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A comparison of ground reaction forces and muscle activity of the Tsunami Bar® against a rigid barbell during back squat phases

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An Institutional Review Board (IRB)-approved study was conducted to investigate the effects of the Tsunami Bar® (TB), a flexible barbell, on ground reaction force (GRF) production and muscle activity in the quadricep, hamstring, and gluteal muscle groups during phases of the squat exercise and compare the effects to the effects to using a rigid barbell (RB). A two-by-two repeated measures Analysis of Variance (ANOVA) test was used to compare the results. Descriptive statistics showed significantly higher GRFs for the TB during the unweighting phase, significant differences in GRFs between speeds for each phase, significantly higher forces on average with the RB during the breaking and propulsive phases at the 90 beats-per-minute (bpm) speed, and significantly higher muscle activity with the RB at the 60-bpm speed. A linkage to the beneficial effects of the TB seen in literature was seen with familiarity with the TB.

DEDICATION

I would like to first express my sincerest gratitude to my committee chair, Dr. Reuben F. Burch V. His support and mentorship during my time at Mississippi State University have left a lasting impact that serves as the basis for my future endeavors. The greatness of his work and the character that he models in all areas has truly been an inspiration in my life.

To Dr. John E. Ball who first brought me into academic research as an undergraduate student. His belief in my potential has allowed me to find a career path that I am excited and honored to partake in. His mentorship has been a vital role in my academic success both in the classroom and in research.

To Dr. Brian K. Smith and Dr. Zack M. Gillen, I thank you for your willingness to offer guidance in my work. Both in the classroom and in research, your mentorship and insight have allowed me to succeed both academically and in the completion of this Thesis.

To my coworkers, David Saucier and Erin Parker, who have been with me the whole way through my research career, our thousands of hours spent together over the last three and a half years are times that will stick with me for the rest of my life. Whether it was long data collection in the lab or spending hours on research papers, we always found a way to make the best of our situations. I will always be grateful for your companionship.

To the students and other members of the Athlete Engineering Research Group at Mississippi State University that assisted in the conducting of this study, I thank you for your participation in assisting me in carrying out this project.

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Weight equipment utilized during the study was donated by Total Strength and Speed. An era of gratitude is extended for their support in furthering academic research.

I would additionally like to acknowledge my friends and family for their ongoing support during my academic career.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCITON

The Athlete Engineering (AE) research program was formed out of a National Science Funded (NSF) project under NSF 18-511 Partnerships for Innovation (PFI-1827652) to develop a wearable smart sock capable of collecting kinetic and kinematic motion capture (MoCap) data based on consumer feedback from a round of ICORPs interviews. The AE research team has also extended its capabilities to validate industry products against gold-standard lab equipment. This research primarily centers around wearable technology; however, efforts also extend to general performance technology. Knowing this, the creators of a commercially available weight training product, known as the Tsunami Bar ® (TB), reached out to the AE team about conducting an external research study of the comparison of the TB against a rigid barbell (RB). The contents of this work discuss the results of the project and AE's research efforts.

1.1 Motivation

The creators of the TB often get push-back at the collegiate and professional levels about the validity of TB as a sports training tool. Although the academic research is quite limited overall, there have been some investigations comparing the TB to a RB; however, most of these investigations were performed by the developers of the TB, so buy-in from consumers has been limited. AE's credibility as a third-party validation center offered a great opportunity for a project partnership. The purpose of this thesis is to expand the research literature surrounding TB.

1.2 Background

When discussing the span of resistance training in history, the use of rigid barbells has been a relatively new adoption, especially compared to other early forms of resistance training tools such as the dumbbell. Early forms of resistive training around the early to mid-1800s were primarily focused on "improving agility and correcting postural issues" (Heffernan, 2023). With burdensome wars and extreme levels of poverty, building muscle and improving health was a luxury that most individuals could not afford, so innovations in training methods and materials were limited. However, the popularity of training began to increase around the mid-1800s with the establishment of public gymnasiums, sparking developments of early versions of barbell-like equipment.

Toward the latter half of the 1800s, a German physique scholar named Edgar Mueller popularized the first variable weight barbell. The barbell was comprised of a long steel rod with two globe-like objects on each end. The globes had a small opening for pouring shot or sand into to vary the weight. Similar iterations were developed over the following years, and in the early 1900s, the creation of the first plate-loaded barbell gave individuals access to an easy weight adjustable tool that was affordable. With this development, individuals were able for the first time to progressively overload weight resulting in more potential for muscle and strength building than ever before. Individuals were finally able to increase physical performance at a much higher level, surging the popularity of bodybuilding, strongman, and competitive physical sport.

The rigid barbell has since served as the staple piece of any resistance training regimen with very few adaptations over the years. However, in the late-2010s, a patent application (US 10,369,401 B2) for a "flexible barbell" was filed marking the first major iteration of the barbell in over one hundred years. The barbell has a very similar appearance to a rigid barbell; however, the mechanical properties of the bar allow for considerably more bend to occur when performing a lift. There has been some research to suggest that the flexible barbell can generate a higher peak force of resistance compared to a rigid barbell. This research is quite limited, however, and further investigation is necessary to fully understand the effects of the bar on individuals and whether the tool provides any additional training benefits compared to a rigid barbell.

1.3 Statement of Problem

Extensive training methods involving RBs have been a primary driver of muscle and strength building across nearly every area involving physical activity. TB claims to be able to train at higher peak forces than with a RB while using the same total weight. Though these results have been extensively tested through mechanical testing, human-trial studies are still quite limited with only a few investigations being performed.

1.4 Significance of the study

Data collected for the study will provide further insight into the viability of the TB to equate or exceed training efficiency compared to an SB. The study will also validate performance assessment procedures using wearable technology.

1.5 Purpose of the study

This study aims to compare the effects of TB to that of a RB on individuals performing a popular exercise to further the academic literature and increase understanding of TB and its properties.

1.6 Research question(s)

Q1: Does the TB produce higher peak ground reaction forces (GRFs) than that of a RB with equal weight and at equal speed?

Q2: Does the TB invoke higher muscle activation in the lower limb segments than a RB with equal weight and at an equal speed?

1.7 Definition of terms

Tsunami Bar® – flexible barbell comprised of special composite materials that allows for oscillation of the barbell when conducting an exercise.

Rigid barbell – a mostly non-flexible barbell made of steel or similar material.

Ground reaction forces – forces exerted by the ground because of the force being applied to it.

1.8 Assumptions

Study assumptions include the differences in repetition cadence to be negligible to the overall results.

1.9 Limitations

Generally, most of the participants will have never been exposed to a flexible barbell and/or any type of instability training. Therefore, slower acclimations to the use of TB and limited exposure to instability training may prove to be limited to the overall performance and results.

