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Measuring the Forces Involved in Single Point Aerial Dance Trapeze

By

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Abstract

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Over the past several decades, the lines between dance, theatre and circus have blurred and circus equipment has found its way into all of the performing arts. With this new exploration of circus equipment, Technical Directors and Riggers frequently find themselves needing to rig apparatus that they are unfamiliar with. This rigging not only occurs in traditional theatres that they have experience with, but also often in found spaces, where load capacities may not be as clear. A thorough understanding of the forces involved when circus and aerial dance equipment are used is important when determining rigging hardware and mount points.

This thesis measures how much force is generated in typical single point aerial dance trapeze movements and, after analyzing that force data provides some insight into what rigging hardware might be needed to properly support such movements. Chapter 1 is a brief introduction to the thesis; Chapter 2 discusses the history of "Aerial Dance" and provides background information on it; Chapter 3 reviews the hardware and software used in the research; Chapter 4 analyses the force data, and provides the formulas used to calculate Working Load Limits; Chapter 5 reviews different rigging hardware options and concerns with each; Chapter 6 is a summary of the thesis.

Acknowledgments

This thesis, and the MFA education behind it, are the results of several years of learning and personal growth and would not have been possible without the support of family, friends, co-workers and the faculty and staff of the UW-Madison Theatre Department.

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I would like to express my great appreciation to my managers at the UW-Madison Office of the Registrar, Scott Owczarek, Phil Hull, and Suzanne Broadberry, for their support and encouragement, and for allowing me flexible time to complete my degree; and to my prior manager, Marilyn McIntyre, for the wise advise to pick a degree in "something I am passionate about", without which I might very well be writing a thesis about business, or administration.

I am most grateful to the Madison Circus Space, for the friendship and support of all of its members and for allowing me to use such a wonderful place to hang my rig and conduct my thesis research; and to Cycropia Aerial Dance, for providing not only the skill, knowledge and most important, love, of trapeze and aerial dance, but also many wonderful friendships.

Finally, this thesis, and my graduate education, would not have been possible without my family: my mom, for inspiring in me a love of dance, without which none of this would have happened; my dad, who awoke a love of theatre and set a good example of a scientific, interrogative mindset; and my daughter Andrea, for her support, love and the wonderful distraction of all the stories of her life in Zambia.

Above all, I would like to thank my partner, Kristi Minahan; she has been a constant rock amidst the chaos of the last 7 years; she has reviewed and edited countless papers, cleaning up what seemed like endless errors; she has listened and provided wonderful advice about the numerous challenges that have come up; and most of all, she has given me her love.

Contents

List of Figures

List of Tables

List of Charts

List of Equations

Nomenclature

ANSI	American National Standards Institute
DF	Design Factor
DIN	Deutsches Institut für Normung –German Institute for Standardization
DIN rail	A metal rail used for mounting electronics components that follows the DIN Standards
HMI	Human Machine Interface
MCS	Madison Circus Space
NC	Numeric Controller
PLASA	Professional Lighting and Sound Association
PLC	Programmable Logic Controller
RA/RR	Risk assessment (RA) and risk reduction (RR)
TSP	Technical Standards Program
WLL	Working Load Limit

Chapter 1

Introduction

Over the past several decades, the lines between dance, theatre and circus have blurred. Circus has become more theatrical, often with less emphasis on the 'ta-da' moments, and more emphasis on a story to provide background for the acts. Dancers are moving up off the floor, exploring spaces and movement qualities that involve equipment rigged from above. Theatre directors and choreographers want to include circus equipment like lyra (circular steel apparatus), aerial silks and trapeze in their plays.

With this new exploration of circus equipment, Technical Directors and Riggers (referred to collectively as riggers) frequently find themselves needing to rig apparatus that they are unfamiliar with. This rigging not only occurs in traditional theatres that they have experience with, but also often in found spaces, where load capacities may not be clear. A thorough understanding of the forces involved when circus and aerial dance equipment are used is important when determining rigging hardware and mount points.

As a Technical Director, I volunteer with several circus, aerial dance, dance and theatre groups in Wisconsin. I am often asked by directors, choreographers, dancers, managers, friends and colleagues about rigging in non-traditional spaces, including gyms, exercise studios, warehouses, and homes. In offering advice and assistance to them, I have found that I often need to fall back on equipment and rigging methods that I have observed others using over the last decade. However, I have not had a thorough understanding of the forces involved in aerial dance, nor the numerous options available for rigging, and therefore I could not always provide concrete reasoning behind why these methods are utilized, other than "that's the way it's done." This unfortunately sometimes results in over designing equipment to try to ensure that it can be safely used, or not using the optimal equipment for the situation, or sometimes not being able to providing any advice at all.

This thesis explores the forces generated in typical single point aerial dance trapeze movements and, after analyzing those forces, provides some insight into what rigging hardware might be needed to properly support such movements. The goal of this thesis is to provide myself, and other riggers, with the knowledge they need to properly rig aerial dance apparatus in spaces that were not originally designed as performance or rehearsal spaces.

The research done for this thesis involved ten volunteer aerialists using a trapeze to perform aerial dance movements that they might use in training, rehearsal or performance. While they were moving on the trapeze, equipment was used to measure how much force they were generating on the rigging. They were also videotaped while on the apparatus, primarily to determine at what point they generated the most force. The data captured was then analyzed, and conclusions and recommendations are presented based on that data.

All research was conducted at the Madison Circus Space (MCS) in Madison, WI. As described on their website, the facility "is an area of celebration for the circus arts. The MCS welcomes clubs and classes in addition to providing a practice space for dedicated performers and hobbyists. Juggling, German wheel, stiltwalking, aerial arts, acrobatic yoga, and hoop dancing are just a few of the activities that take place in the space. While pursuing nonprofit status, the MCS holds workshops and events that are open to the community and meant to foster appreciation for the variety of circus-related talent and creativity in Madison."[1] Additionally, I and the majority of participants in the research are also members of the MCS.

[1] "Madison Circus Space," About the MCS.

Chapter 2

What is "Aerial Dance"?

To better understand the research, results and recommendations in this thesis, a basic knowledge of aerial dance and its history is helpful. This chapter will provide information on how aerial dance was started, who influenced it, the single point aerial dance trapeze it most often uses, and some of the more common movements that are used when aerial dance is performed.

My first encounter with aerial dance was a performance by Madison, WI based Cycropia Aerial Dance. At a folk dance I attended, I noticed a flyer for Cycropia's "Aerial Chautauqua" performance at Taliesin in the summer of 1998. The flyer mentioned the words trapeze, dance and magical, all of which piqued my curiosity. Walking down into the valley behind Taliesin, I spread my blanket amongst the crowd, in front of three large trees that were decorated with brightly colored fabric. As the sun slowly set behind us, the sound of a flute came from out of a field far to our right. Following the music were several tall oddly shaped creatures, which, as they came into focus, turned out to be both stilt walkers and puppets on tall poles. Just as the long train of puppets, stilts, and performers in bright costumes reached the trees, trapezes were lowered from the limbs of the tree. Three of the performers arranged themselves near the trapezes, and the flutes faded out as music began. The performers smoothly grasped the trapezes as they began running in circles, then launched themselves into the air, then back to the ground, then back in the air, and up into the ropes of the trapeze. It was fantastic, it was magical, and I was hooked. Thus began for me more than a decade's long fascination with not only aerial dance, but also performance in general.

2.1. How did aerial dance first get started?

Many of the early artists and teachers in aerial dance primarily have a background in modern dance, though many also have backgrounds in circus arts, gymnastics and climbing. For instance, Batya Zamir, Terry Sendgraff, Robert Davidson and Nancy Smith all have formal dance training and either bachelor's or master's degrees in dance. Keith Hennessy, Stephanie Evanitsky and Diane Van Burg have both degrees in dance and circus backgrounds. Jo Kreiter has a background in Chinese pole acrobatics and gymnastics.[2]

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[2] Sanderson, "FLYING WOMEN."

