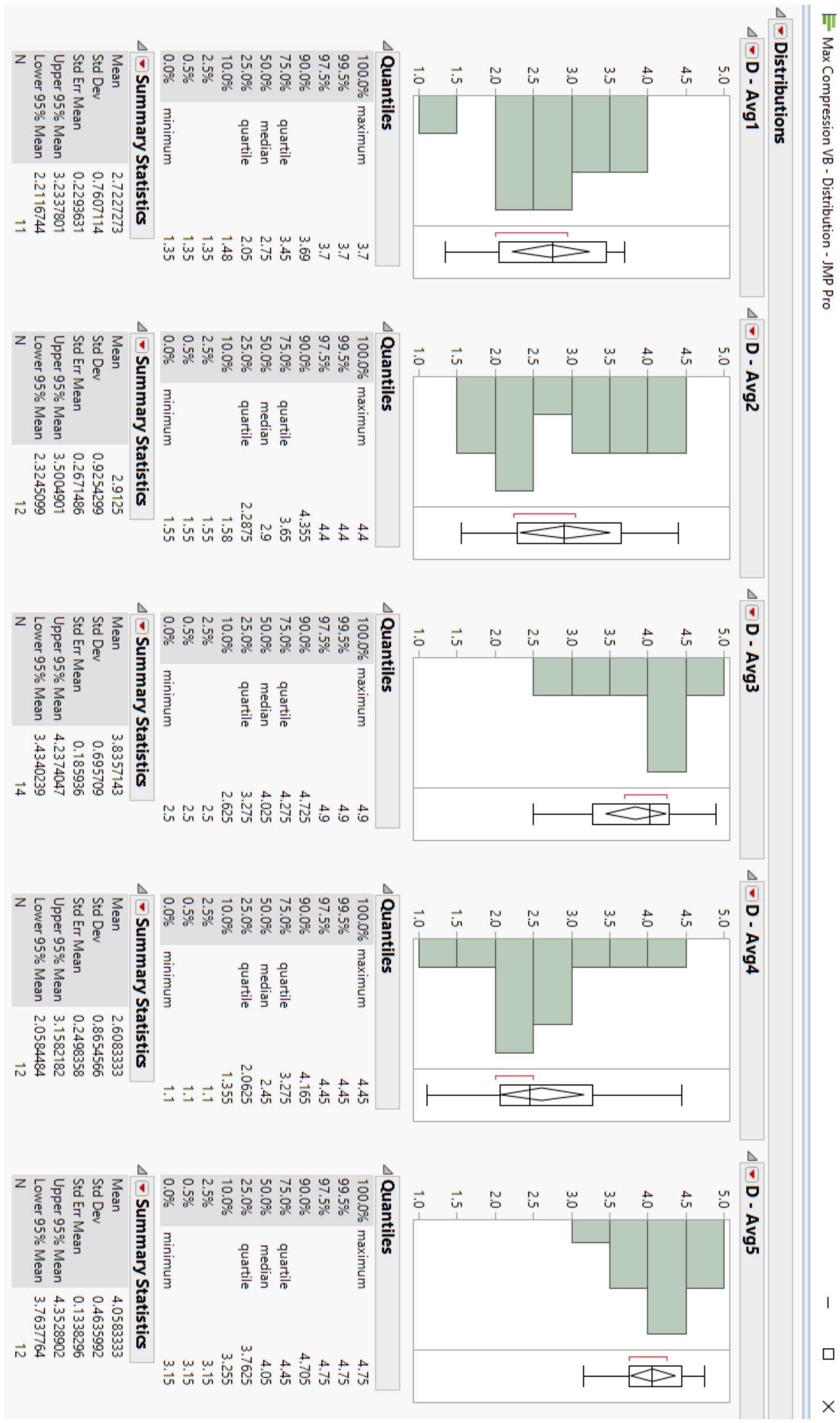


Figure 1C. Average of maximum compression (inches)

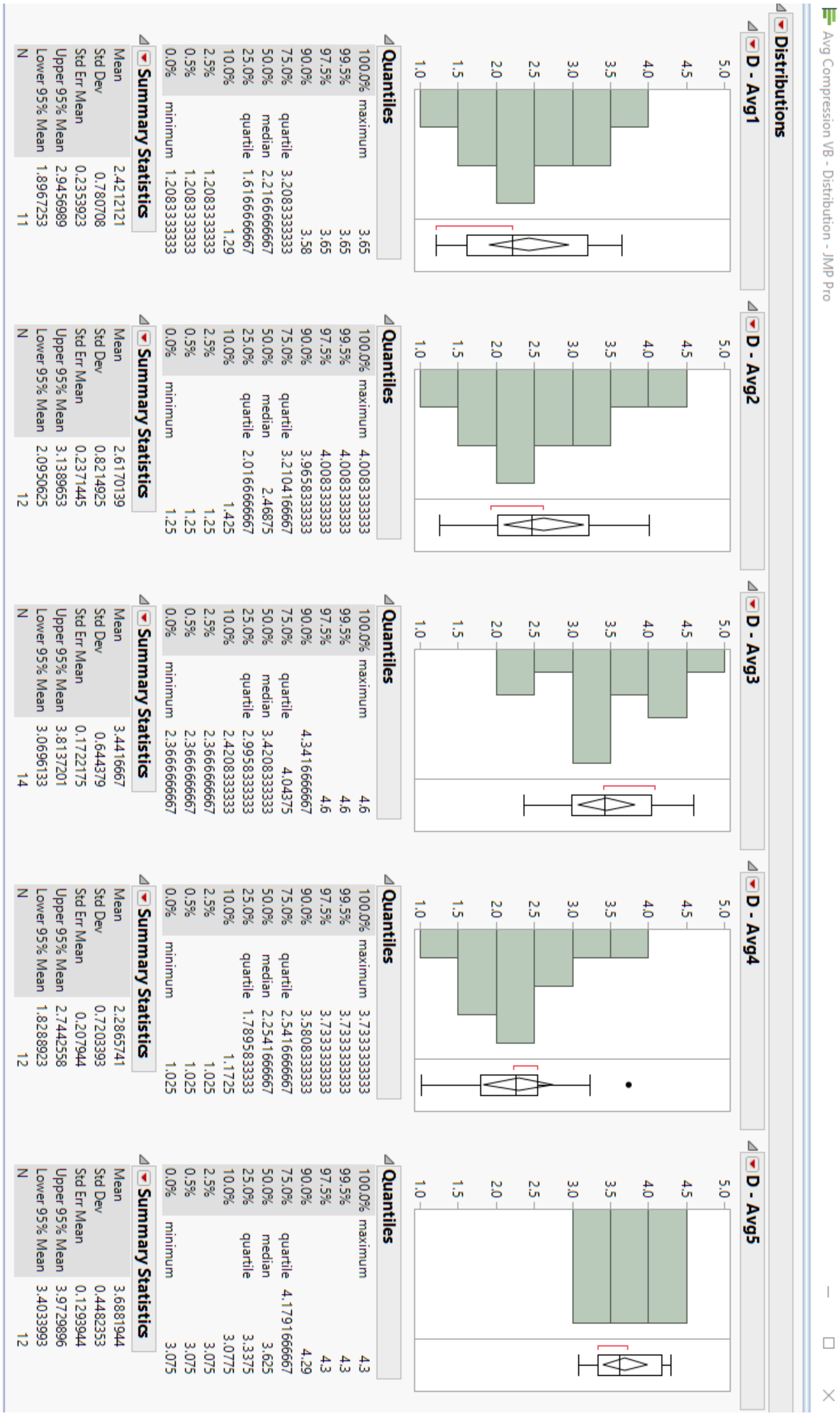


Figure 2C. Average of average compression (inches)

APPENDIX D. KNEE ANGLE

Fixed Effect Tests

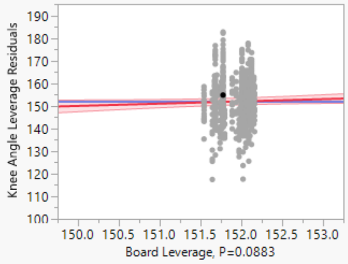
Source	Nparm	DF	DFDen	F Ratio	Prob > F
Board	4	4	157.1	2.0626	0.0883
Phase	2	2	155.7	299.2711	<.0001*
Phase*Board	8	8	155.7	1.6904	0.1047

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	Std Error	95% Lower	95% Upper	Wald p-Value	Pct of Total
Participant	1.2909812	29.974731	12.749867	4.9854507	54.964012	0.0187*	36.277
Phase*Board*Participant	1.2677126	29.434467	3.9018655	21.786951	37.081983	<.0001*	35.623
Residual		23.218565	1.246764	20.956373	25.869889		28.100
Total		82.627763	13.294438	61.703483	116.40397		100.000

Board

Leverage Plot

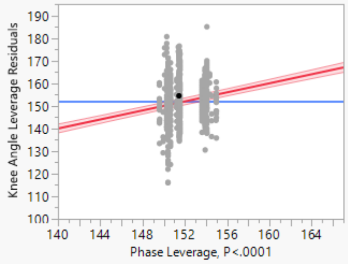


Least Squares Means Table

Level	Least Sq Mean	Std Error
1	150.57656	1.7999934
2	152.63514	1.7756713
3	153.14974	1.7188265
4	149.87560	1.7749244
5	152.28150	1.7721675

Phase

Leverage Plot

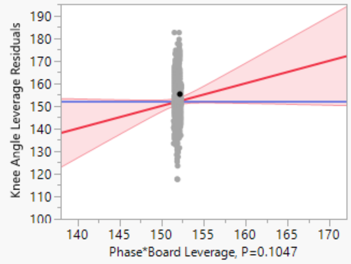


Least Squares Means Table

Level	Least Sq Mean	Std Error
Phase 1 - Initial Contact	148.38972	1.6499951
Phase 2 - Max Compression	140.65450	1.6499951
Phase 3 - Take-off	166.06691	1.6499951

Phase*Board

Leverage Plot



Least Squares Means Table

Random Effect Predictions

Term	BLUP	Std Error	DFDen	t Ratio	Prob>|t|
Participant[11]	-1.583677	2.033977	34.86	-0.78	0.4415
Participant[12]	-3.192235	2.04809	35.6	-1.56	0.1279
Participant[13]	-3.07116	2.040916	35.23	-1.50	0.1413
Participant[14]	-1.356374	2.152333	40.23	-0.63	0.5321
Participant[15]	0.8436561	2.574028	53.25	0.33	0.7444
Participant[16]	2.2956313	2.033977	34.86	1.13	0.2668
Participant[18]	0.969478	2.033977	34.86	0.48	0.6366
Participant[19]	2.4543495	2.30227	46.03	1.07	0.2920
Participant[20]	3.1879962	2.033977	34.86	1.57	0.1261
Participant[21]	13.926241	2.036688	35.01	6.84	<.0001*
Participant[22]	-1.038343	2.033977	34.86	-0.51	0.6129
Participant[23]	-2.092948	2.046633	35.53	-1.02	0.3134
Participant[24]	-10.41539	2.141863	39.68	-4.86	<.0001*
Participant[25]	-0.927222	2.302375	46.03	-0.40	0.6890