An off-the-shelf wearable compression short was used for collecting electromyography (EMG) data. The system had previously been validated and was deemed "capable of tracking surface EMG (sEMG) activity in comparison to a research-grade system" (Davarzani et al., 2020). However, during the data collection process, a major software overhaul was released replacing the older software version being used for the data collection. Some of the participant trials were not exported before the account data was cleared resulting in the loss of ten of the nineteen total participants' EMG data being lost. Additionally, some of the trials were deemed "bad" due to poor sensor contact. For the methodology, the compression short sensor pads were spritzed with water for a better sensor connection, but the contact was not sufficient for about 8 trials, of which the data had to be disregarded for the analysis.

1.10 Delimitations

To mitigate confounding variables, some study delimitations were established to reduce the chance of skewed results. The first major consideration was to establish participant-specific loads by taking a percentage of their one-rep maximum. The second consideration was to implement a metronome to keep the speed of the repetitions consistent. Finally, the last major consideration was to have a box marking the depth of the squat to ensure consistency between repetitions. The use of the box did not reduce the load at the bottom of the lift, as individuals were told to only make slight contact with the box to ensure depth was reached.

1.11 Conclusion

The RB has served as the staple tool for resistance training since its inception in the early 1900s. The development of TB has been the first major revision to the barbell in the last one hundred years. Though TB has been repeatedly shown to produce higher peak forces than a SB, its use in a real resistance training environment to produce the same results are limited. This study aims to serve as a third-party validator of the viability of the TB to meet or exceed the peak force production of a SB.

1.12 Contributions

- Novel analysis of TB effects in relation to squat phases
- Analysis methods of processing force plate data for segmenting squat phases
- Support of significant differences between the Tsunami Bar® and a standard rigid barbell
- Practitioner recommendations on application of Tsunami Bar®

CHAPTER II

REVIEW OF LITERATURE

2.1 Introduction

Stability training is a form of exercise that helps to develop the core muscles of the body. Ideally, this core muscle development would allow for additional and safer increases in muscle development across the body. The concept of stability training is new in the realm of exercise science, and therefore, methods, tools, and research are limited in the space. An emerging technology for stability and performance training known as the Tsunami Bar® has been positioned to fill the gap in stability training. The following sections outline the academic works of flexible barbell research.

2.2 Flexible Barbell (Tsunami Bar®) Research Methods

Testing methods for TB for the limited research primarily included analysis of applied forces and muscle activity during various exercises (Bryce et al., 2015; Hutchison et al., 2013; Hutchison & Caterisano, 2017; Power et al., 2019; Tant et al., 2015). Applied forces were collected using force plates (FPs) and muscle activity was collected using lab-grade sEMG devices. Generally, the working weight for the testing was based on a percentage, around 25-40%, of a participant's one-repetition maximum (1RM). A metronome was implemented to keep the repetition cadence more consistent across trials.

For the analysis, EMG data were normalized against 1RMs and maximum voluntary contractions (MVCs) (Power et al., 2019; Tant et al., 2015). Peak values were analyzed for the GRF data.

2.3 Flexible Barbell (Tsunami Bar®) Research Results

Initial research on the concept of a flexible barbell began in 2012 with the first comparison of the effects of the Tsunami Bar® to a rigid barbell. In the investigation, each bar was attached to a machine that would move each barbell up and down for a total displacement of 2.00 ft (0.61m) at a speed of 1.73 ft/s (0.53 m/s). Each barbell was loaded to the same total weight of 195 lbs (88.45 kg). The results of the testing are shown in Figure 2.1 below.

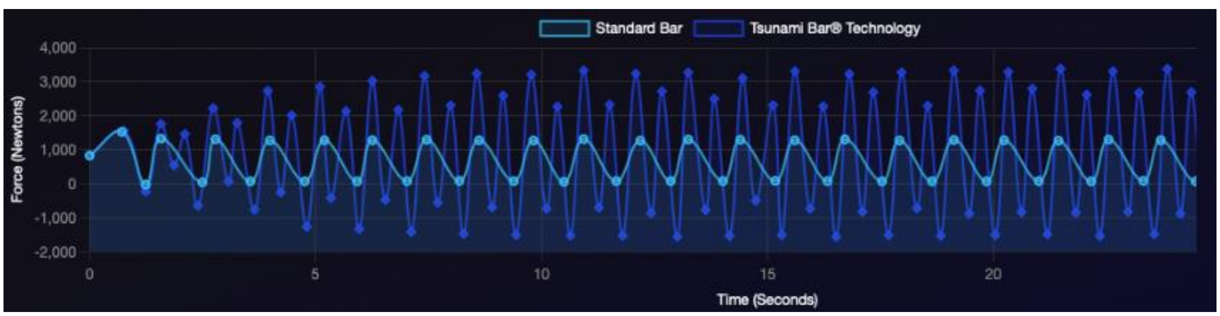

Figure 2.1 Total Forces of Tsunami Bar® vs Rigid Barbell during Machine Testing (*Tsunami Bar® Speed - Tsunami Bar® Sports*, n.d.)

After ramp up period of about six cycles (about seven seconds), the total force output in Newtons of the Tsunami Bar® is about twice as great as that of the standard rigid barbell.

The peak force of each repetition using the RB was recorded to be around 1325 N, while the peak force of each repetition for the TB was around 3331 N. This data shows a 150% increase in peak force production when using the TB over the RB. These results are encouraging for the viability of the TB as a training tool due to its ability to produce higher peak forces at the same weight, allowing for the ability to train for the same peak forces but with less weight than a

RB. However, the testing parameters do not necessarily match that of human capability. One study analyzing repetition speed during the bench press, one of the higher-speed exercises, reported an average repetition speed of 1.28 ft/s (0.39 m/s) (Padulo et al., 2012). This value is 26% less than the value from the testing machine. The machine testing also used a total displacement for each repetition of 24 in, while the average inseam length for the arm, about the range of motion for a bench press, is around 19 in for males and 17 in for females. This observation concludes that the differences seen with the TB may not translate over as drastically to testing with human subjects.

In 2013, Hutchison *et al.'s* comparison of the applied forces of a flexible barbell and a RB during the bench press exercise served as the first study of TB's use within a human context (Hutchison et al., 2013). The results of the study could not be found, but a spinoff poster presentation provided the results of the comparison of muscle activity between the two barbells (Jakiela et al., n.d.). The researchers utilized surface electrodes to measure activation in five upper-body muscle groups. Two measures were used in the analysis with the first being the maximum value for each contraction wave and the second being the integrated mean of the signals, and each of the measures was normalized against the values recorded from the 1RM. The results showed that muscle activity was significantly higher with the TB than with the SB, with activation in the pectoralis major having the greatest difference at 18.7%. The researchers mention higher levels of peak force with TB, claiming this force difference to be the reason for higher muscle activation.

A similar study was conducted by Tant *et al.* in 2015 investigating the differences in muscle activity with a TB and a RB during the push press exercise (Tant et al., 2015). The exercise weight was set to thirty percent of the participants' 1RM, and the exercise speed was set to fifty cycles per minute. The collected EMG data was normalized against a maximum voluntary contraction (MVC) during a squat. A paired T-test was used to compare the data, and the results showed that there were "strong" results for greater muscle activation with the TB than with a SB.