A good definition of aerial dance can be found in the book titled *Aerial Dance*: "Aerial dance can be anything that lifts a dancer off the ground with an apparatus, such as a trapeze, hoop, rope and harness, stilts, bed frames, suspended bicycle, or lawn chairs. However, it's not just the liftoff the makes it aerial dance; it's the intention of the choreographer using aerial and its relationship to modern dance aesthetics." [3] The 'intention' is the significant difference between aerial dance and circus acrobatics and flying acts. In circus, the intention is for the 'ta-da' moment: the moment after the flyer has swung back and forth several times, after he has let go of the trapeze, as he stretches his hands out to the catcher; just after that moment when the audience isn't sure if he will be caught, or go falling to the net below. Circus is about that moment when the talc goes flying as acrobats' hands finally clasp, and the audience lets out their collective breath and cheers. Aerial dance is concerned less with 'ta-da' and more about what the piece has to say. In fact, most of the choreographers I have worked with in aerial dance construct the piece to exclude 'ta-da' moments, and instead, make the aerial work flow seamlessly from one position to the next. What aerial dance has brought from circus that has influenced it greatly are both the equipment (trapeze, lyra, silk/tissue, etc.) and the various positions (knee hang, catchers hang, etc.).

Modern dance and circus are the two most important factors in the formation of aerial dance. The movement style, the equipment, and the theatricality have come from

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[3] Bernasconi and Smith, *Aerial Dance*, 6.

circus. The aesthetics, the principles of choreography, and much of the vocabulary have come from Modern Dance.

2.1.1. Terry Sendgraff: A seminal artist and instructor

There are several people who have contributed to the beginnings of aerial dance, including Stephanie Evanitsky, Diane Van Burg, Robert Davidson, Terry Sendgraff and the other dancers mentioned previously. Arguably the most important of those is Terry Sendgraff, who has been called "the matriarch of aerial dance".

Because of her unique life experiences, and because she was one of the earliest teachers of aerial dance, she uniquely shaped aerial dance. In the video "Can you see me flying? - A portrait of Terry Sendgraff", she says about herself: "My formal training was ballet, modern dance, gymnastics and many hours of ice skating and diving, and I had been very influenced by T'ai chi ch'uan marital arts form. What was I going to do with these, you know, how was I going to put them together?" [4] Her formal training also provided the education and background that would feed various facets of her eventual foray into aerial work; she holds a bachelor's degree in Recreation, a master's degree in Dance from the University of Colorado at Boulder, and a master's degree in Clinical Psychology from John F. Kennedy University.

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[4] Yacker, *Can You See Me Flying: A Portrait of Terry Sendgraff*, 6:15.

She began creating what she at the time called Motivity, and what later became aerial dance, at a late age. "But while teaching dance at the YWCA she learned the trampoline and trapeze and began to revisit her childhood dream of defying gravity. 'When I was 40', I said, 'Wait a minute, what is my dance?' People had always said, 'You're a teacher, not a dancer.' At an age when most dancers already have hung up their shoes, Sendgraff began with a performance on the eve of her 41st birthday. She's been soaring ever since." [5] Sendgraff defines Motivity as "an improvisation-based dance form and performance art. It often includes the use of a suspended apparatus, in particular the single-point low flying trapeze… Motivity emphasizes the individual's discovery of her or his unique aesthetic using a system of sensory awareness while on the ground and in the air. This form blends that which is personal, political, and spiritual." [6]

Perhaps most importantly for the purposes of this research, "Sendgraff is credited with being the inventor of the single-point (or motivity) trapeze, an apparatus that makes possible rotation as well as swinging while suspended." [7] The single-point trapeze is the most common aerial apparatus used in aerial dance, and most of the training I have observed uses it as the first piece of equipment aerialists start on. As compared to a double-point or static trapeze that is used in circus, the single-point

[5] Banyas, "Skylight," 47.
[6] Sendgraff, Terry, "About Motivity."
[7] Sanderson, "FLYING WOMEN," 46.

trapeze allows movement not only back and forth, but also in a circling and spinning motion. Since the bar is located between approximately one and eight feet from the floor, it allows a dancer to transition from floor movement into aerial movement with relative ease.

In the book titled *Aerial Dance*, the authors assert that "Terry Sendgraff influenced a generation of aerial dancers, many of them have gone on to inspire a third generation and beyond." [8] There are approximately twenty aerialists listed in that same Chapter who Sendgraff either taught directly or who were taught by one of her students. One of those was Renee Miller, who founded Cycropia Aerial Dance. The Cycropia collective alone has trained approximately 12 new students per year for the last 15 years.

Sendgraff was also an instructor at the Annual International Aerial Dance Festival in Boulder, Colorado (1999-2005). Nancy Smith, a third generation student of Sendgraff's, has managed the festival from 1999 through 2012. Each year, the festival trains well over 100 students in various forms of aerial dance, including low flying (single-point) trapeze, circus (double-point) trapeze, silks, stilts, bungie, rope/harness, lyra and many other apparatus. The festival also has several public performances over the two weeks it runs, providing students an opportunity to perform and providing the public exposure to aerial dance. Additionally, according to Nancy Smith, "A conservative

[8] Bernasconi and Smith, *Aerial Dance*, 16.

estimate of the number of students we [Smith's dance company, Frequent Flyers Productions] have taught to date would be 5,000." [9] Extrapolating from those numbers for all the other students that Sendgraff taught, it is easy to see just how many aerialists Sendgraff has affected.

2.1.2. Single point aerial dance trapeze

The single point aerial dance trapeze that was used for this research is very similar to the one that Sendgraff developed and used in her dance and her teaching. Figure 2.1 shows a completed single point aerial dance trapeze apparatus. The trapeze bar uses a 1-¼" birch wooden dowel, approximately 28" long. While other species of wood have been considered, experience has shown that birch has a good strength to weight ratio, and provides a comfortable gripping surface. A ½" hole is drilled through the dowel 1" from each end. Then a loop of webbing is passed through the bar, wrapped around the end, and choked back under itself. This webbing loop is made by tying approximately a 24" length of webbing into a loop using a water knot. The webbing loop is covered with padding, most often pipe insulation covered with soft fabric. The free end of the webbing loop is connected to the trapeze ropes using locking carabiners.

[9] Ibid., 54.

Figure 2.1 – Single point aerial dance trapeze bar

2.1.3. Single point aerial dance trapeze movement vocabulary

One of the challenges with describing (and teaching) aerial dance is that there isn't a formal common vocabulary for the movements that are used. Unlike ballet, where terms like arabesque, battement, plié, and relevé are understood by the majority of ballet dancers, in aerial dance, each studio/teacher tends to make up their own terms for the movements. There are a few common terms for static positions, like gazelle, star and flag that have come over from circus, and therefore are fairly well known and used. However, the only common term I know for trapeze movements, where the performer is actually moving on the trapeze bar through the space, is "running a circle". This is as simple as it sounds: the aerialist grasps the trapeze bar in their hand, pulls it out to one side as far as they can, and then runs in a circular path around a center point below the trapeze mounting point. Running a circle is the starting point for many other trapeze movements, including one used in this research, the '*Pegasus*'. The term '*Pegasus*', along with the other terms mentioned in the next section, are local terms from Cycropia, or ones I have made up for this research when a term for the movement did not exist. For instance, I use the term "*Sit-Mount*" as shorthand for when a participant would "Mount the trapeze bar and sit on it."

2.1.4. Specific movement used for this research

Each participant was requested to do the following movements, as described in the "Research Participant Information and Consent Form", Appendix A.

1. *Sit-Mount*: Mount the bar to a sitting position, using your desired method of mounting; sit on the bar for approximately 30 seconds; dismount from the bar using your desired method. - repeat 3 times
2. *Track and Tap*: Do a 'track and tap' movement on the bar for at least 5 swings (out and back is considered one swing), trying to safely achieve the maximum height at the end of each swing. - repeat 3 times
3. *Pegasus*: Run in a circle while holding the trapeze in one hand, complete 3 circles and then move into a '*Pegasus*' movement, completing at least 3 additional circles and trying to safely achieve the maximum height. - repeat 3 times
4. *Free-Fly*: Interact with the trapeze for approximately 3 minutes, using your desired movements.