Phase[Phase 1 - Initial Contact]*Board[1]*Participant[11]	-0.685431	2.789946	297.8	-0.25	0.8061
Phase[Phase 1 - Initial Contact]*Board[1]*Participant[12]	-1.714519	2.797153	299.6	-0.61	0.5404
Phase[Phase 1 - Initial Contact]*Board[1]*Participant[13]	-2.682829	2.793538	298.7	-0.96	0.3376
Phase[Phase 1 - Initial Contact]*Board[1]*Participant[14]	-7.273388	2.850946	285.7	-2.55	0.0113*
Phase[Phase 1 - Initial Contact]*Board[1]*Participant[15]	0.5001878	3.088903	239.4	0.16	0.8715
Phase[Phase 1 - Initial Contact]*Board[1]*Participant[16]	4.6012161	2.789946	297.8	1.65	0.1002
Phase[Phase 1 - Initial Contact]*Board[1]*Participant[18]	6.2648993	2.789946	297.8	2.25	0.0255*
Phase[Phase 1 - Initial Contact]*Board[1]*Participant[20]	-2.561178	2.789946	297.8	-0.92	0.3594
Phase[Phase 1 - Initial Contact]*Board[1]*Participant[21]	5.2657647	2.791348	298.2	1.89	0.0602
Phase[Phase 1 - Initial Contact]*Board[1]*Participant[22]	-2.020187	2.789946	297.8	-0.72	0.4696
Phase[Phase 1 - Initial Contact]*Board[1]*Participant[23]	0.3054642	2.90183	318.7	0.11	0.9162
Phase[Phase 1 - Initial Contact]*Board[2]*Participant[11]	-6.703132	2.760241	310	-2.43	0.0157*
Phase[Phase 1 - Initial Contact]*Board[2]*Participant[12]	-1.513339	2.767811	311.9	-0.55	0.5849
Phase[Phase 1 - Initial Contact]*Board[2]*Participant[13]	3.742721	3.032649	352.1	1.23	0.2180
Phase[Phase 1 - Initial Contact]*Board[2]*Participant[14]	6.3439622	3.080225	334.5	2.06	0.0402*
Phase[Phase 1 - Initial Contact]*Board[2]*Participant[16]	3.9386626	2.760241	310	1.43	0.1546
Phase[Phase 1 - Initial Contact]*Board[2]*Participant[18]	5.2568524	2.760241	310	1.90	0.0578
Phase[Phase 1 - Initial Contact]*Board[2]*Participant[20]	1.0949366	2.760241	310	0.40	0.6919
Phase[Phase 1 - Initial Contact]*Board[2]*Participant[21]	5.2033122	2.870306	330.5	1.81	0.0708
Phase[Phase 1 - Initial Contact]*Board[2]*Participant[22]	-5.446688	2.760241	310	-1.97	0.0494*
Phase[Phase 1 - Initial Contact]*Board[2]*Participant[23]	3.0650643	2.766958	311.8	1.11	0.2688
Phase[Phase 1 - Initial Contact]*Board[2]*Participant[24]	-3.220804	2.818166	294.7	-1.14	0.2540
Phase[Phase 1 - Initial Contact]*Board[2]*Participant[25]	-11.76155	2.908487	274.3	-4.04	<.0001*
Phase[Phase 1 - Initial Contact]*Board[3]*Participant[11]	-3.441255	2.705524	328.2	-1.27	0.2043
Phase[Phase 1 - Initial Contact]*Board[3]*Participant[12]	-0.324422	2.713452	330.2	-0.12	0.9049
Phase[Phase 1 - Initial Contact]*Board[3]*Participant[13]	1.989455	2.709418	329.1	0.73	0.4633
Phase[Phase 1 - Initial Contact]*Board[3]*Participant[14]	3.4450305	2.772969	311.1	1.24	0.2150
Phase[Phase 1 - Initial Contact]*Board[3]*Participant[15]	7.4181791	3.029142	250.3	2.45	0.0150*
Phase[Phase 1 - Initial Contact]*Board[3]*Participant[16]	4.0910989	2.705524	328.2	1.51	0.1315
Phase[Phase 1 - Initial Contact]*Board[3]*Participant[18]	5.236542	2.705524	328.2	1.94	0.0538
Phase[Phase 1 - Initial Contact]*Board[3]*Participant[19]	-2.610366	2.86137	285.7	-0.91	0.3624
Phase[Phase 1 - Initial Contact]*Board[3]*Participant[20]	-9.11743	2.705524	328.2	-3.37	0.0008*
Phase[Phase 1 - Initial Contact]*Board[3]*Participant[21]	3.891914	2.707044	328.6	1.44	0.1515
Phase[Phase 1 - Initial Contact]*Board[3]*Participant[22]	-4.430518	2.705524	328.2	-1.64	0.1025
Phase[Phase 1 - Initial Contact]*Board[3]*Participant[23]	1.2738897	2.825979	351.3	0.45	0.6524
Phase[Phase 1 - Initial Contact]*Board[3]*Participant[24]	1.423047	2.766916	309.8	0.51	0.6074
Phase[Phase 1 - Initial Contact]*Board[3]*Participant[25]	-8.845165	2.861436	285.7	-3.09	0.0022*
Phase[Phase 1 - Initial Contact]*Board[4]*Participant[11]	-1.422318	2.759349	309.8	-0.52	0.6066
Phase[Phase 1 - Initial Contact]*Board[4]*Participant[12]	-1.455453	3.034965	352.5	-0.48	0.6318
Phase[Phase 1 - Initial Contact]*Board[4]*Participant[13]	1.0716983	2.763064	310.7	0.39	0.6984
Phase[Phase 1 - Initial Contact]*Board[4]*Participant[14]	6.8459415	2.823993	295.6	2.42	0.0159*
Phase[Phase 1 - Initial Contact]*Board[4]*Participant[16]	0.7548883	2.759349	309.8	0.27	0.7846
Phase[Phase 1 - Initial Contact]*Board[4]*Participant[18]	-3.109323	2.759349	309.8	-1.13	0.2607
Phase[Phase 1 - Initial Contact]*Board[4]*Participant[19]	-5.946577	2.907706	274.2	-2.05	0.0418*
Phase[Phase 1 - Initial Contact]*Board[4]*Participant[20]	-7.443986	2.759349	309.8	-2.70	0.0074*
Phase[Phase 1 - Initial Contact]*Board[4]*Participant[21]	7.1200783	2.760799	310.2	2.58	0.0104*
Phase[Phase 1 - Initial Contact]*Board[4]*Participant[22]	-1.720594	2.759349	309.8	-0.62	0.5334
Phase[Phase 1 - Initial Contact]*Board[4]*Participant[23]	4.8003532	3.034305	352.5	1.58	0.1145
Phase[Phase 1 - Initial Contact]*Board[4]*Participant[24]	0.5052904	2.817352	294.5	0.18	0.8578
Phase[Phase 1 - Initial Contact]*Board[5]*Participant[11]	-0.384482	2.757881	309.1	-0.14	0.8892
Phase[Phase 1 - Initial Contact]*Board[5]*Participant[12]	-1.190277	3.033852	352.1	-0.39	0.6951
Phase[Phase 1 - Initial Contact]*Board[5]*Participant[13]	0.0365731	2.761637	310.1	0.01	0.9894
Phase[Phase 1 - Initial Contact]*Board[5]*Participant[16]	0.92899	2.757881	309.1	0.34	0.7365
Phase[Phase 1 - Initial Contact]*Board[5]*Participant[18]	3.1109134	2.757881	309.1	1.13	0.2602
Phase[Phase 1 - Initial Contact]*Board[5]*Participant[19]	-4.563248	2.905483	273.9	-1.57	0.1174
Phase[Phase 1 - Initial Contact]*Board[5]*Participant[20]	-2.260229	2.757881	309.1	-0.82	0.4131
Phase[Phase 1 - Initial Contact]*Board[5]*Participant[21]	4.8757261	2.759347	309.5	1.77	0.0782
Phase[Phase 1 - Initial Contact]*Board[5]*Participant[22]	-2.237479	2.757881	309.1	-0.81	0.4178
Phase[Phase 1 - Initial Contact]*Board[5]*Participant[23]	8.6927271	2.764618	310.9	3.14	0.0018*

Phase[Phase 2 - Max Compression]*Board[1]*Participant[11]	3.0343562	2.789946	297.8	1.09	0.2776
Phase[Phase 2 - Max Compression]*Board[1]*Participant[12]	1.6597743	2.797153	299.6	0.59	0.5534
Phase[Phase 2 - Max Compression]*Board[1]*Participant[13]	-4.663684	2.793538	298.7	-1.67	0.0961
Phase[Phase 2 - Max Compression]*Board[1]*Participant[14]	-4.417335	2.850946	285.7	-1.55	0.1224
Phase[Phase 2 - Max Compression]*Board[1]*Participant[15]	-0.444187	3.088903	239.4	-0.14	0.8858
Phase[Phase 2 - Max Compression]*Board[1]*Participant[16]	4.3478285	2.789946	297.8	1.56	0.1202
Phase[Phase 2 - Max Compression]*Board[1]*Participant[18]	-5.044278	2.789946	297.8	-1.81	0.0716
Phase[Phase 2 - Max Compression]*Board[1]*Participant[20]	3.5770631	2.789946	297.8	1.28	0.2008
Phase[Phase 2 - Max Compression]*Board[1]*Participant[21]	8.2945646	2.791348	298.2	2.97	0.0032*
Phase[Phase 2 - Max Compression]*Board[1]*Participant[22]	2.9088263	2.789946	297.8	1.04	0.2980
Phase[Phase 2 - Max Compression]*Board[1]*Participant[23]	-9.25293	2.90183	318.7	-3.19	0.0016*
Phase[Phase 2 - Max Compression]*Board[2]*Participant[11]	4.1366941	2.760241	310	1.50	0.1350
Phase[Phase 2 - Max Compression]*Board[2]*Participant[12]	3.7985924	2.767811	311.9	1.37	0.1709
Phase[Phase 2 - Max Compression]*Board[2]*Participant[13]	1.3276951	3.032649	352.1	0.44	0.6618
Phase[Phase 2 - Max Compression]*Board[2]*Participant[14]	6.3043446	3.080225	334.5	2.05	0.0415*
Phase[Phase 2 - Max Compression]*Board[2]*Participant[16]	2.5134723	2.760241	310	0.91	0.3632
Phase[Phase 2 - Max Compression]*Board[2]*Participant[18]	-6.705887	2.760241	310	-2.43	0.0157*
Phase[Phase 2 - Max Compression]*Board[2]*Participant[20]	4.6794009	2.760241	310	1.70	0.0910
Phase[Phase 2 - Max Compression]*Board[2]*Participant[21]	2.8645036	2.870306	330.5	1.00	0.3190
Phase[Phase 2 - Max Compression]*Board[2]*Participant[22]	-3.589691	2.760241	310	-1.30	0.1944
Phase[Phase 2 - Max Compression]*Board[2]*Participant[23]	-7.515701	2.766958	311.8	-2.72	0.0070*
Phase[Phase 2 - Max Compression]*Board[2]*Participant[24]	-8.273675	2.818166	294.7	-2.94	0.0036*
Phase[Phase 2 - Max Compression]*Board[2]*Participant[25]	0.4602512	2.908487	274.3	0.16	0.8744
Phase[Phase 2 - Max Compression]*Board[3]*Participant[11]	0.377396	2.705524	328.2	0.14	0.8891
Phase[Phase 2 - Max Compression]*Board[3]*Participant[12]	2.8032417	2.713452	330.2	1.03	0.3023
Phase[Phase 2 - Max Compression]*Board[3]*Participant[13]	0.6257047	2.709418	329.1	0.23	0.8175
Phase[Phase 2 - Max Compression]*Board[3]*Participant[14]	5.1907209	2.772969	311.1	1.87	0.0622
Phase[Phase 2 - Max Compression]*Board[3]*Participant[15]	0.008294	3.029142	250.3	0.00	0.9978
Phase[Phase 2 - Max Compression]*Board[3]*Participant[16]	0.136148	2.705524	328.2	0.05	0.9599
Phase[Phase 2 - Max Compression]*Board[3]*Participant[18]	0.5906043	2.705524	328.2	0.22	0.8273
Phase[Phase 2 - Max Compression]*Board[3]*Participant[19]	8.4636464	2.86137	285.7	2.96	0.0034*
Phase[Phase 2 - Max Compression]*Board[3]*Participant[20]	-2.362085	2.705524	328.2	-0.87	0.3833
Phase[Phase 2 - Max Compression]*Board[3]*Participant[21]	-1.445011	2.707044	328.6	-0.53	0.5938
Phase[Phase 2 - Max Compression]*Board[3]*Participant[22]	-4.585042	2.705524	328.2	-1.69	0.0911
Phase[Phase 2 - Max Compression]*Board[3]*Participant[23]	-5.181895	2.825979	351.3	-1.83	0.0675
Phase[Phase 2 - Max Compression]*Board[3]*Participant[24]	-7.023318	2.766916	309.8	-2.54	0.0116*
Phase[Phase 2 - Max Compression]*Board[3]*Participant[25]	2.4015945	2.861436	285.7	0.84	0.4020
Phase[Phase 2 - Max Compression]*Board[4]*Participant[11]	1.3765313	2.759349	309.8	0.50	0.6182
Phase[Phase 2 - Max Compression]*Board[4]*Participant[12]	2.3771953	3.034965	352.5	0.78	0.4340
Phase[Phase 2 - Max Compression]*Board[4]*Participant[13]	0.2428663	2.763064	310.7	0.09	0.9300
Phase[Phase 2 - Max Compression]*Board[4]*Participant[14]	3.5986555	2.823993	295.6	1.27	0.2036
Phase[Phase 2 - Max Compression]*Board[4]*Participant[16]	5.9721911	2.759349	309.8	2.16	0.0312*
Phase[Phase 2 - Max Compression]*Board[4]*Participant[18]	-2.210688	2.759349	309.8	-0.80	0.4237
Phase[Phase 2 - Max Compression]*Board[4]*Participant[19]	5.144114	2.907706	274.2	1.77	0.0780
Phase[Phase 2 - Max Compression]*Board[4]*Participant[20]	-2.572176	2.759349	309.8	-0.93	0.3520
Phase[Phase 2 - Max Compression]*Board[4]*Participant[21]	4.2182858	2.760799	310.2	1.53	0.1276
Phase[Phase 2 - Max Compression]*Board[4]*Participant[22]	0.2145211	2.759349	309.8	0.08	0.9381
Phase[Phase 2 - Max Compression]*Board[4]*Participant[23]	-4.563711	3.034305	352.5	-1.50	0.1335
Phase[Phase 2 - Max Compression]*Board[4]*Participant[24]	-13.79778	2.817352	294.5	-4.90	<.0001*
Phase[Phase 2 - Max Compression]*Board[5]*Participant[11]	-0.075244	2.757881	309.1	-0.03	0.9783
Phase[Phase 2 - Max Compression]*Board[5]*Participant[12]	1.6269781	3.033852	352.1	0.54	0.5921
Phase[Phase 2 - Max Compression]*Board[5]*Participant[13]	-0.517922	2.761637	310.1	-0.19	0.8514
Phase[Phase 2 - Max Compression]*Board[5]*Participant[16]	5.2114031	2.757881	309.1	1.89	0.0597
Phase[Phase 2 - Max Compression]*Board[5]*Participant[18]	-3.144223	2.757881	309.1	-1.14	0.2551
Phase[Phase 2 - Max Compression]*Board[5]*Participant[19]	1.9648721	2.905483	273.9	0.68	0.4994
Phase[Phase 2 - Max Compression]*Board[5]*Participant[20]	1.1584502	2.757881	309.1	0.42	0.6747
Phase[Phase 2 - Max Compression]*Board[5]*Participant[21]	-1.033917	2.759347	309.5	-0.37	0.7081
Phase[Phase 2 - Max Compression]*Board[5]*Participant[22]	-0.200773	2.757881	309.1	-0.07	0.9420