Bryce *et al.* investigated the differences between TB and a RB in a 2015 study in which participants performed five sets of one repetition at various loads (40, 50, 60, 70, and 80 percent) of their self-reported 1RM (Bryce et al., 2015). A position transducer and force plate were used to assess the lifts. The results showed no significant difference in the force production between the two barbells.

Caterisano *et al.* researched the lower extremity joint kinetics between the TB and a RB during the back squat exercise (Caterisano & Hutchison, 2016). An eight-camera 3D MoCap system was used to analyze the lower kinetics. The results showed that TB generates greater joint power in the knee and hip joints than the SB. No significant difference was attained between the bars at the ankle joint.

A similar study that followed was Hutchinson *et al.'s* expansion of TB's use during the back squat exercise (Hutchison & Caterisano, 2017). This investigation explored the muscle activity and ground reaction forces that occurred between the two barbells during the squat exercise. A machine-driven experiment was also performed to eliminate the human variability, as to know solely the mechanical differences of the TB to the SB. The participants endured a familiarization trial to acclimate to the characteristics of the TB and RB at the repetition speed signaled by a metronome set at 52 repetitions per minute. EMG surface electrodes were placed at six major muscles: rectus femoris (RF), biceps femoris (BF), rectus abdominis (RA), erector spinae (ES), external oblique (EO), and vastus lateralis (VL). The weight used for the experiment was set at thirty percent of each participant's 1RM. The results showed that the EMG activity for the TB was significantly higher for the VL, RA, FR, and EO; also, GRFs were significantly higher for the TB compared to the SB. Based on the results, the researchers recommended TB for increasing stabilizer core muscle group activation and knee extensors during the squat exercise.

After seeing promising results in a lab setting, the translation from the lab to the weight room was investigated (Caterisano et al., 2018). in a study observing the results of a five-week training program using the TB compared to a combined weight training program of speed lifts and plyometrics. The goal was to see which of the two programs led to better power increases over the five weeks. For the TB, the weight was fixed at 125 lbs. (56.82 kg); however, the weight for the group using the RB varied at 45-65 % of their respective 1RMs. The results showed both training methods to be effective for improving power over the training period but suggested that the TB program may be more effective at lower-body power development. These results make sense, as the testing methods reflect more explosive-type movement patterns, which is what the TB is primarily designed to target. The significantly greater improvements in the Margaria-Kalamen Stair test and standing LJ reflect this concept.

The following study deviated from the human subjects' approach where GRFs were analyzed at differing bar end displacements for the TB. A machine was used to perform the lifts simulating bench press and squat exercises; lifting velocities varied from 0.49 ft/s to 5.09 ft/s (0.15 m/s to 1.55 m/s). The researchers concluded that bar end displacement could serve as a predictor of peak external loading.

The latest work investigating the effects of TB on human subjects was published in 2019 in a study comparing the effects of TB to a RB regarding GRFs, joint kinetics and kinematics, and muscle activity during the back squat exercise. The methods for the study included loading each bar to 30% of each participant's 1RM and performing ten repetitions. The integrated-peak values of the GRF and EMG data were analyzed for each of the barbells. The results showed significant increases in peak joint kinetics, peak vertical GRFs, and muscle activity of the TB over the SB, inferring the potential biomechanical and physiological benefits of the TB.

2.4 Summary of Literature

Much of the literature investigating the effects of the TB were performed with elite-level athletes. Methodologies primarily involved collecting GRF and muscle activity data and comparing the results of using a TB to that of using a RB. Significantly higher peak GRFs were commonly seen with the TB over the RB. Additionally, significantly higher muscle activity was seen in certain muscle segments with the TB over the RB. None of the discovered studies included an investigation breaking down the various phases of the squat exercise. None of the discovered studies involved investigating multiple repetition cadences within the same subject group.

CHAPTER III

METHODS AND MATERIALS

3.1 Participants

Nineteen recreationally trained males (n=12, age=23.5$\pm$4.5y, mass=84.6$\pm$12.6kg, height$=$181.6$\pm$7.4cm) and females (n=7, age=22.1$\pm$3.1y, mass=64.8$\pm$4.7kg, height$=$164.7$\pm$4.3cm) were recruited to participate in this study. Participants were required to meet the ACSM Physical Activity Guidelines (150 minutes of aerobic activity per week and two muscle-strengthening activities per week) with experience performing the squat exercise regularly (Piercy et al., 2018). Participants were screened via PAR-Q and Foot/Ankle Disability Index surveys to determine any physical limitations; individuals who reported physical limitations or discomforts were excluded from the study to limit confounding effects in the analysis. All participants signed informed consent documentation prior to engagement of any study protocol. The study was approved by the Mississippi State University's (MSU) Institutional Review Board (IRB 21-029).

3.2 Materials and Equipment

Data collection was performed at the Human Performance Lab (HPL) at the Center for Advanced Vehicular Systems (CAVS) at MSU. Equipment used included MoCap, force plates, two-dimensional video cameras, EMG compression shorts, and training equipment.

A twelve-camera, three-dimensional MoCap system was used to capture barbell mechanical properties (Vicon, Oxford, UK). A set of two force plates (Kistler, Michigan, US) integrated with the MoCap system into The MotionMontior software program (Innovative Sports Training, Chicago, IL, US). Two GoPro Hero 5s were used to collect the two-dimensional video data (GoPro, San Mateo, CA, US). The sEMG data were measured using the Strive™ Sense3 compression shorts. A standard squat rack, a 20kg barbell, weight plates, and a Tsunami Bar® Speed were the training equipment used (Total Strength and Speed, West Columbia, SC, US).

3.3 Study Procedure

The participants were asked to first attend a familiarization session in the Sanderson Center at MSU in either the Strength and Aerobic Conditioning Room or the AMP'd room, where their one-repetition maximum (1RM) was determined using a RB. Participants were permitted to bring any necessary accessories (belts, sleeves, wraps) for 1RM testing. Participants were granted the option to follow a provided dynamic warm-up protocol or perform a self-selected protocol prior to determining the 1RM. The 1RM was then determined based on an Epley chart (Distasio, 2010). This protocol consisted of five repetitions at 30% self-reported 1RM followed by two minutes of rest, four repetitions at 50% followed by two minutes of rest, three repetitions at 70% followed by three minutes of rest, and one repetition at 90% followed by three minutes of rest. From the last warm-up set, loading was increased through participant feedback on the level of repetition intensity so that 1RM could be achieved within three trials. Four minutes of rest were given between each 1RM effort.

During this process, the researchers helped the participant get familiar with the testing procedures and ensured that correct form and posture were used during the squat exercise. The investigators confirmed proper form by observing when the squat reaches the parallel position, which occurs when the greater trochanter of the femur is lowered to the same level as the knee, and let the participant know verbally when they have reached parallel.