> Note: During the *Free-Fly* movement, all participants used movements that were primarily in the vertical direction, with little or no horizontal component. For instance, one movement that a participant elected to do during *Free-Fly* was a *Roll Drop*.

Part way through the research, beginning with Participant 7, participants were also asked to do an additional movement, which was called a *Sit-Bounce*.

5. *Sit-Bounce*: sit on the trapeze bar; pull up off the bar as high as you feel safe to go; then drop straight down till you are sitting back on the bar. - repeat 3 times

This protocol was added because of observations of, and discussions with, the participants about trapeze movements that might occur and generate significant force. It was only captured for participants 7 - 10, but did in fact generate significantly high force values.

These movements were selected because they represent two entirely different kinds of movements: First, the *Track and Tap* and the *Pegasus*, which are cyclical movements, where the aerialist moves in a repeated motion; and second, *Sit-Bound*, *Sit-Mount* and *Roll Drop*, which are non-cyclical movements that are done only once.

2.1.4.1. ***Track and Tap*** description

The *Track and Tap* is a cyclical, pendulum form of movement, where the aerialist moves back and forth on the trapeze bar. The following illustrations describe this movement. The aerialist starts from a standing position, runs toward the trapeze bar and grasps the bar while continuing to run forward. In Figure 2.2, the aerialist has just grasped the trapeze bar.

Figure 2.2 - *Track and Tap* Position 1

The aerialist continues to run forward, till they come up off the ground and fly up into the air. At the apex, they pivot their body and the trapeze bar around and return back towards the floor. The swivel located at the top of the trapeze ropes allows them to easily pivot around at the top of their swing. In Figure 2.3, the aerialist is shown at the top of their swing, just after they have pivoted around.

Figure 2.3 – *Track and Tap* Position 2

As the aerialist approaches the lowest part of the swing, as shown in Figure 2.4, they pike, holding their legs in front with their feet just skimming the floor. This aligns them for the next movement.

Figure 2.4 – *Track and Tap* Position 3

As the aerialist begins to leave the floor, as shown in Figure 2.5, they 'tap' or push off with one foot, adding energy to the movement, allowing them to go higher into the air. By adding energy on each 'tap', the aerialist can move higher off the floor, easily reaching angles of 75 degrees or more.

Figure 2.5 – *Track and Tap* Position 4

In Figure 2.6, the aerialist has reached their apex, pivoted the trapeze bar, and is 'tracking' back over their path again. The 'tap', followed by 'tracking' back across the floor, gives the movement its name, *Track and Tap*.

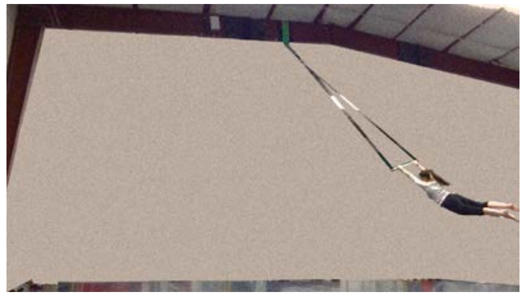

Figure 2.6 – *Track and Tap* Position 5

The *Pegasus* is also a cyclical movement similar to the *Track and Tap*, but its path is more circular. It is normally started by running a circle and then pushing off with one foot and leaping into the air.

The *Sit-Bounce* and *Sit-Mount* are non-cyclical movements that are not normally done repetitively, but are done only once. They occur at a stationary point rather than moving around the rig point.

The *Free-Fly* allowed the participants to perform any movement they desired and participants were instructed to select movements that they believed would generate large amounts of force. Most of the movements selected by the participants were non-cyclical and involved moving up and down on the trapeze and ropes instead of flying around on them. The purpose of the *Free-Fly* was to introduce movements that would generate a large force value that I might not have considered.

Chapter 3

Hardware / software / equipment

3.1. Introduction

A thorough explanation of the equipment used in the research is important both for an understanding of how the research data was captured and to allow the research to be duplicated or extended by others in the future. It will also aid the rigger in using the results of research to select the proper rigging hardware for an aerial trapeze installation, which is discussed in detail in Chapter 5. This explanation of the equipment includes: the hardware used to rig the trapeze; the hardware used to measure and record the force, with particular emphasis on load cells; and the software interface used to measure and record the force.

3.2. Rigging Hardware

Figure 3.1 shows the load cell installed into the standard rigging with an extra carabiner added above the swivel. An explanation of purpose of each of the equipment in the rigging will be of aid to the rigger. Starting at the top:

- A round sling is used to connect to the building structure by a choke around the I-beam (not shown).
- The carabiners are standard aluminum climbing carabiners.
- Information on the load cell is presented in Section 3.3.2.
- To provide reassurance to the aerialists, a webbing loop was added in parallel to the load cell as a safety item. While the load cell rating was well over the anticipated load, it was a new piece of hardware and the aerialists were unfamiliar with it. The loop was long enough that it did not support any load.

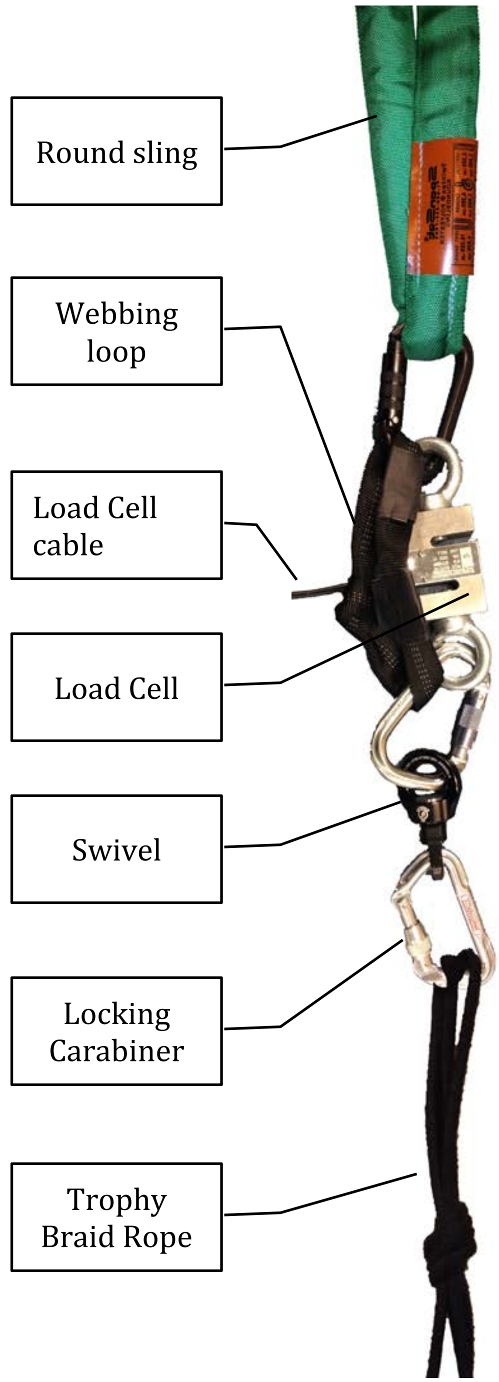

Figure 3.1 – Load cell in rigging

- The swivel allows the apparatus to easily rotate around the rig point. Using a swivel is one of the main differences between the way circus trapezes and dance trapezes are rigged.

- The rope is designed to be used for sailing rigging. It has a good elongation factor (discussed in Chapter 4) and provides a good gripping surface. This is another difference between circus and dance trapezes. Circus trapeze tends to use large 1" diameter cotton rope, often with a wire core, with one for each side of the trapeze.[10] Dance trapezes tend to use 3/8" synthetic rope, tied in a loop and doubled over, for a total of two lines for each side of the trapeze bar, with overhand knots tied in it to provide hand holds, shown in Figure 3.2.