Phase[Phase 2 - Max Compression]*Board[5]*Participant[23]	-0.326356	2.764618	310.9	-0.12	0.9061
Phase[Phase 2 - Max Compression]*Board[5]*Participant[24]	-7.821451	2.81471	294.2	-2.78	0.0058*
Phase[Phase 2 - Max Compression]*Board[5]*Participant[25]	3.158182	2.905434	273.9	1.09	0.2780
Phase[Phase 3 - Take-off]*Board[1]*Participant[11]	4.5793765	2.789946	297.8	1.64	0.1018
Phase[Phase 3 - Take-off]*Board[1]*Participant[12]	-4.223314	2.797153	299.6	-1.51	0.1321
Phase[Phase 3 - Take-off]*Board[1]*Participant[13]	-2.25493	2.793538	298.7	-0.81	0.4202
Phase[Phase 3 - Take-off]*Board[1]*Participant[14]	-10.12768	2.850946	285.7	-3.55	0.0004*
Phase[Phase 3 - Take-off]*Board[1]*Participant[15]	-0.79938	3.088903	239.4	-0.26	0.7960
Phase[Phase 3 - Take-off]*Board[1]*Participant[16]	-4.12646	2.789946	297.8	-1.48	0.1402
Phase[Phase 3 - Take-off]*Board[1]*Participant[18]	3.0651177	2.789946	297.8	1.10	0.2728
Phase[Phase 3 - Take-off]*Board[1]*Participant[20]	4.9493367	2.789946	297.8	1.77	0.0771
Phase[Phase 3 - Take-off]*Board[1]*Participant[21]	1.8932364	2.791348	298.2	0.68	0.4981
Phase[Phase 3 - Take-off]*Board[1]*Participant[22]	13.091182	2.789946	297.8	4.69	<.0001*
Phase[Phase 3 - Take-off]*Board[1]*Participant[23]	-6.046489	2.90183	318.7	-2.08	0.0380*
Phase[Phase 3 - Take-off]*Board[2]*Participant[11]	-0.158125	2.760241	310	-0.06	0.9544
Phase[Phase 3 - Take-off]*Board[2]*Participant[12]	-2.569187	2.767811	311.9	-0.93	0.3540
Phase[Phase 3 - Take-off]*Board[2]*Participant[13]	-3.770766	3.032649	352.1	-1.24	0.2146
Phase[Phase 3 - Take-off]*Board[2]*Participant[14]	-2.753131	3.080225	334.5	-0.89	0.3721
Phase[Phase 3 - Take-off]*Board[2]*Participant[16]	-6.963748	2.760241	310	-2.52	0.0121*
Phase[Phase 3 - Take-off]*Board[2]*Participant[18]	0.7460705	2.760241	310	0.27	0.7871
Phase[Phase 3 - Take-off]*Board[2]*Participant[20]	4.5305033	2.760241	310	1.64	0.1017
Phase[Phase 3 - Take-off]*Board[2]*Participant[21]	-6.34226	2.870306	330.5	-2.21	0.0278*
Phase[Phase 3 - Take-off]*Board[2]*Participant[22]	0.2345856	2.760241	310	0.08	0.9323
Phase[Phase 3 - Take-off]*Board[2]*Participant[23]	2.3547099	2.766958	311.8	0.85	0.3954
Phase[Phase 3 - Take-off]*Board[2]*Participant[24]	6.9518846	2.818166	294.7	2.47	0.0142*
Phase[Phase 3 - Take-off]*Board[2]*Participant[25]	7.739462	2.908487	274.3	2.66	0.0083*
Phase[Phase 3 - Take-off]*Board[3]*Participant[11]	-2.894342	2.705524	328.2	-1.07	0.2855
Phase[Phase 3 - Take-off]*Board[3]*Participant[12]	3.1591847	2.713452	330.2	1.16	0.2452
Phase[Phase 3 - Take-off]*Board[3]*Participant[13]	3.4001016	2.709418	329.1	1.25	0.2104
Phase[Phase 3 - Take-off]*Board[3]*Participant[14]	-2.572431	2.772969	311.1	-0.93	0.3543
Phase[Phase 3 - Take-off]*Board[3]*Participant[15]	-5.854644	3.029142	250.3	-1.93	0.0544
Phase[Phase 3 - Take-off]*Board[3]*Participant[16]	-6.245031	2.705524	328.2	-2.31	0.0216*
Phase[Phase 3 - Take-off]*Board[3]*Participant[18]	1.6375341	2.705524	328.2	0.61	0.5454
Phase[Phase 3 - Take-off]*Board[3]*Participant[19]	-3.27268	2.86137	285.7	-1.14	0.2537
Phase[Phase 3 - Take-off]*Board[3]*Participant[20]	0.2395657	2.705524	328.2	0.09	0.9295
Phase[Phase 3 - Take-off]*Board[3]*Participant[21]	-8.689923	2.707044	328.6	-3.21	0.0015*
Phase[Phase 3 - Take-off]*Board[3]*Participant[22]	1.8170361	2.705524	328.2	0.67	0.5023
Phase[Phase 3 - Take-off]*Board[3]*Participant[23]	4.1833287	2.825979	351.3	1.48	0.1397
Phase[Phase 3 - Take-off]*Board[3]*Participant[24]	8.534335	2.766916	309.8	3.08	0.0022*
Phase[Phase 3 - Take-off]*Board[3]*Participant[25]	6.5579651	2.861436	285.7	2.29	0.0226*
Phase[Phase 3 - Take-off]*Board[4]*Participant[11]	0.8440855	2.759349	309.8	0.31	0.7599
Phase[Phase 3 - Take-off]*Board[4]*Participant[12]	-2.545004	3.034965	352.5	-0.84	0.4023
Phase[Phase 3 - Take-off]*Board[4]*Participant[13]	-2.017047	2.763064	310.7	-0.73	0.4659
Phase[Phase 3 - Take-off]*Board[4]*Participant[14]	-5.916619	2.823993	295.6	-2.10	0.0370*
Phase[Phase 3 - Take-off]*Board[4]*Participant[16]	-5.961537	2.759349	309.8	-2.16	0.0315*
Phase[Phase 3 - Take-off]*Board[4]*Participant[18]	-1.188413	2.759349	309.8	-0.43	0.6670
Phase[Phase 3 - Take-off]*Board[4]*Participant[19]	3.2296946	2.907706	274.2	1.11	0.2677
Phase[Phase 3 - Take-off]*Board[4]*Participant[20]	4.1507397	2.759349	309.8	1.50	0.1335
Phase[Phase 3 - Take-off]*Board[4]*Participant[21]	-5.642482	2.760799	310.2	-2.04	0.0418*
Phase[Phase 3 - Take-off]*Board[4]*Participant[22]	4.5189832	2.759349	309.8	1.64	0.1025
Phase[Phase 3 - Take-off]*Board[4]*Participant[23]	2.9189989	3.034305	352.5	0.96	0.3367
Phase[Phase 3 - Take-off]*Board[4]*Participant[24]	7.6086012	2.817352	294.5	2.70	0.0073*
Phase[Phase 3 - Take-off]*Board[5]*Participant[11]	-0.139245	2.757881	309.1	-0.05	0.9598
Phase[Phase 3 - Take-off]*Board[5]*Participant[12]	-3.02415	3.033852	352.1	-1.00	0.3195
Phase[Phase 3 - Take-off]*Board[5]*Participant[13]	0.4545567	2.761637	310.1	0.16	0.8694
Phase[Phase 3 - Take-off]*Board[5]*Participant[16]	-6.944868	2.757881	309.1	-2.52	0.0123*

Phase[Phase 3 - Take-off]*Board[5]*Participant[18]	-3.553718	2.757881	309.1	-1.29	0.1985
Phase[Phase 3 - Take-off]*Board[5]*Participant[19]	0.0006565	2.905483	273.9	0.00	0.9998
Phase[Phase 3 - Take-off]*Board[5]*Participant[20]	5.0676226	2.757881	309.1	1.84	0.0671
Phase[Phase 3 - Take-off]*Board[5]*Participant[21]	-6.79856	2.759347	309.5	-2.46	0.0143*
Phase[Phase 3 - Take-off]*Board[5]*Participant[22]	0.4262116	2.757881	309.1	0.15	0.8773
Phase[Phase 3 - Take-off]*Board[5]*Participant[23]	3.2373227	2.764618	310.9	1.17	0.2425
Phase[Phase 3 - Take-off]*Board[5]*Participant[24]	5.7615369	2.81471	294.2	2.05	0.0416*
Phase[Phase 3 - Take-off]*Board[5]*Participant[25]	5.5126341	2.905434	273.9	1.90	0.0588