Once the 1RM was determined, participants performed the squat exercise with the TB at 25% of their 1RM several times to get familiar with the feeling of the TB, as well as mitigate any potential learning effects in determining how to keep the barbell stable while squatting. Participants were also conditioned to match the repetition cadence of the two test speeds that would be used in the data collection session. A metronome and verbal cues ("down" and "up") were used to maintain consistent repetition cadence at each of the 60 and 90 beats-per-minute (bpm) tempos. Participants were advised not to "pause" at the bottom of the squat but to keep constant motion throughout each repetition.

The participants arrived at HPL for data collection no sooner than 48 hours after the 1RM session. The participant again performed the dynamic warmup protocol followed in the previous session. Two GoPro cameras were set up for recording from the side and in front of the participant, and subjects performed maximal voluntary isometric contraction (MVIC) exercises for normalizing sEMG measurements. The participant was again conditioned to the two repetition cadences, and a squat box was set to the same depth as used in the 1RM session. Foot position was also marked on the force plates to keep consistency across all trials. Assisted by two spotters, the participant performed two sets of five repetitions of the squat exercise at the 60 and 90 bpm tempos for both the TB and RB for a total of 40 repetitions of the squat exercise across eight sets, or trials. The order of barbell type was randomized for each session. Upon completion of the data collection, participants completed a subjective survey (Appendix A) assessing their impression of each barbell and the Strive™ shorts. The Strive™ shorts were sanitized in a washing machine with non-bleach laundry detergent before the following data collection. The duration of the two test sessions lasted less than two and a half hours in total.

3.4 Data Processing

The data from the force plates and the EMG shorts, firstly, had to be processed for comparison. The data from the sessions included the repetitions as well as some extra data from the time the participant unracked the barbell to when they stepped off the platform (shown in Figures 3.1 and 3.2); thus, the signal must be windowed to only include the necessary data.

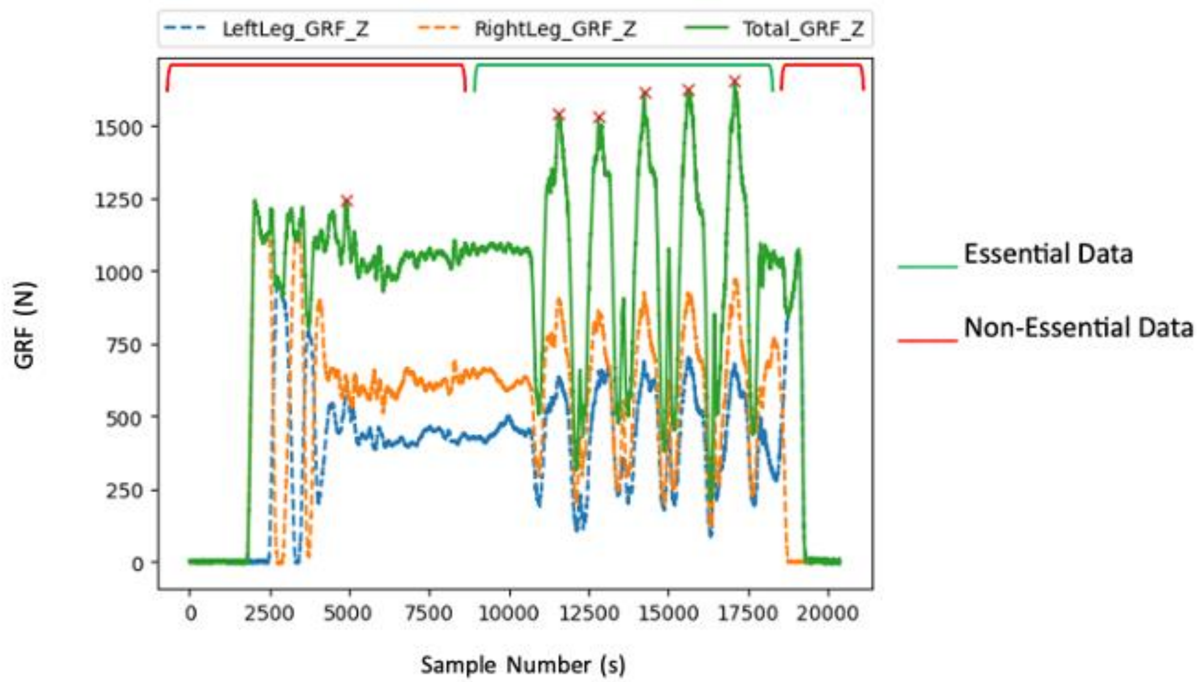

Figure 3.1 Total GRF Data

The initial about 8,000 samples and last about 2,000 samples for this trial need to be cut for the algorithm to correctly identify the peaks. In this instance, an outlier that is not one of the squat repetitions is being marked, signifying the importance of trimming the signal.

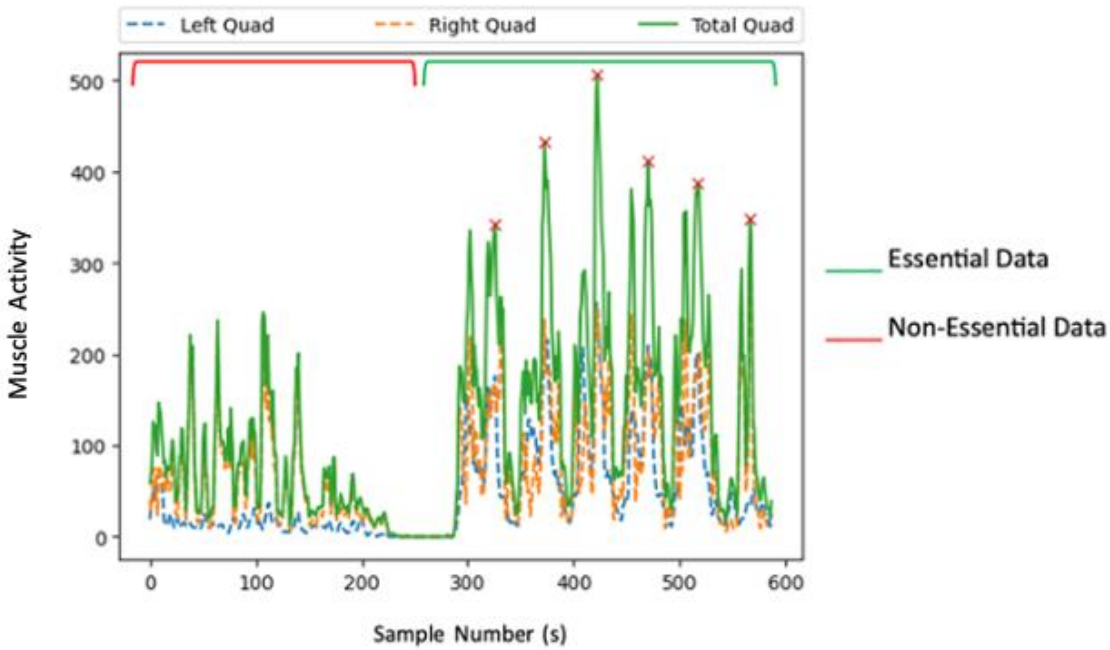

Figure 3.2 Total EMG Data

The initial about 250 samples for this trial need to be cut for the algorithm to correctly identify the peaks.