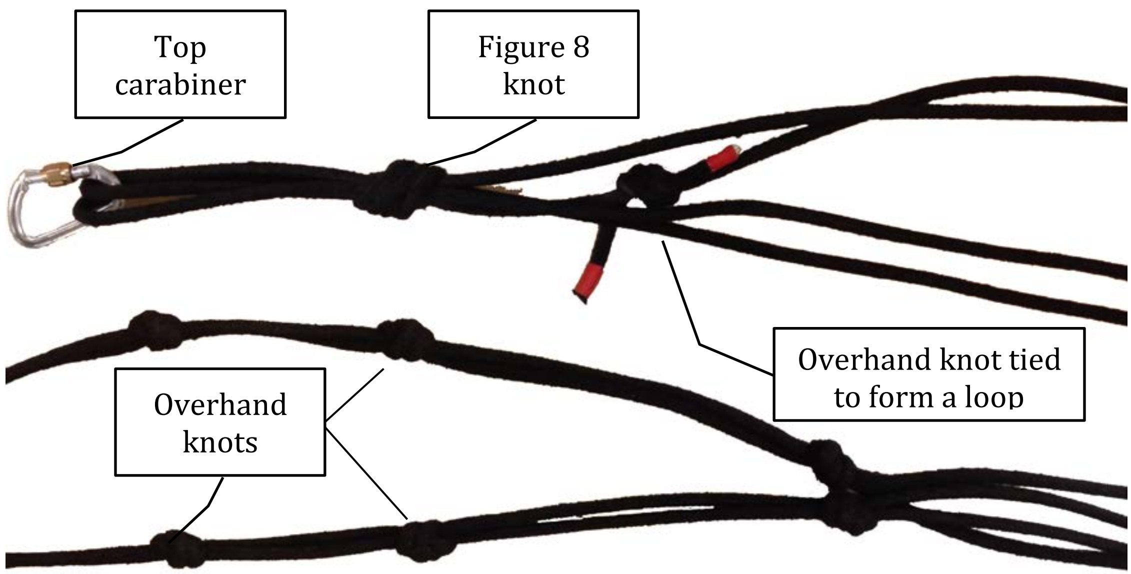

Figure 3.2 - Typical 3/8" single point aerial dance trapeze rope

Detailed information on the specific models of equipment used and their load ratings is presented in Section 4.9.6.

[10] Santos, *Introduction to rigging lyras and trapeze bars*, 54–55, 79.

3.3. Measurement hardware

3.3.1. System Overview

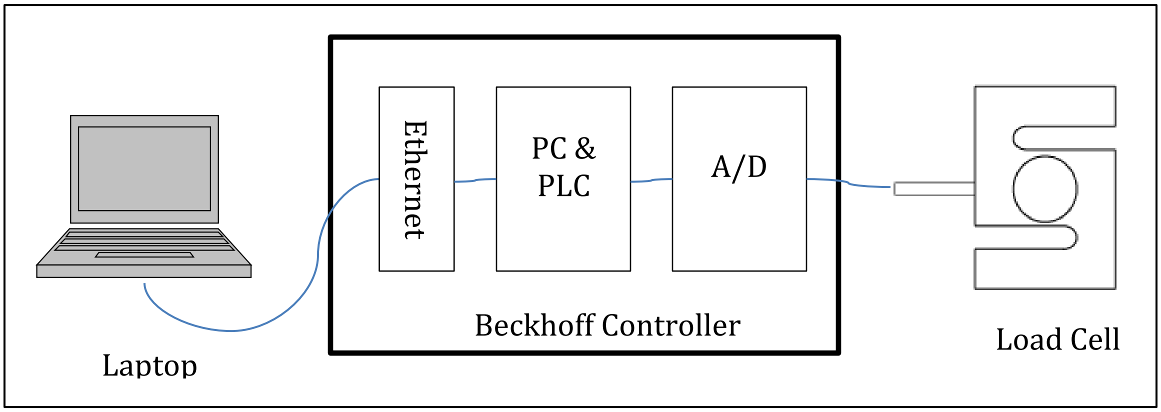

Figure 3.3 – System overview diagram

The following explanation of the hardware configuration used to measure and record the force begins with a high level overview of the system, followed by a detailed overview of each of the components. Starting on the right side of the system overview diagram, Figure 3.3, the load cell is a resistive device, and is supplied by a +10 volt supply. As the force on the load cell changes, the resistance of the load cell changes and its output voltage increases or decreases proportionally. The output from the load cell is connected to a Beckhoff controller.

Beckhoff Automation GmbH (Beckhoff) is a German manufacturer of PC-based automation technology, including the electronics modules used in this research. An Analog to Digital converter (A/D) in the Beckhoff controller converts the analog output from the load cell to a digital number, which is read by the Programmable Logic Controller (PLC) module. The Beckhoff controller also contains an embedded Windows

CE PC module, which provides a local interface, though the local interface was not used in the research. An Ethernet module was added which allowed communications with a Windows Laptop running Beckhoff's TwinCAT software, which provided the user interface for controlling the system. The TwinCAT software provided the following functions: calibration; zero offset; starting/stopping of the measurements of force; a display of the current and maximum force; resetting maximum for readout; a graph of the current force; and saving the data out to a file in Comma Separated Value (csv) format. These software functions will be explained in detail in the Section 3.4.

3.3.2. Load cells

A load cell converts force into a measurable electrical output. There are numerous types of load cells, including hydraulic, pneumatic, strain-gage, piezoelectric, capacitive, etc. The load cell used for this research, shown in Figure 3.4, is a strain-gage load cell, manufactured by Keli, model DEFY 2klb, and is most typically used in crane scales.

Figure 3.4 – Keli DEFY S-Type load cell

A strain-gage is a thin piece of resistive material, often foil, that is bonded to a material that will slightly deform when pressure is exerted upon it. Depending on how it is mounted, it can have the ability to measure both tension and compression. The S-type load cell used in this research can measure both tension and compression; for this research all forces were tension.

Before using the load cell in the research, it was desirable to calibrate it while it was connected to the rest of the system. For this purpose, the load cell was connected to a certified 1000 lb. load provided by Capitol Scale, a certified scale calibration company. Figure 3.5 shows the load cell connected between the two large orange shackles at the Capitol Scale's facility. Once the load cell was measuring the full 1000 lb. load, the calibration function in the TwinCAT software was used to store the calibration reference value. The 1000 lb. load was removed, and replaced with both 50 lb. and 100 lb. certified weights to verify the calibration accuracy. Certificates for the weights and the calibration are provided in Appendix C.

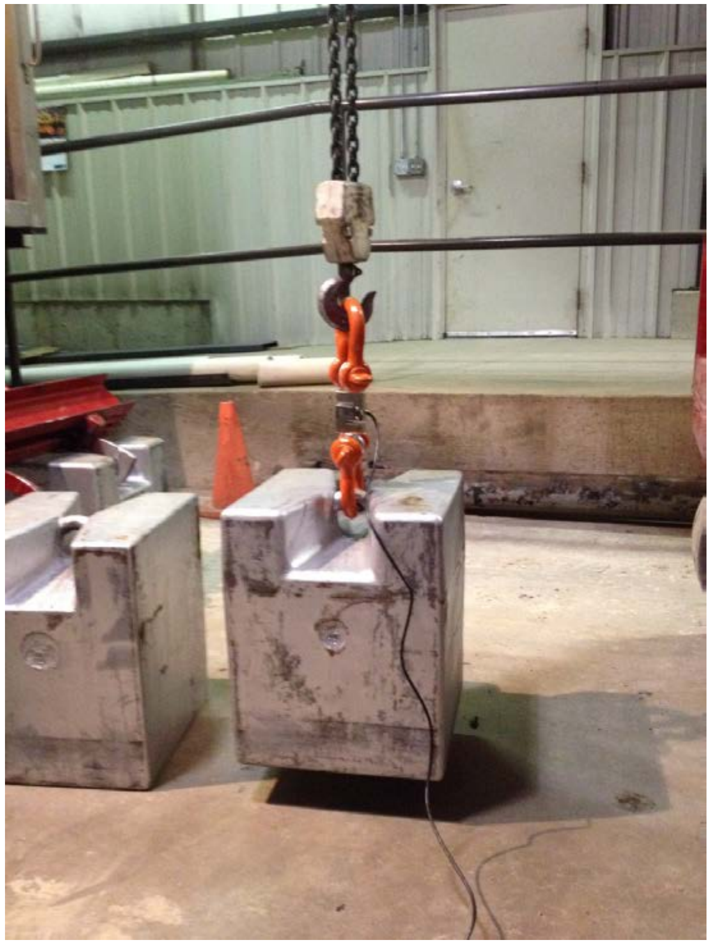

Figure 3.5 – Calibration of load cell used in research

3.3.3. Electronics enclosure

The length of the cable that connected the load cell to the Beckhoff modules was only 15' in length, and could not be easily lengthened without effecting the calibration. Because the load cell itself needed to be installed near the top of the rigging hardware over 20' from the floor, the Beckhoff modules needed to be located on the ceiling, near an I-beam supporting the building's roof. The Beckhoff modules and the 24 VDC power supply are mounted on a DIN rail, but there was not a convenient and safe way to mount the DIN rail directly to the I-beam or ceiling. Since this was above an area that is used on a regular basis, and also to protect the equipment itself, any chance of the equipment becoming detached and falling needed to be eliminated.