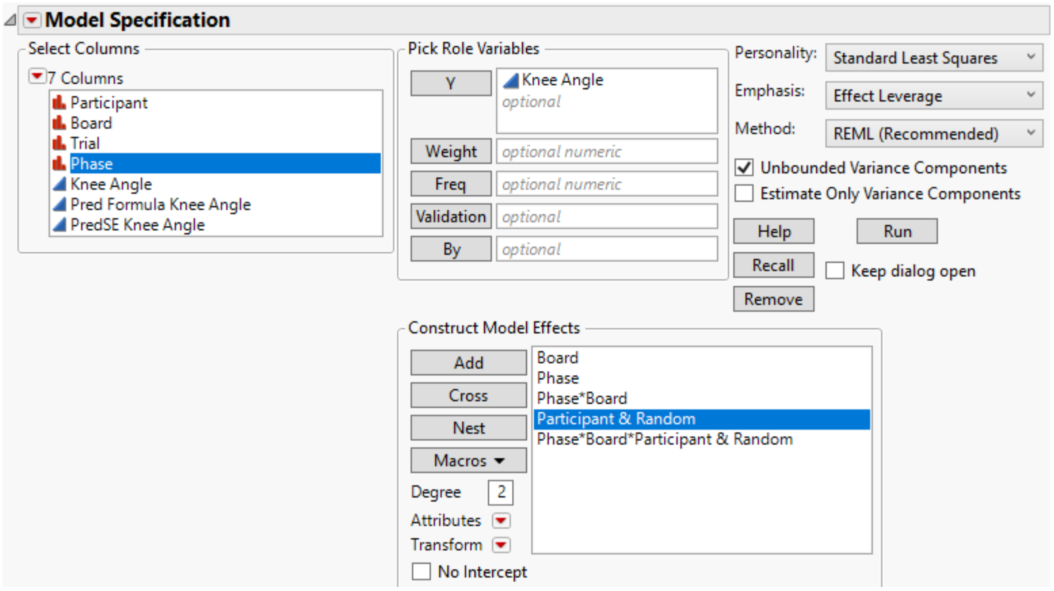


Figure 1D. JMP Analysis – 5 vault boards x3 contact phases x14 participants within-factor repeated measure ANOVA

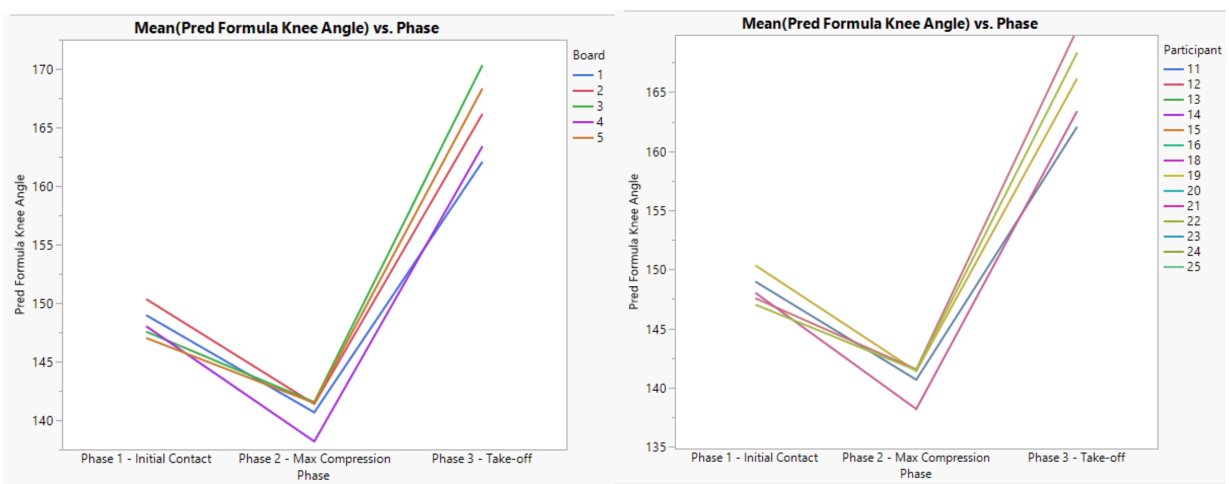


Figure 2D. Mean knee angle across vault board phases (across vault boards, across participants)

Table 1D. Average knee angle for 5 vault timers across phases per participant and vault board

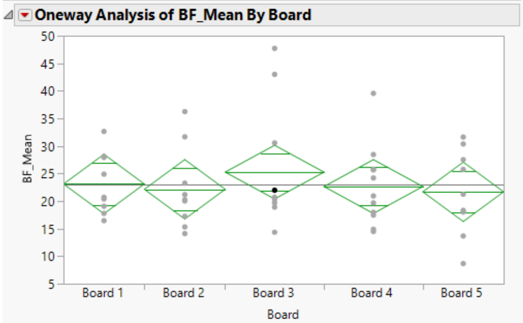
Participant	Vault Board	Average Knee Angle for 5 vault timers (degrees) Phase 1 Initial Contact	Phase 2 Maximum Compression	Phase 3 Take-Off
11	1	146.60	142.60	165.80
	2	141.00	144.60	164.40
	3	142.00	140.40	165.40
	4	144.80	138.20	162.80
	5	145.00	139.80	166.60
12	1	143.80	139.40	154.00
	2	145.40	142.60	160.00
	3	144.00	141.60	170.80
	4	143.00	138.00	157.00
	5	142.33	140.33	161.33
13	1	139.20	132.20	156.40
	2	152.00	140.00	158.33
	3	146.80	139.20	171.20
	4	146.20	135.40	158.00
	5	144.00	137.80	165.80
14	1	139.20	134.20	149.00
	2	157.00	148.00	161.33
	3	150.20	146.20	166.00
	4	154.60	141.00	155.20
15	1	150.40	141.00	162.00
	3	157.00	142.40	164.40
16	1	156.60	148.00	159.60
	2	157.20	146.60	160.40
	3	154.60	144.00	165.40
	4	151.20	147.40	158.80
	5	150.40	149.80	162.60
18	1	157.20	135.80	166.60
	2	157.40	134.60	168.00
	3	154.60	143.20	173.20
	4	145.40	136.60	163.00
	5	151.60	138.80	165.20
19	3	147.00	153.80	169.00
	4	143.60	146.60	169.60
	5	144.20	146.20	170.80
20	1	149.20	148.00	171.00

Table 1D. (continued)

	2	154.80	150.00	174.60
	3	140.20	142.00	173.80
	4	142.60	138.40	171.40
	5	147.60	146.00	177.40
21	1	169.00	164.20	178.20
	2	170.50	158.75	172.50
	3	166.00	153.80	174.20
	4	170.20	157.00	170.80
	5	166.60	154.20	174.40
22	1	145.60	143.00	176.20
	2	143.00	136.20	165.40
	3	141.40	135.20	171.40
	4	145.00	137.40	167.60
	5	143.40	140.20	167.80
23	1	147.25	127.50	152.75
	2	151.80	130.60	166.80
	3	147.00	133.25	173.25
	4	152.00	130.33	165.00
	5	155.00	139.00	170.00
24	2	136.20	121.40	163.80
	3	138.80	123.00	169.80
	4	138.20	111.80	161.80
	5	135.60	122.00	164.60
25	2	135.80	141.00	174.20
	3	136.40	143.40	177.00
	5	139.00	144.20	173.80
Average		148.42	140.79	166.35

APPENDIX E. EMG ANALYSIS

Oneway Analysis of BF_Mean By Board



Oneway Anova

Summary of Fit

Rsquare	0.027384
Adj Rsquare	-0.06104
Root Mean Square Error	8.024293
Mean of Response	23.05598
Observations (or Sum Wgts)	49

Analysis of Variance

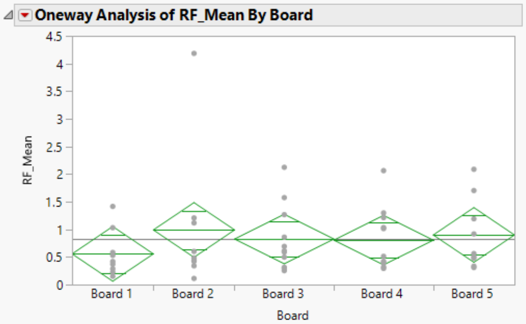
Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Board	4	79.7676	19.9419	0.3097	0.8699
Error	44	2833.1280	64.3893		
C. Total	48	2912.8956			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Board 1	9	23.1145	2.6748	17.724	28.505
Board 2	9	22.1547	2.6748	16.764	27.545
Board 3	11	25.2688	2.4194	20.393	30.145
Board 4	11	22.6484	2.4194	17.772	27.524
Board 5	9	21.6923	2.6748	16.302	27.083

Std Error uses a pooled estimate of error variance

Oneway Analysis of RF_Mean By Board



Oneway Anova

Summary of Fit

Rsquare	0.037834
Adj Rsquare	-0.04964
Root Mean Square Error	0.737006
Mean of Response	0.815945
Observations (or Sum Wgts)	49

Analysis of Variance

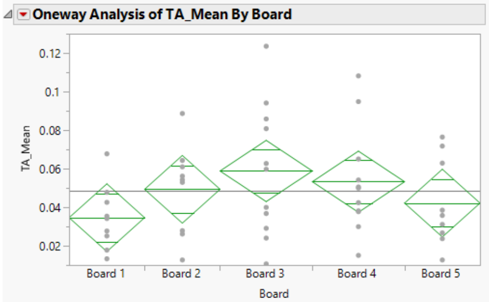
Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Board	4	0.939787	0.234947	0.4325	0.7843
Error	44	23.899843	0.543178		
C. Total	48	24.839630			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Board 1	9	0.557527	0.24567	0.06241	1.0526
Board 2	9	0.990386	0.24567	0.49527	1.4855
Board 3	11	0.826092	0.22222	0.37825	1.2739
Board 4	11	0.806202	0.22222	0.35836	1.2540
Board 5	9	0.899428	0.24567	0.40432	1.3945

Std Error uses a pooled estimate of error variance

Oneway Analysis of TA_Mean By Board



Oneway Anova

Summary of Fit

Rsquare	0.104934
Adj Rsquare	0.023564
Root Mean Square Error	0.026138
Mean of Response	0.048333
Observations (or Sum Wgts)	49

Analysis of Variance

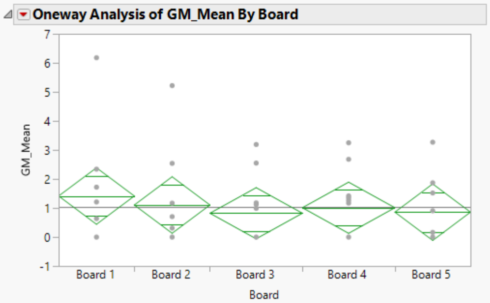
Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Board	4	0.00352430	0.000881	1.2896	0.2887
Error	44	0.03006165	0.000683		
C. Total	48	0.03358596			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Board 1	9	0.034621	0.00871	0.01706	0.05218
Board 2	9	0.049327	0.00871	0.03177	0.06689
Board 3	11	0.058838	0.00788	0.04295	0.07472
Board 4	11	0.053271	0.00788	0.03739	0.06915
Board 5	9	0.042177	0.00871	0.02462	0.05974

Std Error uses a pooled estimate of error variance

Oneway Analysis of GM_Mean By Board



Oneway Anova

Summary of Fit

Rsquare	0.022511
Adj Rsquare	-0.06635
Root Mean Square Error	1.449443
Mean of Response	1.032136
Observations (or Sum Wgts)	49

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Board	4	2.128861	0.53222	0.2533	0.9061
Error	44	92.438964	2.10089		
C. Total	48	94.567825			

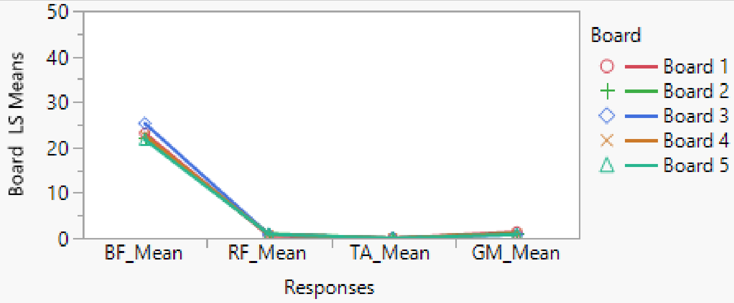
Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Board 1	9	1.41478	0.48315	0.4411	2.3885
Board 2	9	1.10518	0.48315	0.1315	2.0789
Board 3	11	0.82164	0.43702	-0.0591	1.7024
Board 4	11	1.01182	0.43702	0.1311	1.8926
Board 5	9	0.85856	0.48315	-0.1152	1.8323