Additionally, only the middle three repetitions are being investigated to limit the "ramp up" effects of the Tsunami Bar, where the beginning repetition does not have the momentum to fully bend the barbell. This concept is shown in Figure 3.3 where there is a visible difference in the signal generated in the first repetition and the following repetitions.

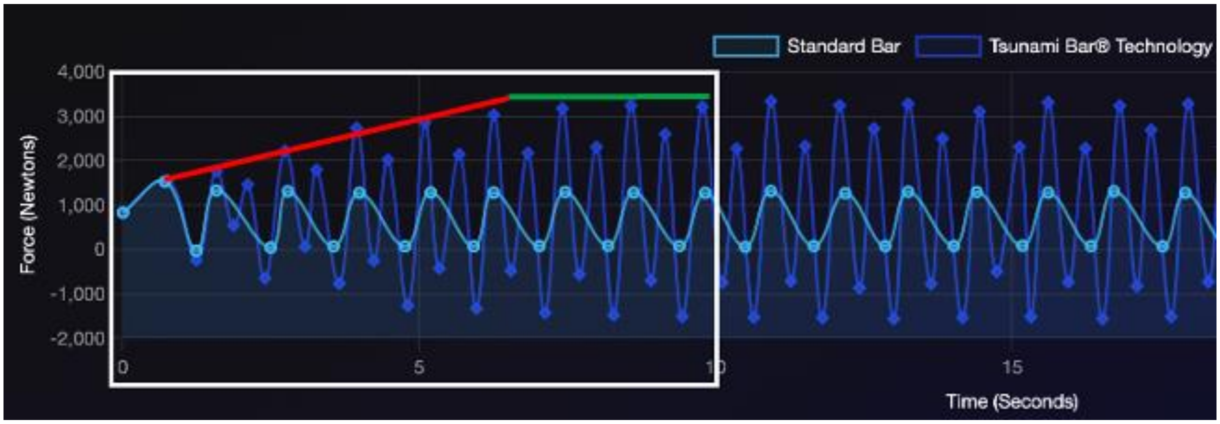

Figure 3.3 Tsunami Bar® Ramp Up Effect

The red line denotes the ramp up period, and the green line represents the signal stabilizing.

Therefore, the signals must be windowed accordingly such that only the middle three repetitions are shown. Analysis of the signal showed that cutting the first repetition to be sufficient to reduce the ramp up effects.

3.5 Data Analysis

For the analysis of the data, the squat exercise will be broken into three phases, shown in Figure 5: the unweighting phase (1), the braking phase (2), and the propulsive phase (3). To determine the location of the phases for the analysis, the mean weight before the beginning of the first squat was taken to serve as the threshold value (0). The beginning of the unweighting phase was set at the point where the GRF signal crosses the threshold after the peak of the previous squat. The end of the unweighting phase and beginning of the breaking phase was set at the point where the GRF signal crossed back over the threshold. The end of the breaking and beginning of the propulsive phase was set at the point where the middle MoCap marker on the barbell was at its minimum. Finally, the end of the propulsive phase was marked when the signal again crossed the threshold. The phases in relation to the signal generated for the force plates are shown in Figure 3.4.

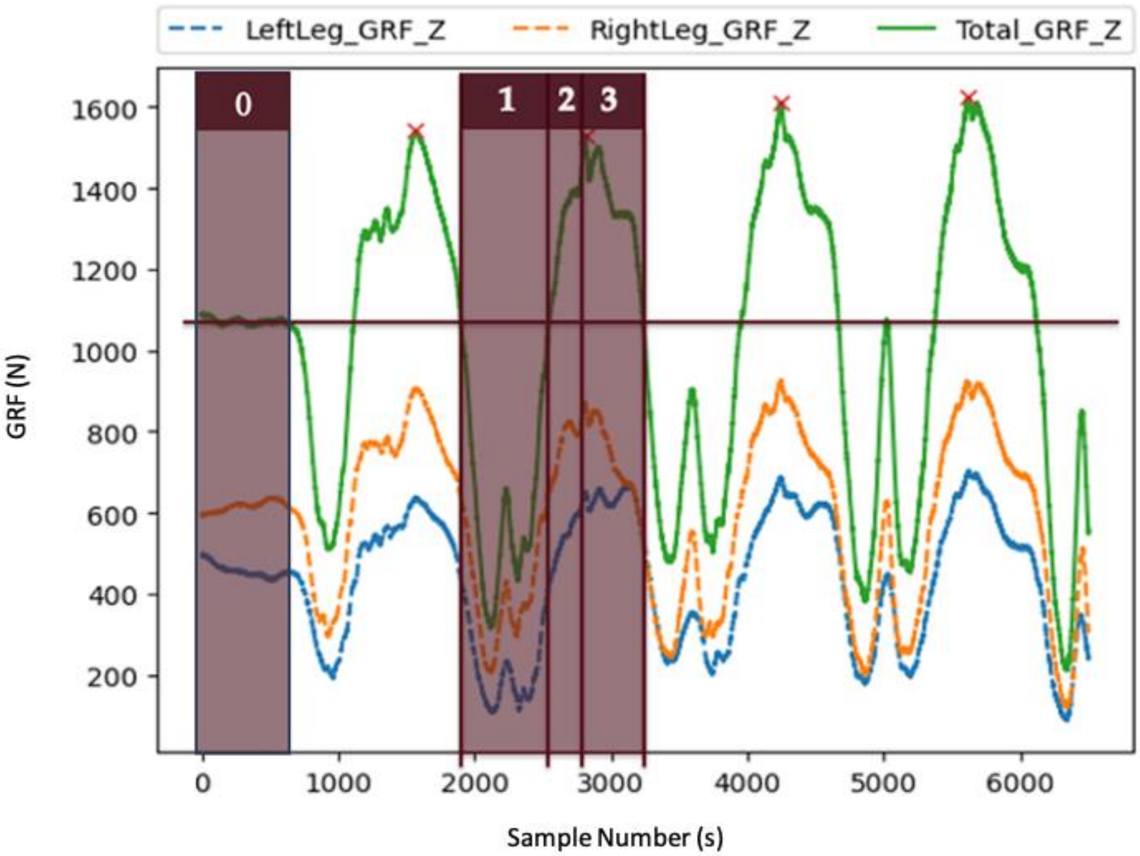

Figure 3.4 Squat Phases of Force Plate Signal

Zone 0 denotes the area for which the threshold is calculated. Zones 1, 2, and 3 represent the area for which the unweighting, breaking, and propulsive zones are calculated respectively. The line across the middle denotes the threshold value.