An enclosure was purchased and modified to hold both the Beckhoff modules and a 24 volt power supply. This enclosure not only provided a secure method for mounting the Beckhoff equipment but also provided some protection for the electronics from dust while it was mounted in the Madison Circus Space where the research was conducted. A DIN rail was installed on a removable metal plate at the bottom of the enclosure, and the Beckhoff modules and the 24 VDC power supply were mounted on the DIN rail. Connections for power (120 VAC), Ethernet and the load cell cable were mounted into the enclosure and appropriate connecters were installed on all cables. Appropriate ventilation holes were drilled into the enclosure in line with the fans in the Beckhoff CX1030 to provide adequate airflow and reduce the chances of the modules overheating. The completed enclosure is shown in Figure 3.6. The 24 VDC power supply is in the upper right corner and the Beckhoff modules fill the majority of the rest of the enclosure. The 110 VAC connection power cable is in the bottom right, the load cell cable is next to it, and the Ethernet cable is in the lower left.

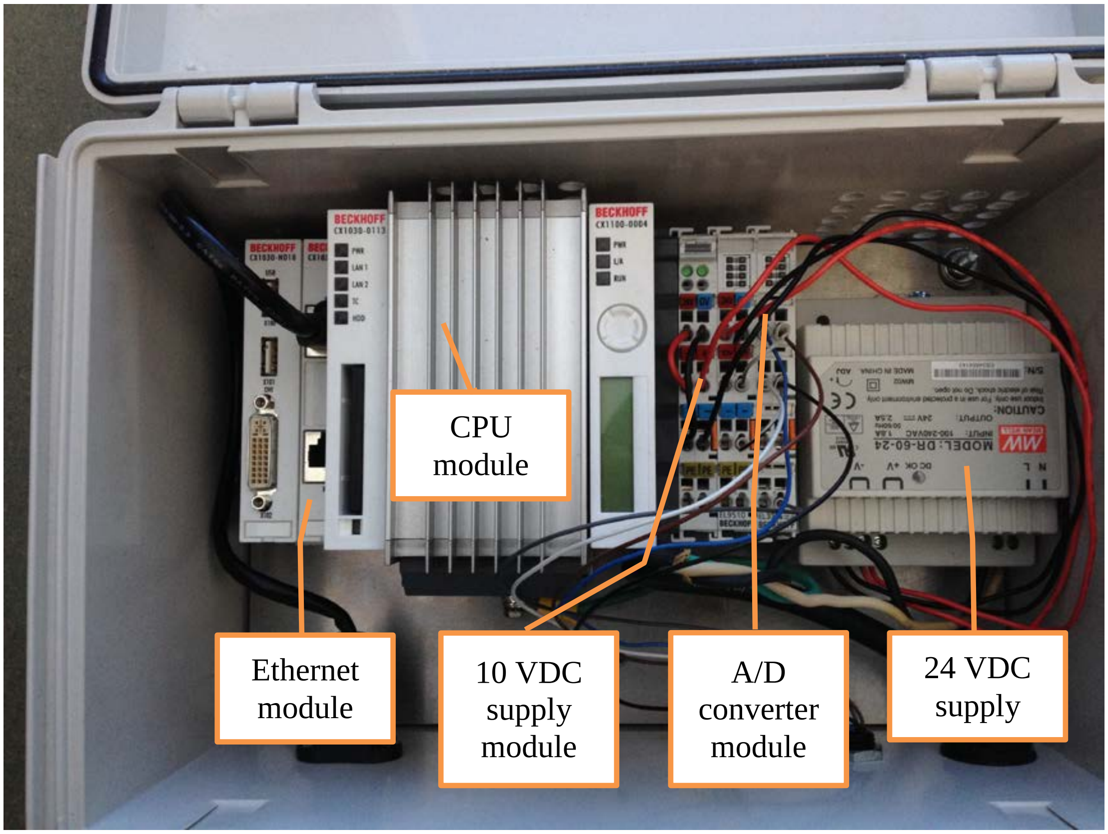

Figure 3.6 – Completed enclosure with all modules installed

3.3.4. Beckhoff modules

The following Beckhoff modules were used:

- CX1030 - CPU module
  - Runs Windows CE and the TwinCAT software which executes the Structured Text program discussed in Section 3.4
- CX1100 – Power supply and I/O interface
- CX1030 – N060 – Ethernet Interface
- EL9510 – 10 VDC power supply module
- EL3356 – Resistance bridge A/D converter

The EL3356 converts the analog voltage from the load cell into a digital value that the controller can use. It monitors both the supply voltage (+10VDC) to the load cell and the output voltage from the load cell (mV), and develops a ratio of mV/V. Because it uses a ratio, the supply voltage can be easily changed to a different voltage if necessary.

3.4. Measurement software

A Structured Text program running on Beckhoff's TwinCAT software was used to capture the data. As described on the Beckhoff website, "The Beckhoff TwinCAT software system turns almost any compatible PC into a real-time controller with a multi-PLC system, NC axis control, programming environment and operating station."[11]

The Structured Text program used to create a Human Machine Interface (HMI) for this research was built upon an example provided by Beckhoff Automation. While much of the functionality provided in the example was not needed for the research, it was not removed from the code. However, the code was modified to provide new functionality, including capturing, resetting and displaying max weight and saving the data out to a .csv file.

[11] "Beckhoff Automation," The Windows Control and Automation Technology.

Structured Text is a text based language defined in the IEC 61131-3 standard.[12] It executes blocks of code in a continuous loop, allows for loops like While-Do and Repeat-Until and condition statements like IF-Else-Then and Case statements. Functions can be defined by the programmer, though numerous functions are provided. Variables can also be defined which can be used to store values from other components in the system like the EL3356 – Resistance bridge A/D converter. Variables can also be used to store input from the HMI and display values on the HMI. Figure 3.7 shows an example of Structure Text used in this research; it verifies if the output file is open, and if it is open, moved to the next step. The top part of Figure 3.7 shows the If/Else/End loop that executes the dbFileOpen function and the bottom part shows the variables that store the state of db_FileOpen variable. Appendix D contains the entire code.

```
2:(* Wait until open not busy *)
    fbFileOpen( bExecute := FALSE, bError => bFileError, nErrID => nErrID, hFile => hFile );
    IF NOT fbFileOpen.bBusy THEN
        IF NOT fbFileOpen.bError THEN
            step := 3;
        ELSE(* Error: file not found? *)
            step := 100;
        END_IF
    END_IF
fbFileOpen    : FB_FileOpen;(* Opens file *)
fbFileClose   : FB_FileClose;(* Closes file *)
fbFilePuts    : FB_FilePuts;(* Writes one record (line) *)
fbWriter      : FB_CSVMemBufferWriter;(* Helper function block used to create CSV data bytes (single record line) *)

    MAX_CSV_ROWS            : UDINT := 264000;
    MAX_CSV_COLUMNS         : UDINT := 2;
    MAX_CSV_FIELD_LENGTH    : UDINT := 100;
```

Figure 3.7 - Structured Text Example

[12] International Electrotechnical Commission, *Programmable Controllers. Part 3, Part 3,*, 1.