Std Error uses a pooled estimate of error variance

Figure 1E. JMP Analysis – One-way repeated measure ANOVA (mean peak height) (top left/right- biceps femoris/rectus femoris, bottom left/right – tibialis anterior/gastrocnemius medialis)

Board



Board

	BF_Mean	RF_Mean	TA_Mean	GM_Mean
Board 1	23.1144724	0.55752667	0.03462076	1.41477778
Board 2	22.154722	0.99038563	0.04932732	1.10518222
Board 3	25.2688202	0.82609224	0.05883754	0.82164
Board 4	22.6483997	0.80620179	0.05327143	1.01181818
Board 5	21.6923343	0.89942787	0.04217664	0.85855556

All Between

Test	Value	Exact F	NumDF	DenDF	Prob>F
F Test	0.0244646	0.2691	4	44	0.8963

Intercept

Test	Value	Exact F	NumDF	DenDF	Prob>F
F Test	10.448014	459.7126	1	44	<.0001*

Board

Test	Value	Exact F	NumDF	DenDF	Prob>F
F Test	0.0244646	0.2691	4	44	0.8963

Within Subjects

Contrast

M Matrix

M-transformed Parameter Estimates

Sphericity Test

Mauchly Criterion	0.0036898
ChiSquare	239.33779
DF	5
Prob >Chisq	1.065e-49

All Within Interactions

Test	Value	Approx. F	NumDF	DenDF	Prob>F
Wilks' Lambda	0.9156484	0.3144	12	111.41	0.9856
Pillai's Trace	0.0862952	0.3258	12	132	0.9835
Hotelling-Lawley	0.0900083	0.3089	12	69.305	0.9857
Roy's Max Root	0.0539951	0.5939	4	44	0.6688
Univar unadj Epsilon=	1	0.3218	12	132	0.9843
Univar G-G Epsilon=	0.3568928	0.3218	4.2827	47.11	0.8733
Univar H-F Epsilon=	0.391832	0.3218	4.702	51.722	0.8884

Muscle

Test	Value	Exact F	NumDF	DenDF	Prob>F
F Test	12.465767	174.5207	3	42	<.0001*
Univar unadj Epsilon=	1	358.8495	3	132	<.0001*
Univar G-G Epsilon=	0.3568928	358.8495	1.0707	47.11	<.0001*
Univar H-F Epsilon=	0.391832	358.8495	1.1755	51.722	<.0001*

Muscle*Board

Test	Value	Approx. F	NumDF	DenDF	Prob>F
Wilks' Lambda	0.9156484	0.3144	12	111.41	0.9856
Pillai's Trace	0.0862952	0.3258	12	132	0.9835
Hotelling-Lawley	0.0900083	0.3089	12	69.305	0.9857
Roy's Max Root	0.0539951	0.5939	4	44	0.6688
Univar unadj Epsilon=	1	0.3218	12	132	0.9843
Univar G-G Epsilon=	0.3568928	0.3218	4.2827	47.11	0.8733
Univar H-F Epsilon=	0.391832	0.3218	4.702	51.722	0.8884

Figure 2E. 5 vault board x4 muscles x14 participants within-factor repeated measure MANOVA