For the unweighting phase, the minimum of the signal will be taken for the analysis of the force plate data. For the breaking and propulsive phases, the peak and mean values will be recorded. Each of the three middle repetitions are average together into a single value. Both trials for each participant are analyzed separately to provide a larger input into the statistical model.

The EMG data were analyzed based on the peak values of “Total Muscle”, where the middle three repetitions were averaged into a single value. Again, both trials were analyzed separately for each participant.

A Python script was developed to automatically segment the data based on the phases and save the analysis variables into a table.

3.6 Statistical Analysis

Two-by-two repeated measures ANOVA tests were conducted using the JASP software program (Version 0.17.1) for both the force plate and EMG datasets. The two testing factors were Barbell Type (RB or TB) and Speed (60 bpm or 90 bpm). Each of the squat phase metrics were analyzed in separate repeated measures ANOVA tests using a 95 % confidence interval. Post hoc tests were performed on any interactions between measures, using a Bonferroni correction factor.

3.7 Participant Survey

Participants were presented a survey, shown in Appendix A, upon completion of the data collection to gauge overall impressions of each barbell type. Survey responses were presented based on a subjective one to five scale. Five total questions were presented as below:

- Q1: How did the rigid barbell feel when squatting?
- Q2: How did the flexible barbell (Tsunami Bar®) feel when squatting?
- Q3: How difficult was it to use the rigid barbell when squatting?
- Q4: How difficult was it to use the flexible barbell (Tsunami Bar®) when squatting?
- Q5: Of the two barbells, which would you prefer to use for resistance training?

1 – Rigid Barbell

2 – Flexible Barbell (Tsunami Bar®)

Quantitative descriptive statistics were analyzed for the survey results, including the mean and standard deviation for each response. Additional qualitative (subjective) comments were also provided in the survey to add context to the participants' responses.

CHAPTER IV

RESULTS

4.1 Preliminary Results

The preliminary analysis of one of the participants included an assessment of the peak GRF data. The participant had previously used the TB and was familiar with using the flexible barbell during the squat exercise. The results showed that there was no significant difference (p = 0.997) between the two barbells at the 60-bpm speed; however, there is a significant difference (p = 0.023) in GRF production between the barbells at the 90-bpm speed with the TB generating higher peak GRFs. Table 4.1 summarizes the results from the initial test.

Table 4.1 Peak GRF for each barbell in initial pilot testing

Speed	Rigid Barbell	Tsunami Bar®
60	1431 +/- 42	1430 +/- 60
90	1593 +/- 66	**1687 +/- 72***

***** denotes statistical significance with $p < 0.05$

4.2 Force Plate Results

The two-by-two repeated measures ANOVA test results are shown below in Table 4.2 with descriptive statistics in Table 4.3. The statistical analysis showed significant differences in each of the phases.

Table 4.2 Multivariate repeated measures ANOVA test for two within-subject effects and their interaction effects for GRF data

Squat Phase	Barbell Type		Speed		Barbell Type * Speed	
	F value	P value	F value	P value	F value	P value
Unweighting (Minimum)	45.667	**< .001***	228.59	**< .001***	0.017	0.897
Breaking (Peak)	1.216	0.277	306.97	**< .001***	0.007	0.936
Breaking (Average)	2.244	0.143	280.52	**< .001***	10.253	**0.003***
Propulsive (Peak)	0.146	0.705	299.42	**< .001***	0.479	0.493
Propulsive (Average)	6.857	**0.013***	310.87	**< .001***	2.203	0.146

***** denotes statistical significance with p < 0.05

For all phases, speed was a significant factor in determining differences in the GRFs produced ($p < 0.001$). Significant differences in GRFs were seen between barbell types in the unweighting ($p < 0.01$) and average propulsive ($p = 0.013$) phases. A significant interaction existed between barbell type and speed during the average breaking phase ($p = 0.003$). Descriptive statistics are provided in Table 4.3 for insight into the degree of differences seen.

Table 4.3 Descriptive statistics of ANOVA test for GRF data

Squat Phase	Barbell Type	Speed	N	Mean	SD	SE
Unweighting	RB	60	38	6.624	1.383	0.224
(Minimum)		90	38	4.387	0.785	0.127
	TB	60	38	7.442	0.875	0.142
		90	38	5.229	1.104	0.179
Breaking	RB	60	38	16.326	1.991	0.323
(Peak)		90	38	19.564	2.52	0.409
	TB	60	38	16.515	2.207	0.358
		90	38	19.73	2.551	0.414
Breaking	RB	60	38	14.696	1.742	0.283
(Average)		90	38	16.759	1.972	0.32
	TB	60	38	14.803	1.93	0.313
		90	38	16.345	1.861	0.302
Propulsive	RB	60	38	16.756	2.14	0.347
(Peak)		90	38	19.643	2.485	0.403
	TB	60	38	16.593	2.122	0.344
		90	38	19.68	2.496	0.405
Propulsive	RB	60	38	15.057	1.855	0.301
(Average)		90	38	16.827	1.951	0.317
	TB	60	38	14.868	1.853	0.301
		90	38	16.39	1.871	0.303

***** denotes statistical significance with $p < 0.05$; N represents the sample count; SD represents the standard deviations from the mean; SE represents the standard error

Analyzing the means of the data in Table 4.3, lower GRFs were seen with the RB than with the TB during the unweighting phase. Analysis of the Peak Breaking measure showed only a significant difference in speed. No interaction was seen between Barbell Type and Speed for this test. A significant difference was seen between the two speeds of the Average Breaking test ($p < 0.001$). Additionally, an interaction was seen between barbell type and speed ($p = 0.003$). As expected, the interaction was primarily attributed to the differing speeds, but there was also a significant interaction between the two barbells at the 90-bpm speeds ($p = 0.014$). With the propulsive peak measure, the only significant factor was speed ($p < 0.001$). No significant difference was seen with barbell type, and no interaction between barbell type and speed was seen. Within the average propulsive test, both barbell type and speed attributed to significant differences in GRFs. Further analysis showed significantly higher means for the RB over the TB during the propulsive phase. No interaction was seen between barbell type and speed.

4.3 EMG Results

The two-by-two repeated measures ANOVA test results are shown below in Table 4.4 with descriptive statistics in Table 4.5. For the EMG statistical test, a significant difference was seen between barbell types (p = 0.005).

Table 4.4 Repeated measures ANOVA test for two within-subject effects and their interaction effects for EMG data

EMG Peaks	Barbell Type		Speed		Barbell Type * Speed	
	F value	P value	F value	P value	F value	P value
Total Muscle	10.903	**0.005***	0.627	0.441	1.106	0.31

***** denotes statistical significance with $p < 0.05$

No significant difference was seen between speeds, and no interaction was seen between barbell type and speed. The descriptive statistics table can be analyzed to gain further insight into the direction of the differences between the two barbell types.