The Human Machine Interface (HMI) is shown in Figure 3.8, and shows the following functionality:

- Maximum Weight Display
- Current Weight Display
- Graph of weight in lbs. vs time
- Reset Max Weight button
- Calibration buttons
- Save Data button

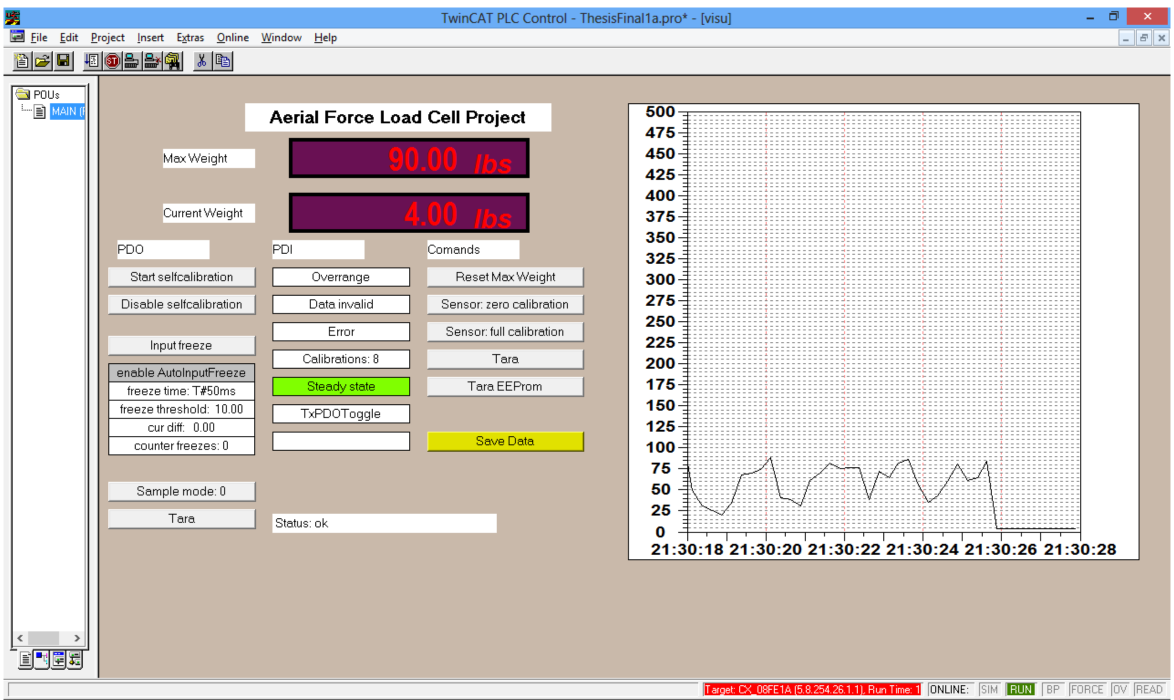

Figure 3.8 - TwinCAT software running load cell program

Chapter 4

Data Analysis

4.1. Research protocol

The research for this thesis involved ten participants, each of whom is a trained aerial dancer (aerialist). The participants signed both an Informed Consent Form that explained the protocol behind the research (Research Participant Information and Consent Form - Appendix A) and a liability waiver form (Acknowledgement of Risk, Waiver and Release of Claims - Appendix A).

Prior to the actual research, the protocol for the study was reviewed by each of the UW-Madison Institutional Review Boards (IRBs): the Health Sciences IRB, the Health Sciences Minimal Risk IRB, and the Education and Social/Behavioral Science IRB. All three boards agreed that while the research involved human subjects, the actual research was not on the subjects themselves, but instead was on equipment that the human subjects utilized. Therefore a formal IRB review process was not required.

The protocol for the research required each of the participants to perform five aerial dance movements that are often performed as part of a normal aerial dance routine. These five movements are: *Sit-Mount*; *Track and Tap*; *Pegasus*; *Free-Fly*; and *Sit-Bounce*. Their weight was also recorded while they were sitting on the trapeze in a stationary position. Each movement is described in detail in Chapter 2, "What is Aerial Dance?"

Each participant performed each of these five movements three times, to help reduce the possibility of outlier data adversely affecting the results. The analysis of the data looks at the data in several ways, including the average force for each participant for a movement, the maximum force for each participant for a movement, a ratio of each participant's weight to the force generated for a movement, and a graph of the force generated by each participant throughout each movement.

Besides the five aerial dance movements, each participant was also asked to sit on the bar with as little movement as possible, so that the participant's normal weight could be recorded. The participants verbally verified that their weight recorded by the equipment used in the study was approximately equal to their known weight. This provided a quick check of the nominal accuracy of the equipment at the start of each participant's protocol.

4.2. Raw data

Data was automatically recorded by the equipment in two different ways. First, at least every 10 milliseconds, the equipment recorded the force at that moment. This resulted in approximately 100 data points per second. Note that there was some variability in the rate of data capture, and for some movements, it was as high as 350 data points per second, or every 2.8 milliseconds. An example of this data is shown in Table 4.1. Note the time values: in '19:35:02.864', the 02 represents seconds and the .864 represents milliseconds. Examining the table below, force was recorded at 864 milliseconds, 867 milliseconds, 870 milliseconds, 873 milliseconds, etc., or approximately every 3 milliseconds.

Time	Force (lbs.)
2013-12-19-19:35:02.864	16
2013-12-19-19:35:02.867	17
2013-12-19-19:35:02.870	18
2013-12-19-19:35:02.873	19
2013-12-19-19:35:02.876	20
2013-12-19-19:35:02.879	21
2013-12-19-19:35:02.882	22
2013-12-19-19:35:02.885	23
2013-12-19-19:35:02.888	24
2013-12-19-19:35:02.891	25

Table 4.1 – Force generated at regular intervals

Second, the equipment automatically recorded the maximum force (weight) that each participant generated as they performed each movement. This maximum force data is shown in Table 4.2. The *Sit-Bounce* movement was added partway through the research (starting with Participant 7) and therefore that data is not captured for all participants.

Movement	**P 1**	**P 2**	**P 3**	**P 4**	**P 5**	**P 6**	**P 7**	**P 8**	**P 9**	**P 10**
Participant's Weight	155	150	142	120	92	134	185	141	155	136
Sit-Mount 1	239	319	188	199	130	181	321	237	196	209
Sit-Mount 2	251	363	249	214	123	181	305	212	178	210
Sit-Mount 3	220	234	256	169	138	172	246	236	201	190
Track & Tap 1	250	256	210	199	133	232	316	220	307	255
Track & Tap 2	254	297	194	193	133	189	346	210	291	249
Track & Tap 3	250	274	217	208	141	195	294	220	256	237
Pegasus 1	188	236	189	221	126	176	255	214	283	176
Pegasus 2	209	224	189	187	120	217	310	225	251	200
Pegasus 3	215	197	187	171	140	233	289	214	248	213
Free-Fly 1	284	479	216	193	137	208	476	199	389	245
Free-Fly 2	312	236	283	307	127	203	298	291	603	637
Free-Fly 3	479	309	252	221	305	309	497	359	364	353
Sit-Bounce 1	-	-	-	-	-	-	562	451	562	607
Sit-Bounce 2	-	-	-	-	-	-	623	504	751	540
Sit-Bounce 3	-	-	-	-	-	-	641	540	766	489

Table 4.2 – Maximum force (in lbs) for each participant's run of each movement

4.3. Analysis of the averages of the maximums of the data

For the data in Table 4.2, for each participant, for each movement, the average of the maximums of the data was calculated and then data was transposed (x and y axis were swapped) and sorted by each participant's weight. For instance, for Participant 5 performing a *Sit-Mount*, the average of 130, 123 and 138 (shaded area Table 4.2) is 130 (shaded area Table 4.3).