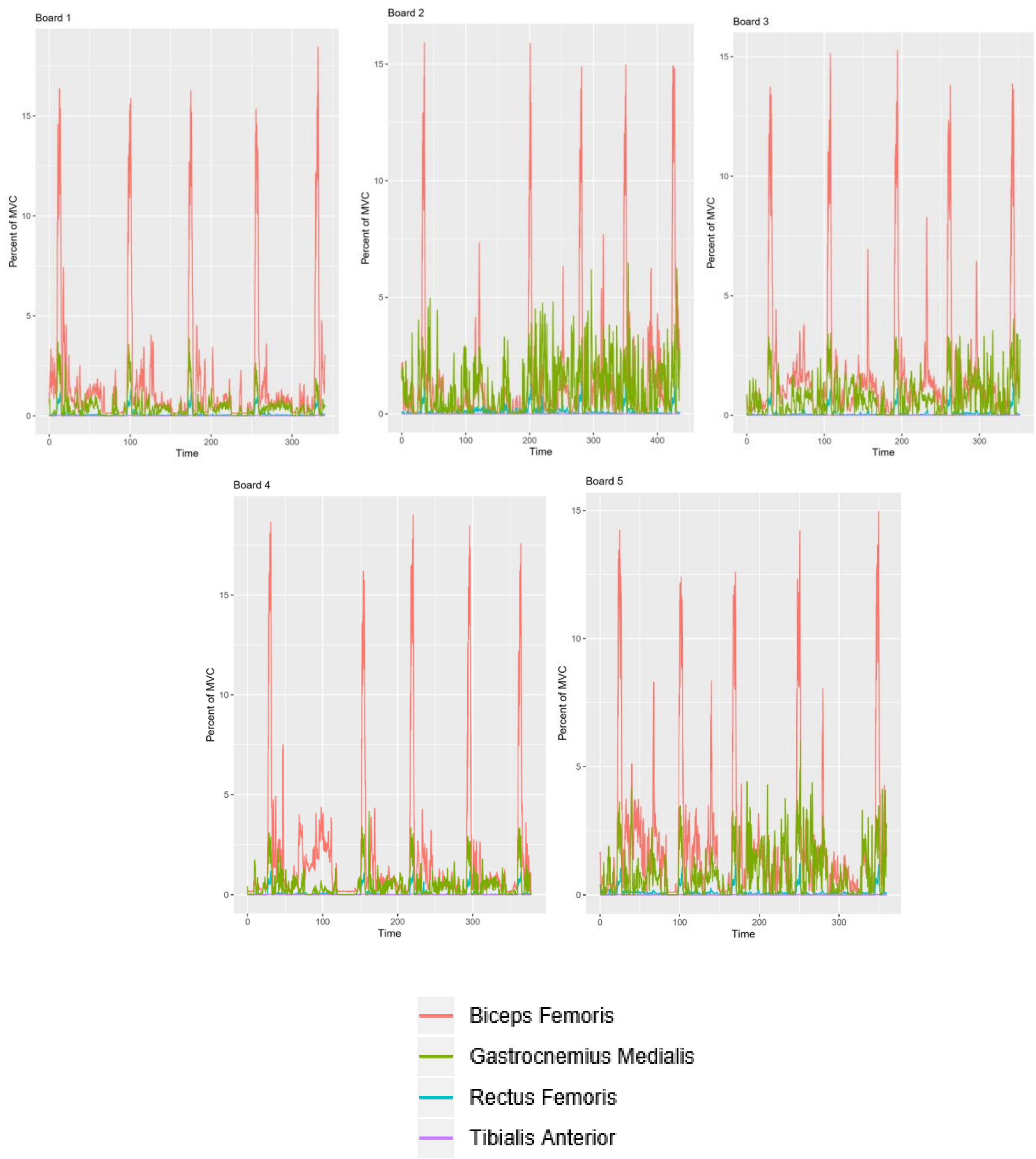


Figure 3E. EMG profiles - Participant 11

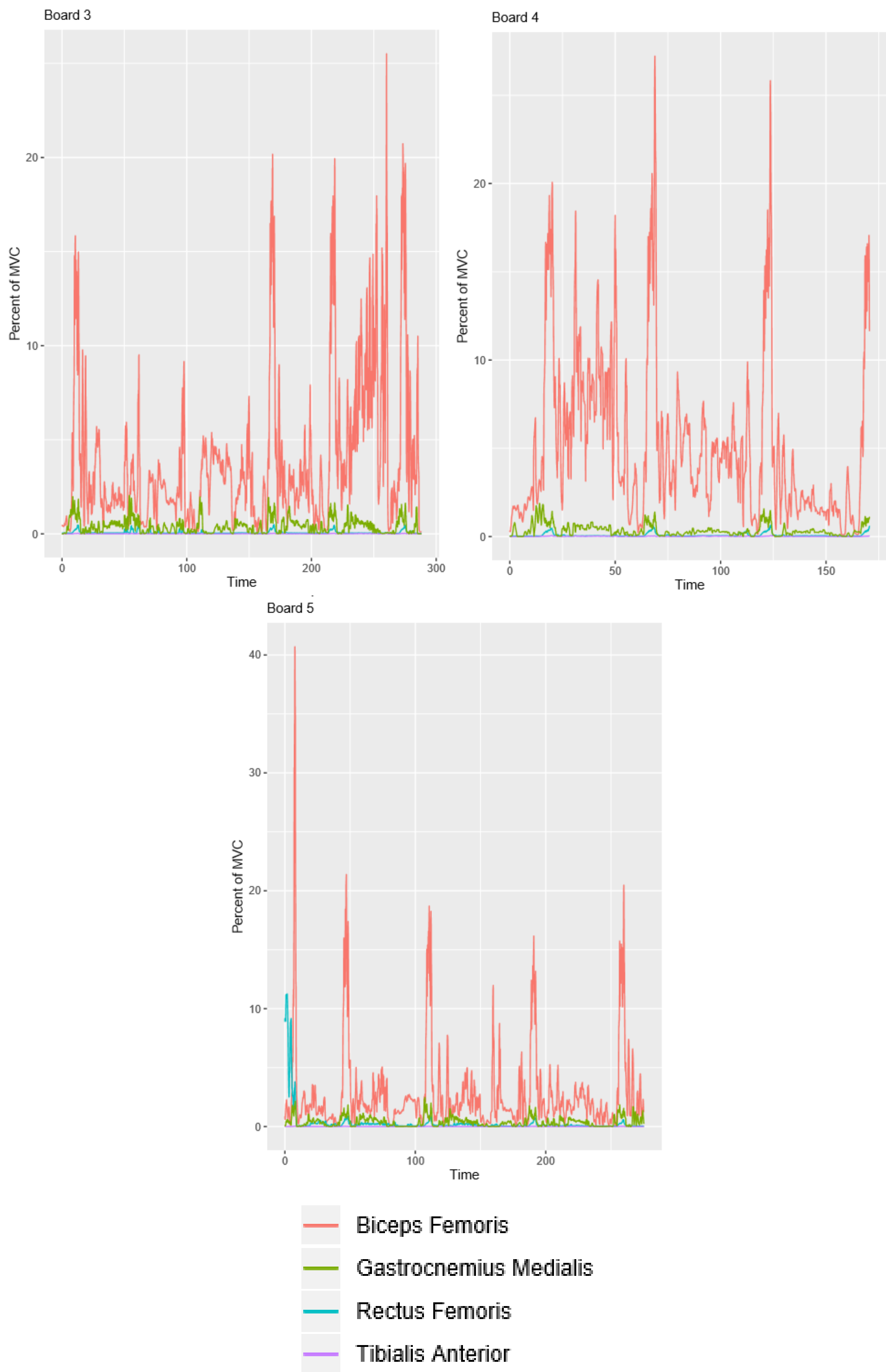


Figure 4E. EMG profiles - Participant 12

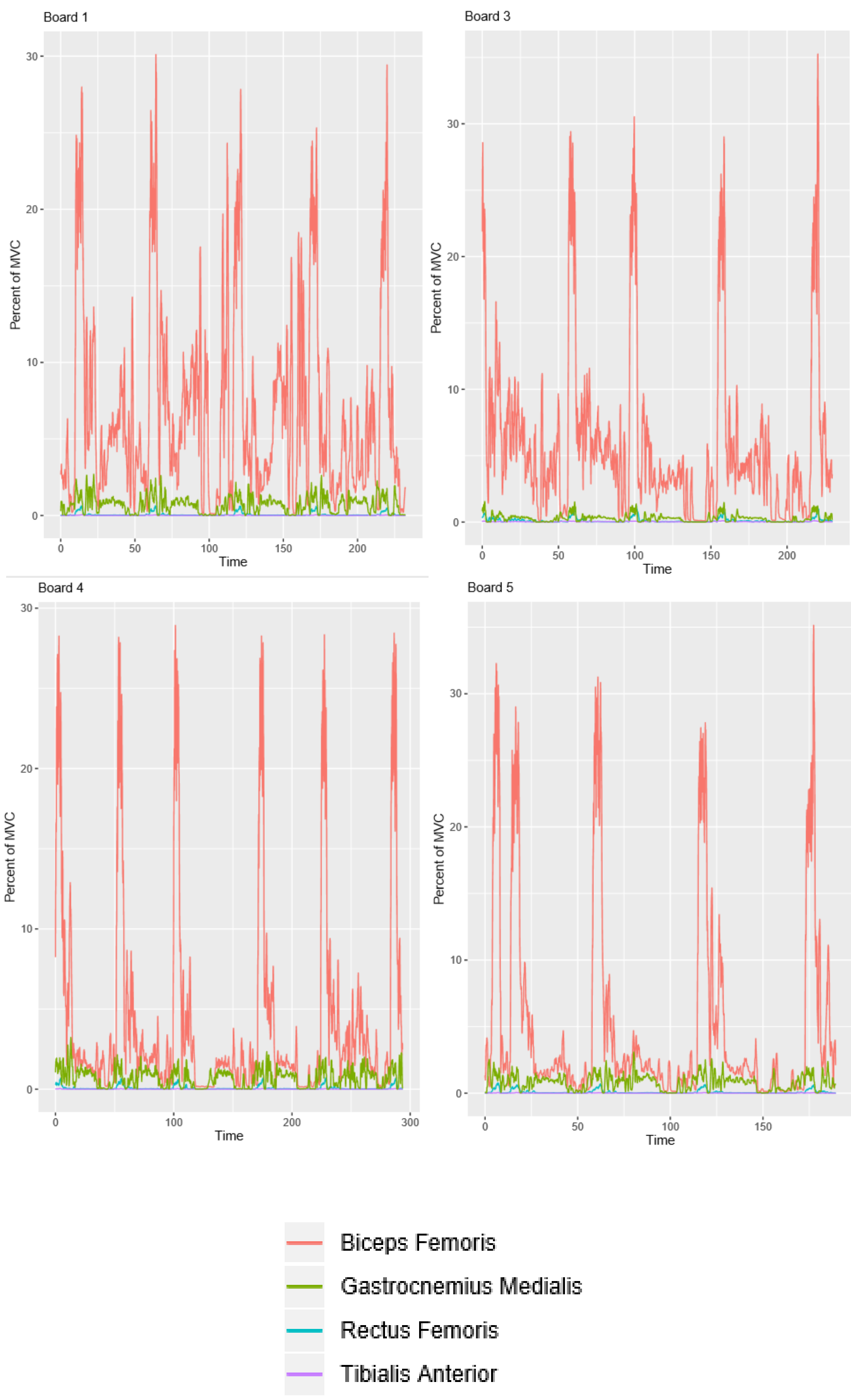


Figure 5E. EMG profiles - Participant 13

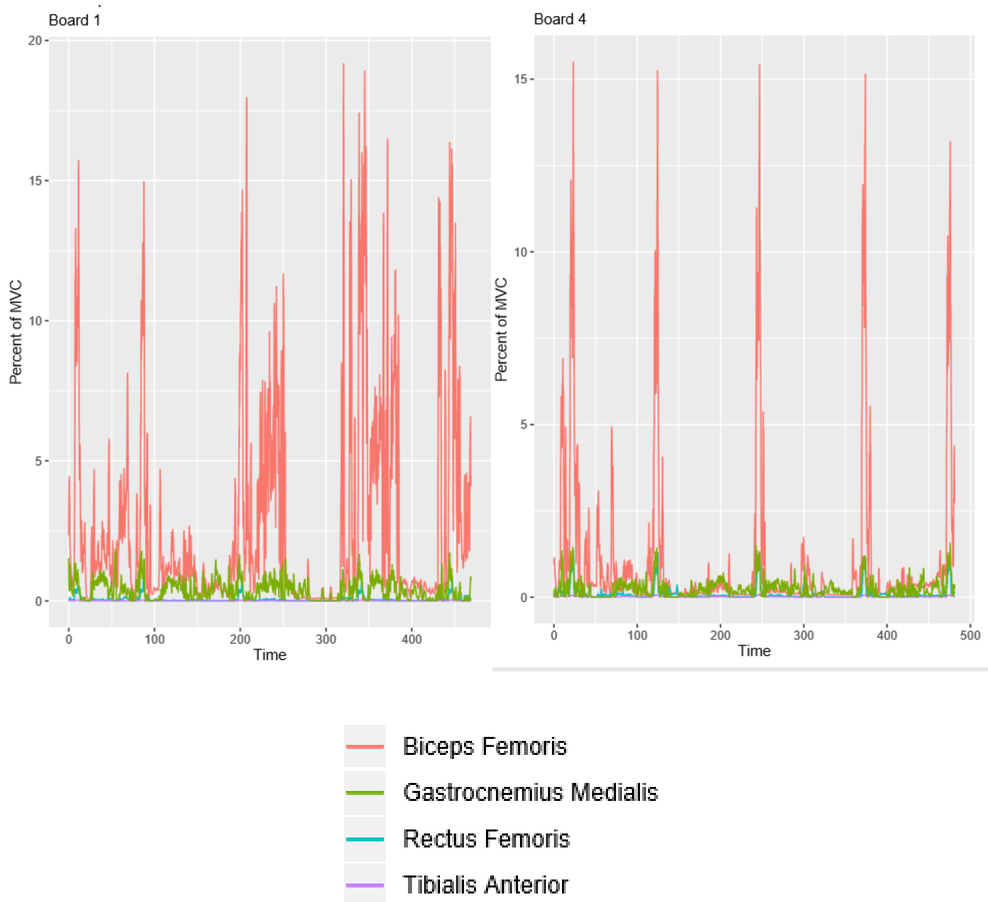


Figure 6E. EMG profiles - Participant 14