Table 4.5 Descriptive statistics for ANOVA test for EMG data

EMG Measure	Barbell Type	Speed	N	Mean	SD	SE
Total Muscle	RB	60	16	680.354	132.586	33.146
		90	16	675.813	144.447	36.112
	TB	60	16	591.333	171.875	42.969
		90	16	637.354	172.198	43.050

N represents the sample count; SD represents the standard deviations from the mean; SE represents the standard error

From the data in Table 4.5, higher muscle activity was seen with the RB during each of the tested speeds. Further analysis linked the significant difference between the two barbells to the 60-bpm speed with the mean of the RB being significantly higher than that for the TB.

4.4 Survey Results

The data for the survey responses are presented in Table 4.6.

Table 4.6 Summary statistics of survey responses

Survey Results	Q1	Q2	Q3	Q4	Q5
Average	4.526	3.947	1.368	2.526	1.316
Standard Deviation	0.612	0.848	0.597	1.172	0.478

See Chapter 3 Section 7 for details on Q1-Q5.

Participants reported overall that the RB (4.562) “felt” better than the TB (3.947) when squatting. Additionally, participants rated the TB to be “more difficult” to use than the RB. The RB was selected as the barbell of choice for the participants by thirteen to six. Some of the subjective feedback in support of the RB included more familiarity and the “ease of control” of the barbell. Subjective feedback in support of the TB included the barbell’s “comfort” and “core engagement”.

CHAPTER V

DISCUSSION

5.1 Discussion

For all the phases, speed was a significant factor. Forces were consistently higher with the faster speed, with exception to the unweighting phase where forces were higher during the 60-bpm speed (likely because the minimum was taken instead of the average or maximum for this phase). These results also follow another study where lifting cadences were varied (Bentley et al., 2010). The researchers found significantly higher GRFs during higher cadence trials compared to the lower cadence trials.

Contrary to previous research (Power et al., 2019), no significant difference was seen in the peak GRFs during the squat exercise. Significantly higher forces were seen when using the TB during the unweighting phase, which suggests that utilization of the TB could enhance training by enacting higher loading during the eccentric portion (seen in Figure 5.1) of the squat.

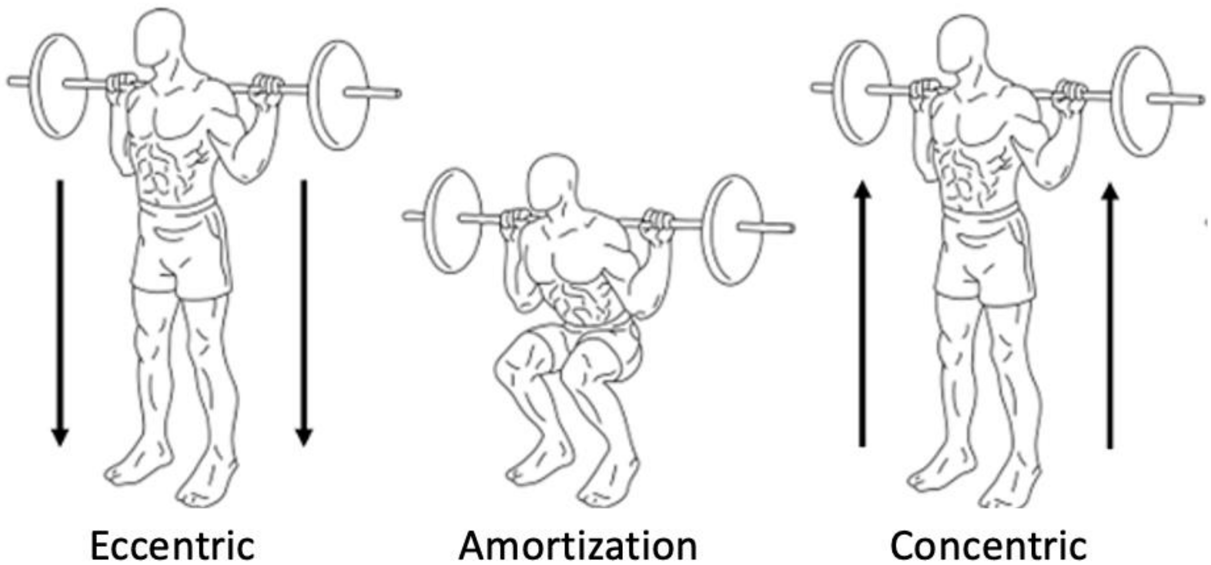

Figure 5.1 Eccentric, Amortization, and Concentric Portions of Squat

Eccentric, amortization, and concentric phases in relation to different positions during the squat exercise. These are the common phase terms when discussing muscle activity, as opposed to the raw signal terminology of unweighting, breaking, and propulsive.

Eccentric training has been shown to benefit muscle hypertrophy and lower extremity functional performance more than concentric training (Büker et al., 2021). Thus, due to the significantly higher forces during the unweighting phase, the adaptations acquired while using the TB could lead to additional hypertrophy and functional performance improvements than with the RB. Significantly higher forces were seen with the RB during the breaking phase, which is the latter half of the eccentric phase. Thus, a combination of both barbell types could offer more rounded training adaptations during the eccentric training phase.

A significant interaction was seen between barbell type and speed with the average breaking test. Post hoc tests showed a significant difference between the TB and the RB at the 90-bpm speed with the RB having a higher mean. Thus, the results suggest higher forces on average during the breaking phase of the squat. Additionally, a significant difference in barbell type was seen during the average propulsive test. Further analysis tests linked the significant differences to the 90-bpm trials, where higher average forces were seen with the RB.

The first consideration as to why the results were not following the literature were the test group. Participants were only required to meet ACSM Physical Activity Guidelines; the test group for most of the studies in currently literature were elite-level athletes. Force development or rate of force development with non-elite athletes may not be sufficient to realize the effects of the TB, as elite athletes have been studied to have higher rate of force development (Slawinski et al., 2010).

The second consideration as to not seeing any significant differences in peak forces was the test weight. The TB used during the testing was the standard "speed" version of the TB, which is loadable up to 45 lbs. per side. According to the TB website, the optimal widow to realize the oscillation effects is 35 lbs. per side (*Tsunami Bar® Speed - Tsunami Bar® Sports*, n.d.). This test weight would require a minimum of a 340 lb. 1RM to operate at or above the optimal oscillation window. Of the nineteen tested participants, only three individuals met the 340 lb. minimum 1RM. Within these subjects, the results did eliminate the statistical differences between the two barbells for the average breaking and propulsive; thus, operating within the ideal range did trend positively for the TB.

The most revealing results found in the data were with the one individual who had previously been exposed to the TB. The participant reported extensive use of the barbell and was confident in the use of the barbell. Though these measures were not statistically significant, the peak forces for both the breaking and propulsive were noticeably higher at the 90-bpm speed, as seen in Figure 5.2.