Participant	Weight	*Sit-Mount*	*Track & Tap*	*Pegasus*	*Free-Fly*	*Sit-Bounce*
P 5	92	130	136	129	190	-
P 4	120	194	200	193	240	-
P 6	134	178	205	209	240	-
P 10	136	203	247	196	412	545
P 8	141	228	217	218	283	498
P 3	142	231	207	188	250	-
P 2	150	305	276	219	341	-
P 1	155	237	251	204	358	-
P 9	155	192	285	261	452	693
P 7	185	291	319	285	424	609

Table 4.3 – Average of maximum force (in lbs) for each participant for each movement

The average of the maximum data was then plotted on a three dimensional bar chart in Chart 4.1. Participants' weights are displayed on the x (horizontal) axis; the various movements are displayed on the z (depth) axis; and the average of the maximum force generated by each of the movements for each participant is displayed on the y (vertical) axis.

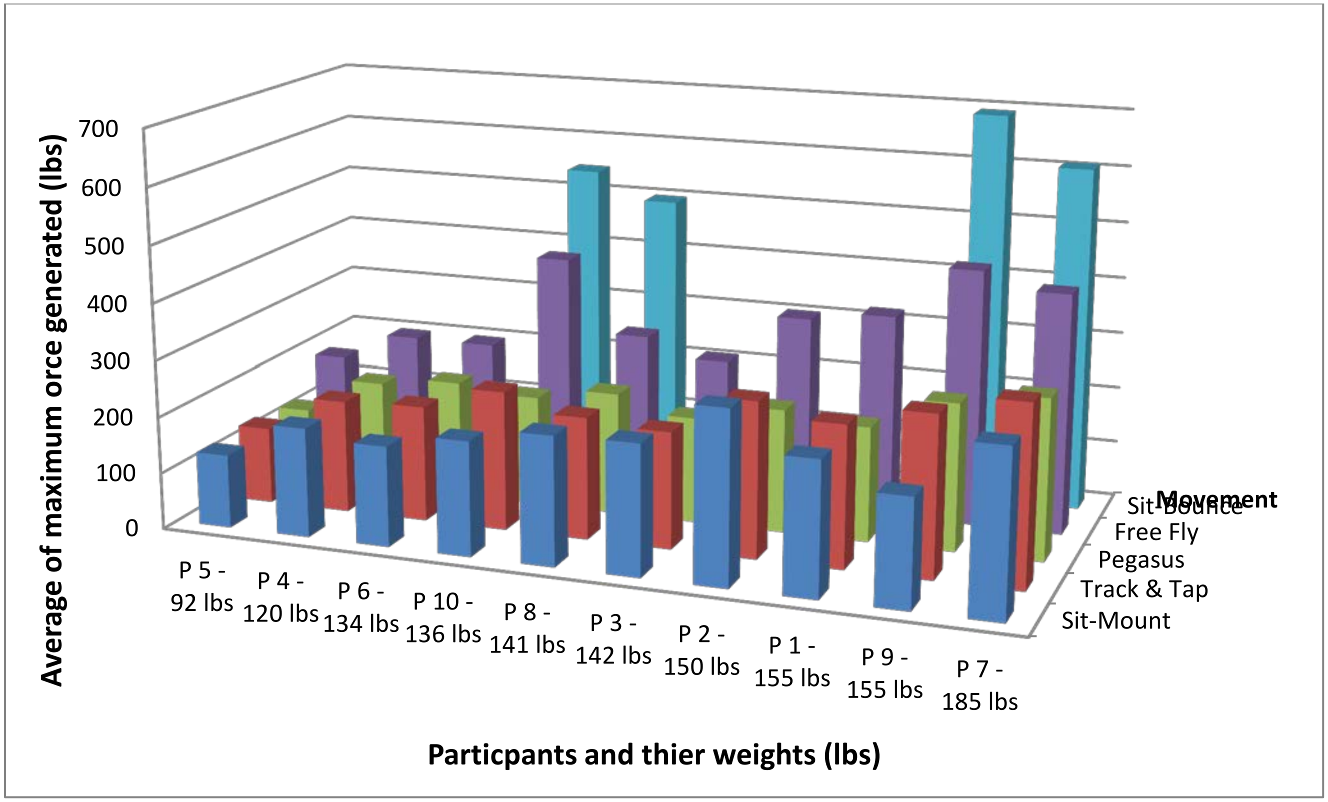

Chart 4.1 – Average of maximum force for each participant for each movement (lbs)

4.4. Analysis of the maximum data

As shown in Table 4.4, the maximum force of each participant's data for each movement was also calculated and then data was again transposed and sorted by each participant's weight.

Participant	Weight	*Sit-Mount*	*Track & Tap*	*Pegasus*	*Free-Fly*	*Sit-Bounce*
P 5	92	138	141	140	305	-
P 4	120	214	208	221	307	-
P 6	134	181	232	233	309	-
P 10	136	210	255	213	637	607
P 8	141	237	220	225	359	540
P 3	142	256	217	189	283	-
P 2	150	363	297	236	479	-
P 1	155	251	254	215	479	-
P 9	155	201	307	283	603	766
P 7	185	321	346	310	497	641

Table 4.4 – Maximum force for each participant for each movement (in lbs)

The maximum data was then plotted on a three dimensional bar chart in Chart 4.2. Participants are displayed on the x (horizontal) axis; the various movements are displayed on the z (depth) axis; and the maximum force generated by each of the movements for each participant is displayed on the y (vertical) axis.

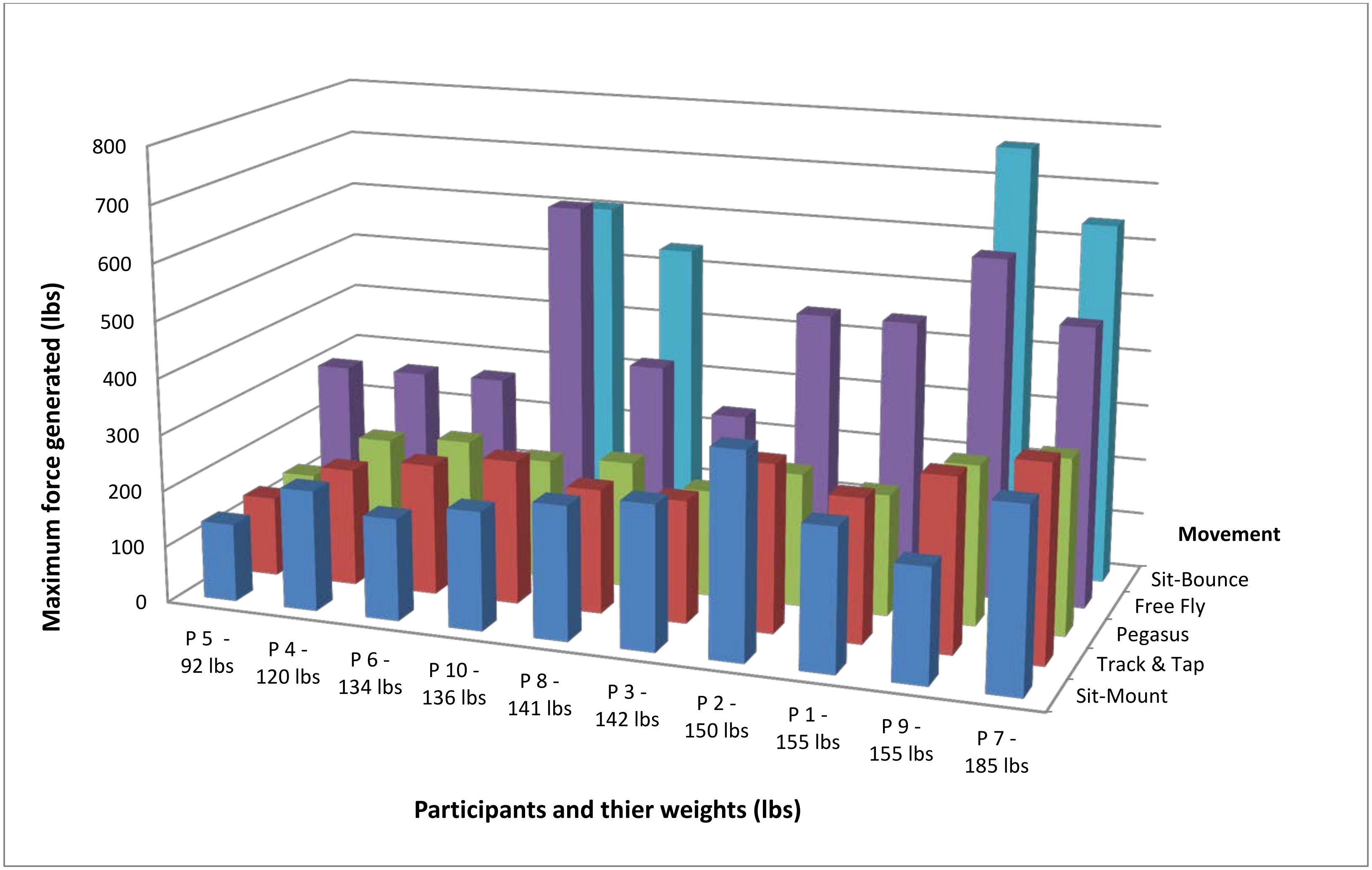

Chart 4.2 – Maximum force for each particpant for each movement (in lbs)