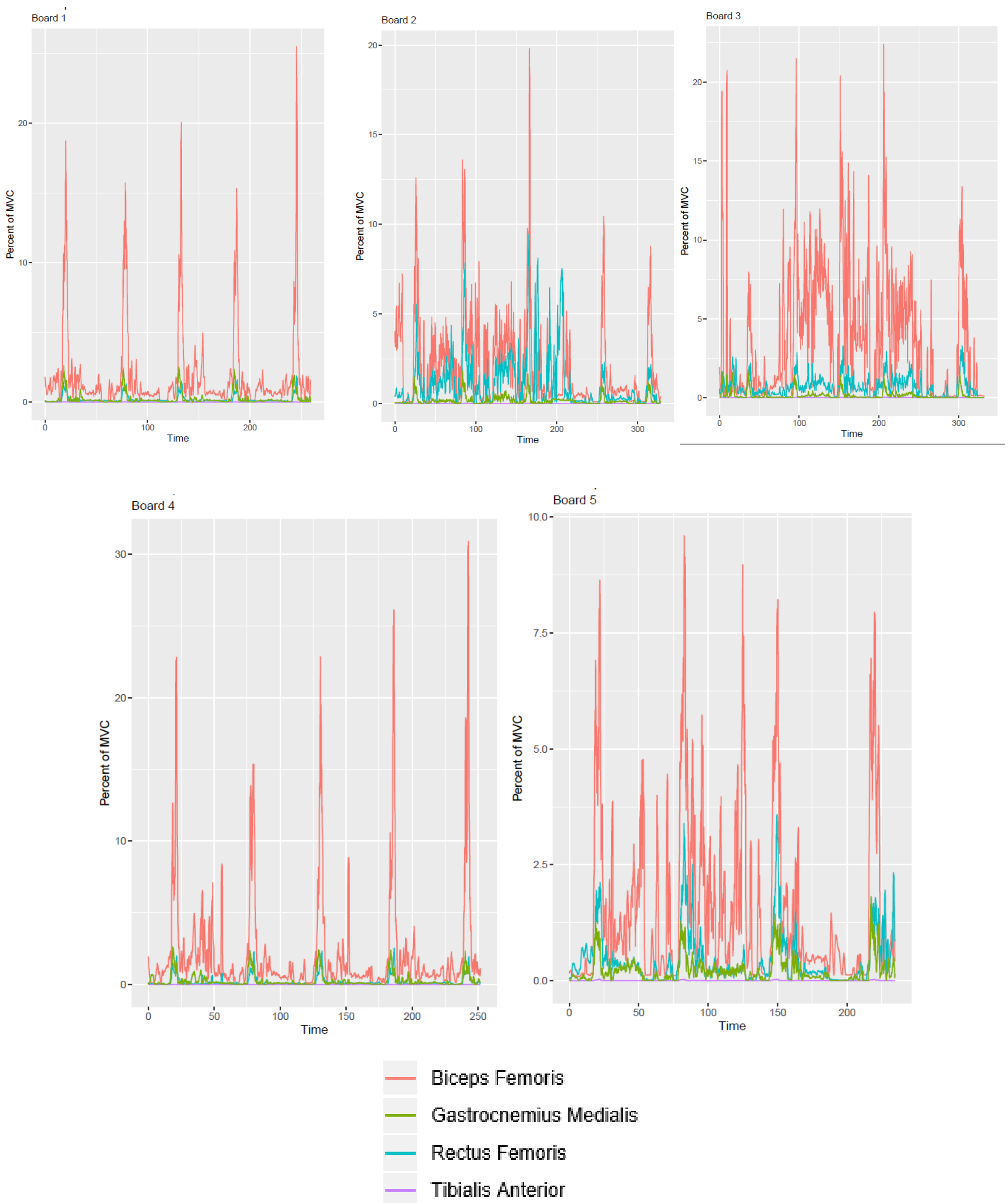


Figure 7E. EMG profiles - Participant 16

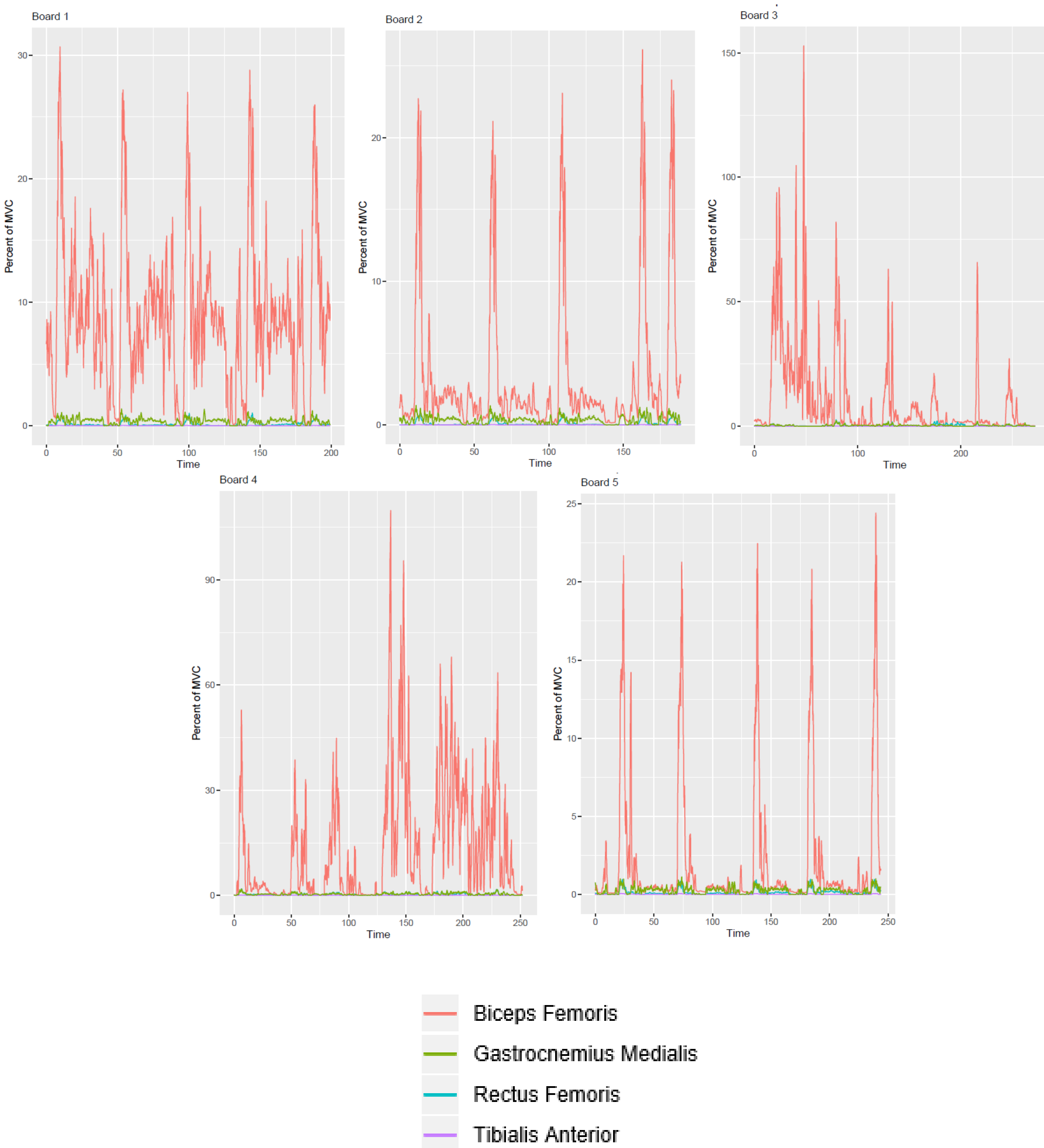


Figure 8E. EMG profiles - Participant 18

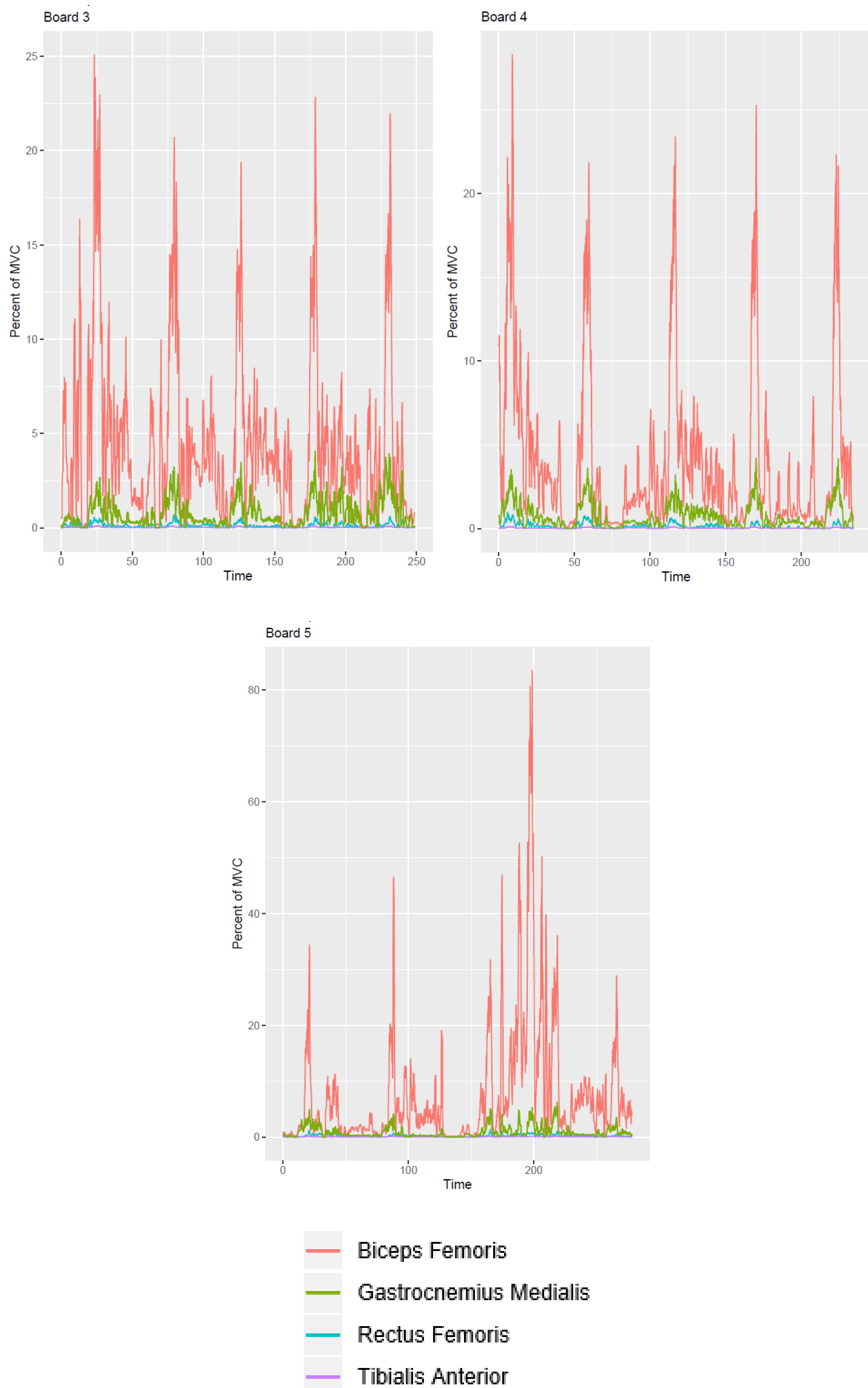


Figure 9E. EMG profiles - Participant 19

Participant 20

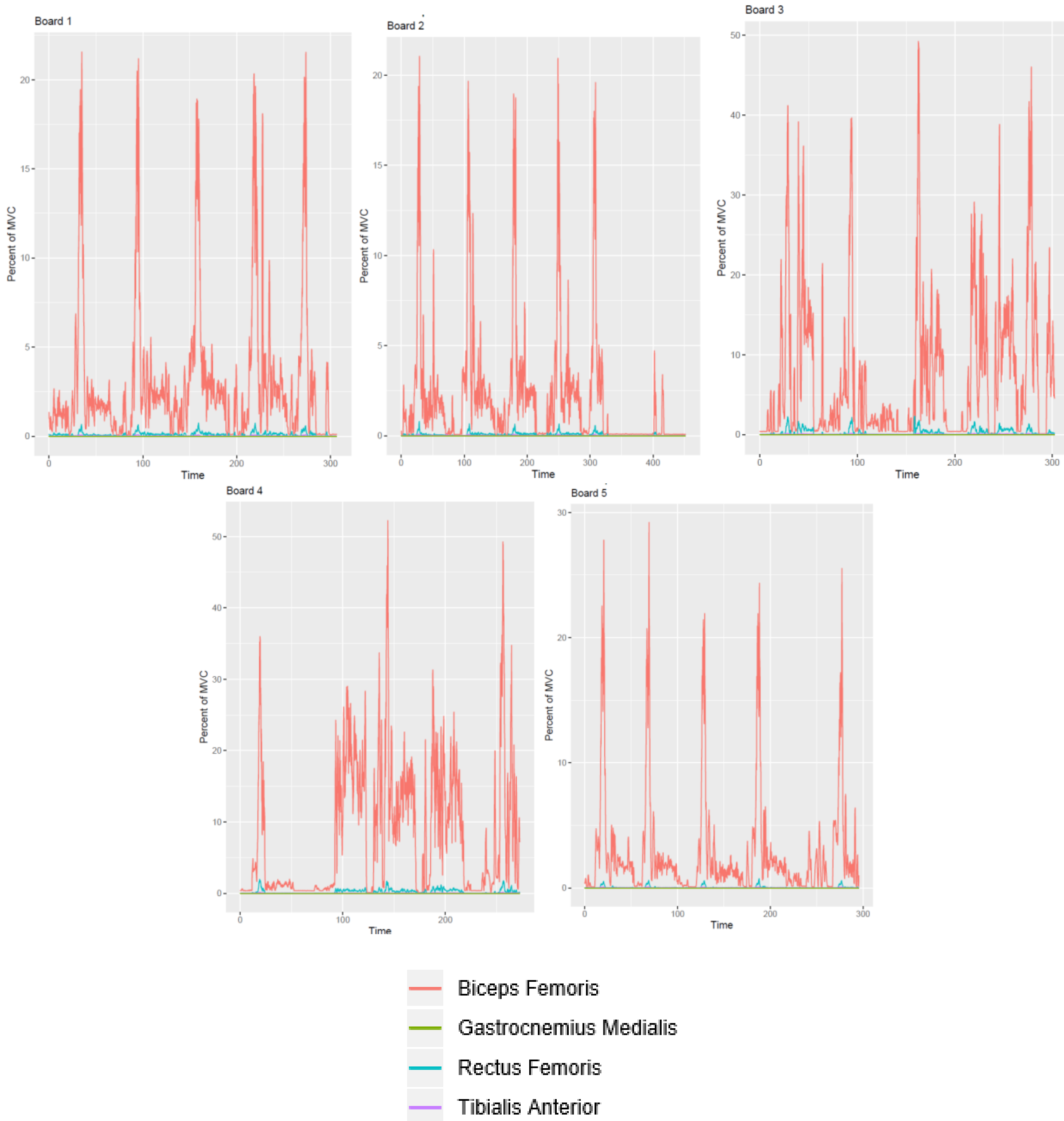


Figure 10E. EMG profiles - Participant 20