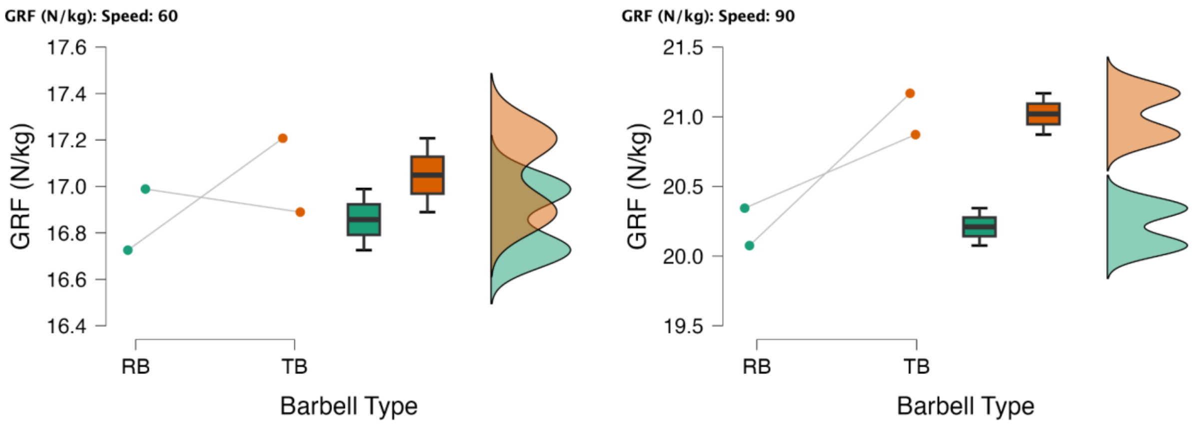

Figure 5.2 GRF Comparison for Participant Familiar with TB

The plot on the far left for each chart denotes the values of each trial for the participant. The middle plot for each chart represents the data as a box and whisker plot with the middle line denoting the median value. The plot on the right denotes the data as a one-sided violin plot. The two charts are separated by repetition speed (60 or 90 bpm). From the charts, the higher speed had a greater increase in GRFs for the TB than with the RB.

Being that this was the only participant of the nineteen total that had previous experience with the TB, inferences are nearly impossible to draw based on this dataset; however, it does potentially suggest that there is a linkage between familiarity and beneficial results when training with the TB in terms of peak GRFs. Caterisano *et al.* studied athletes who had previous training experience with the TB, where significantly higher core muscle activity was seen with the TB over the RB (Caterisano et al., 2015). These conclusions provide additional backing for the role of familiarity in realizing the benefits of the TB.

5.2 Limitations

A few limitations arose within the study. Firstly, only nine of the nineteen total participants' data for the EMG analysis was utilized due to a software bug in an update causing several of the trials to be lost. Additionally, four of the trials (P006_RB_60, P006_RB_90, P010_RB_90, and P010_TB_60) resulted in poor data with no visible peaks to identify the repetitions. Figure 5.3 illustrates a “good” trial, where the repetitions are easily identifiable, and Figure 5.4 illustrates a “bad” trial, where the repetitions are not identifiable.

Figure 5.3 Good EMG Trial

Place all detailed caption, notes, reference, legend information, etc here

Figure 5.4 Bad EMG Trial

Peaks for each of the five repetitions are not clearly identifiable; thus, data had to be discarded.

In addition, only EMG data were analyzed for the muscle group areas of the rectus femoris, biceps femoris, and gluteus maximus. No EMG data were collected in other muscle segments to understand how the instability of the TB aspects such as core stability. Core muscle activity has been suggested to be greater with the TB than with the RB (Caterisano et al., 2015).

5.3 Future Work

Additional to the GRF and EMG data, both video and MoCap data was collected. Two GoPros were placed in front and to the side of participants, allowing for potential analysis of joint kinematics. From this data, analysis could be performed to gain insight into the biomechanics of each barbell type. Biomechanical and muscular asymmetries could be investigated to see if the instability of the TB has any profound affects.

Markers were also placed on each barbell; future work could include an investigation into the flexion of the TB and how that translated to GRFs and EMG. Following Mallick *et al's.* investigation, bar end flexion could be analyzed to understand if it played a factor in the lack of higher peak forces with the TB (Mallick et al., 2018). Through this analysis, the validity of the argument as to whether the majority of the test weights being less than the manufacturer recommended optimal oscillation window affecting the results could be more accurately assessed.

Familiarity appears to be a more important factor for realizing benefits with the TB than previously known. A follow-up study to the contributions of this document could include an investigation into determining what practices and timelines are necessary for ensuring sufficient familiarization with the TB. A study of individuals with no previous TB training experience who perform a multi-week training regimen with the TB and evaluating them on their performance with both TB and RB exercises would be a beneficial contribution to understanding how familiarity factors into performance benefits with the TB.

The 1RM is a common metric that is used to gauge strength progress. Follow-up studies could involve a comparison of a TB to a RB for 1RM values during various popular exercises, such as the back squat, the bench press, and power clean.

5.4 Overall Conclusions and Practitioner Feedback

The results of this study signify that there are significant differences in the training responses between a TB and a RB. Though these differences do not necessarily attribute benefit of one barbell over the other, it does suggest the two barbells require different training adaptations. A combination of both the TB and RB could result in a more rounded approach to eccentric training. The results of the study and other supporting literature suggest that familiarization is a key element toward realizing the benefits of the TB. Individuals who had previous training experience with the TB recorded higher peak GRFs with the flexible barbell over a RB, while individuals with no previous training experience with the TB tended to see equal or better responses with the RB. Thus, education and training on the effects and proper usage of the bar are strongly encouraged when incorporating the TB into a training program.

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APPENDIX A

PARTICIPANT SURVEY TEMPLATE

A.1 Survey Template

A template for the survey presented to the participants upon completion of the study is shown in Figure A.1. new appendix figure

Participant ID: __________

Tsunami Bar and Strive Shorts Comfort Questionnaire

Circle one for each question

1. How did the rigid barbell feel when squatting?

   Very Comfortable | Comfortable | Indifferent | Uncomfortable | Very Uncomfortable

   Any other comments? ____

2. How did the flexible barbell (Tsunami Bar) feel when squatting?

   Very Comfortable | Comfortable | Indifferent | Uncomfortable | Very Uncomfortable

   Any other comments? ____

3. How difficult was it to use the rigid barbell when squatting?

   Very Difficult | Somewhat Difficult | Neutral | Not Difficult | Not Difficult at All

   Any other comments? ____

4. How difficult was it to use the flexible barbell (Tsunami Bar) when squatting?

   Very Difficult | Somewhat Difficult | Neutral | Not Difficult | Not Difficult at All

   Any other comments? ____

5. Out of the two barbells, which would you prefer to use for resistance training?

   Rigid Barbell | Flexible Barbell (Tsunami Bar)

   Explain why: ____

Figure A.1 Participant survey for Tsunami Bar® and rigid barbell

The contents of the survey included information on comfort, difficulty, and preference of the barbells.