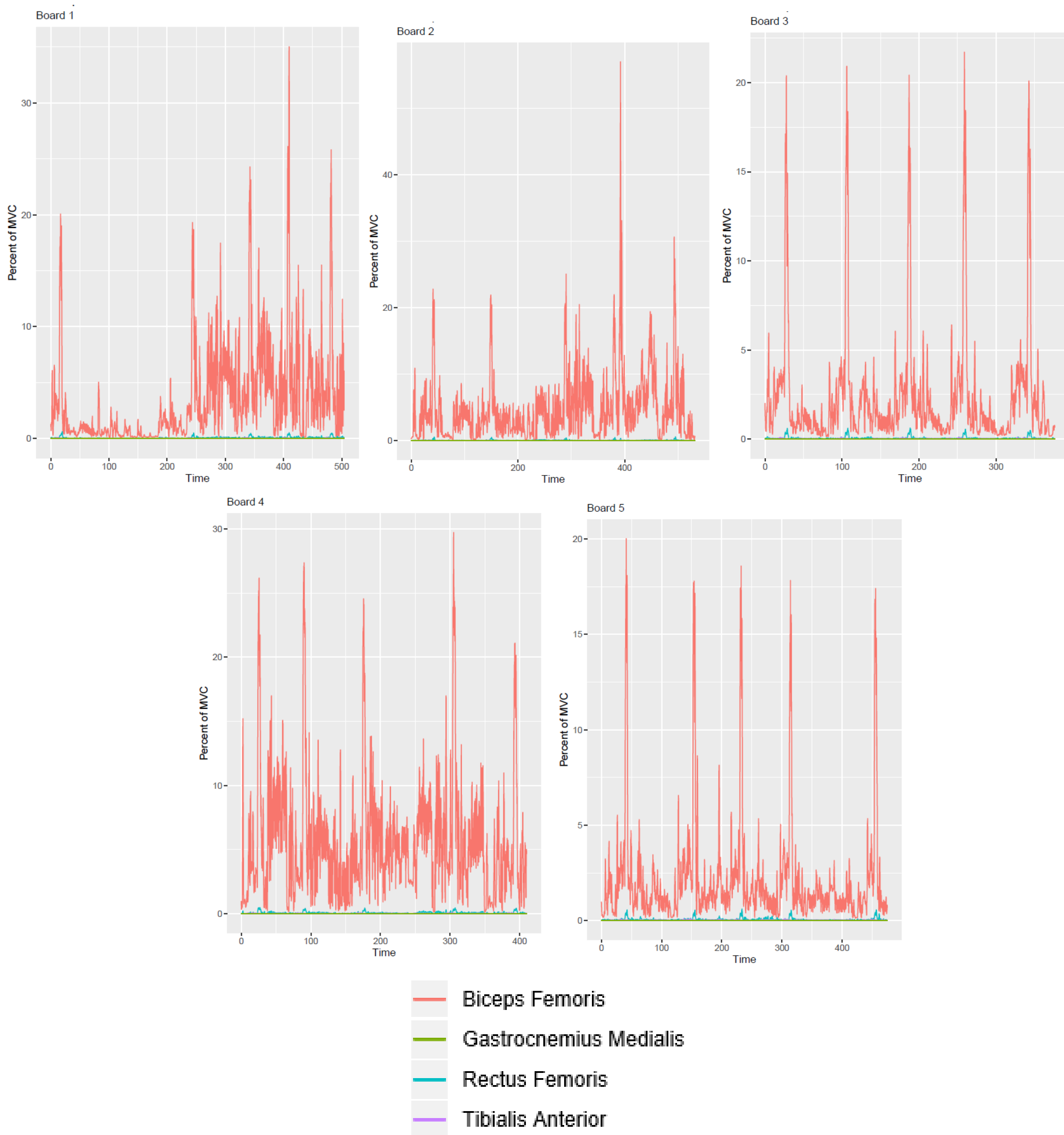


Figure 11E. EMG profiles - Participant 21

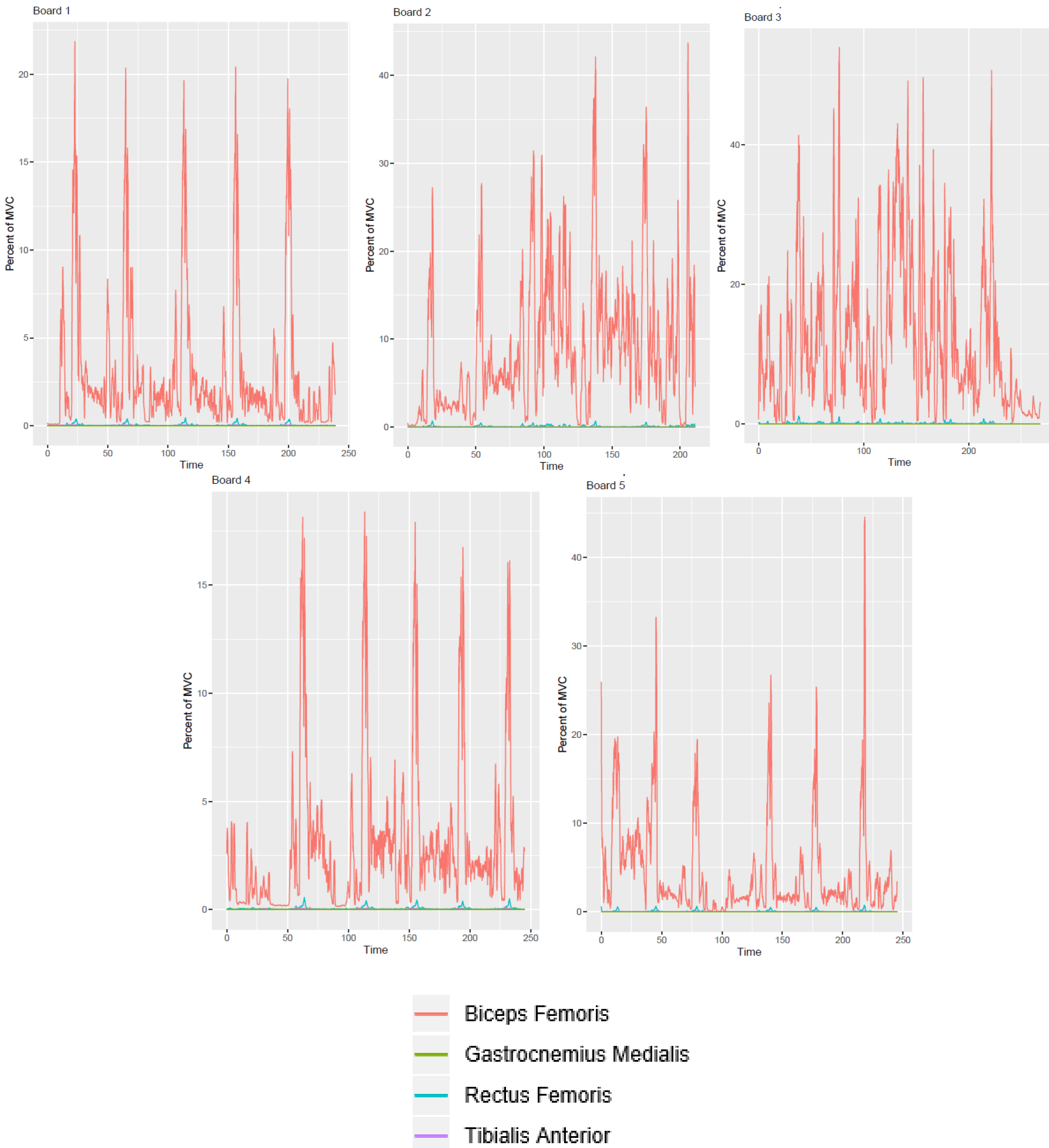


Figure 12E. EMG profiles - Participant 23

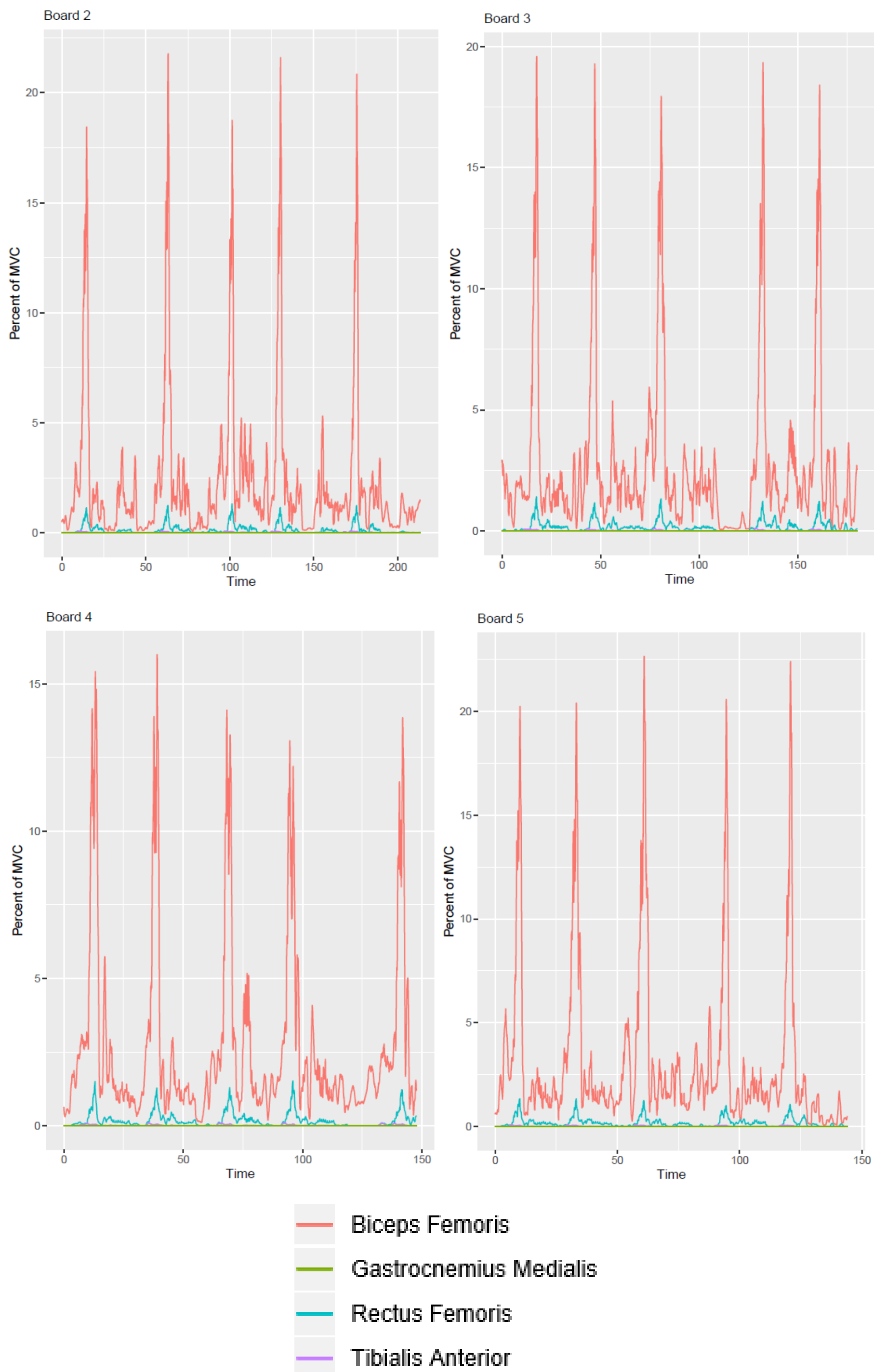


Figure 13E. EMG profiles - Participant 24

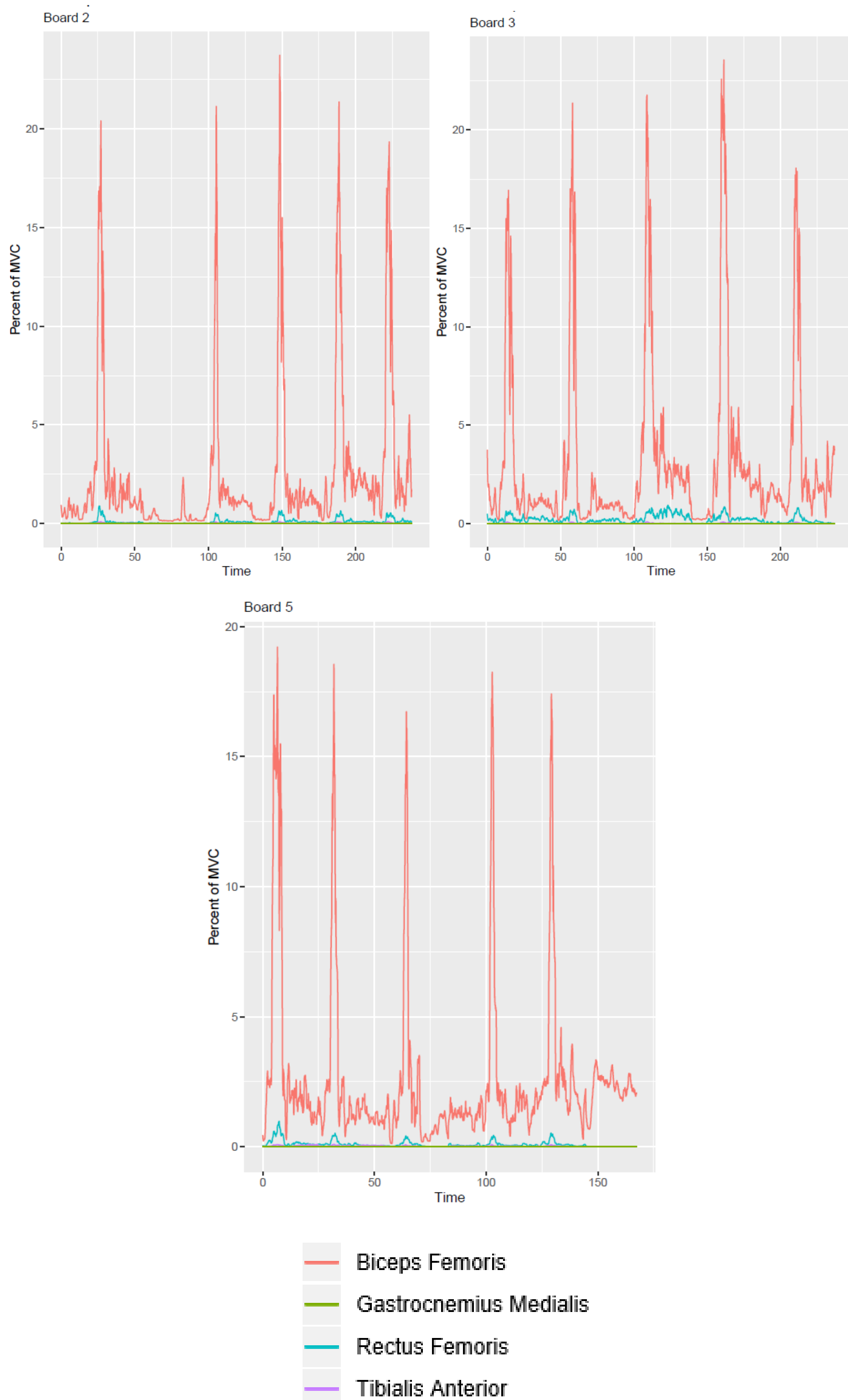


Figure 14E. EMG profiles - Participant 25