4.5. Analysis of the ratio of maximum force to aerialist's weight

As shown in Table 4.5 , the ratio of the participant's weight to the maximum force each participant generated for each movement was also calculated. The data was then transposed and sorted by each participant's weight.

Participant	Weight	*Sit-Mount* Ratio	*Track & Tap* Ratio	*Pegasus* Ratio	*Free-Fly* Ratio	*Sit-Bounce* Ratio
P 5	92	1.50	1.53	1.52	3.32	-
P 4	120	1.78	1.73	1.84	2.56	-
P 6	134	1.35	1.73	1.74	2.31	-
P 10	136	1.54	1.88	1.57	4.68	4.46
P 8	141	1.68	1.56	1.60	2.55	3.83
P 3	142	1.80	1.53	1.33	1.99	-
P 2	150	2.42	1.98	1.57	3.19	-
P 1	155	1.62	1.64	1.39	3.09	-
P 9	155	1.30	1.98	1.83	3.89	4.94
P 7	185	1.74	1.87	1.68	2.69	3.46

Table 4.5 – Ratios of particpant's weight to maximum force generated for each movement

This ratio was then plotted on a three dimensional bar chart in Chart 4.3. Participants are displayed on the x (horizontal) axis; the various movements are displayed on the z (depth) axis; and the ratio of maximum weight to force generated by each of the movements for each participant is displayed on the y (vertical) axis.

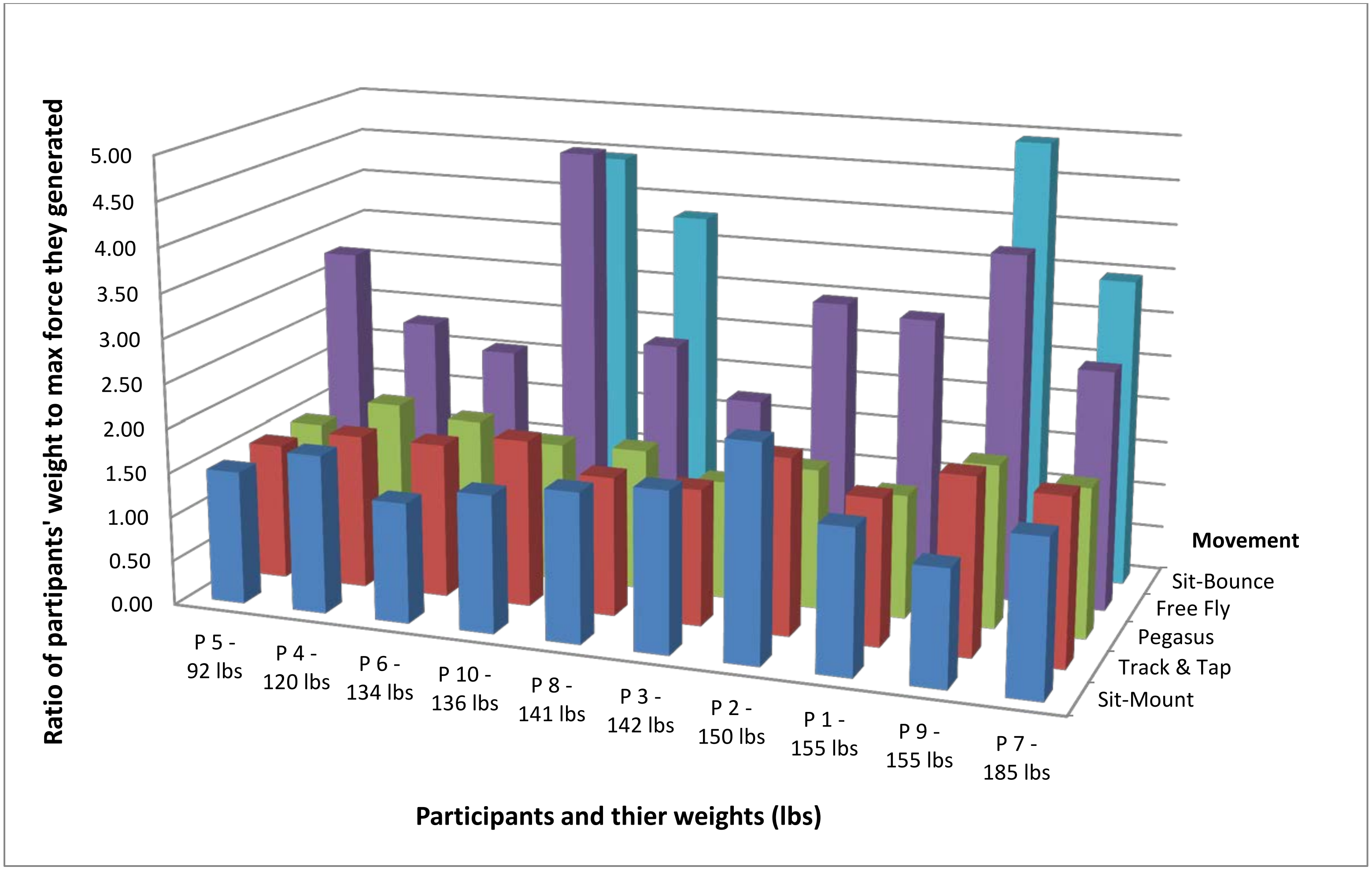

Chart 4.3 – Ratios of particpant's weight to maximum force generated for each movement

4.6. Inferences based on the analysis of the data

After reviewing the data as presented in both the tables and the charts, some initial inferences can be reached. As discussed in Chapter 2, there is some benefit in separating the movements into two types: cyclical movements, including *Track and Taps* and *Pegasus*, where the participant moves back in forth in a regular pattern; and non-cyclical movements, including all other movements, where the participant either does a quick instantaneous movement like a *Sit-Bounce*, or moves on the trapeze in an irregular manner. These two types of movements generate force at different angles: the cyclical movements are not directly perpendicular to the floor, but are instead at angles ranging up to approximately 85 degrees from vertical; while all the other movements tend to be forces generated perpendicular to the floor, in a vertical direction (down).

In the example in Figure 4.1 – the participant has pulled themselves up from the trapeze bar and is about to drop down onto the bar in a *Sit-Bounce*. The force in this movement is almost completely vertical, or straight down.

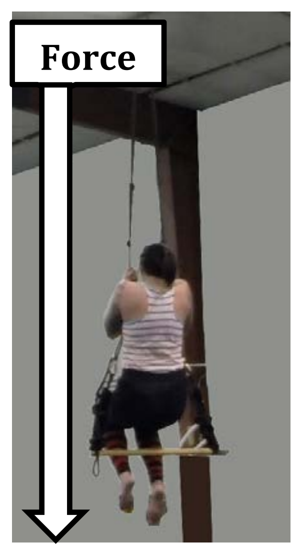

Figure 4.1 – Force in non-cyclical movement (i.e. *Sit-Bounce*)

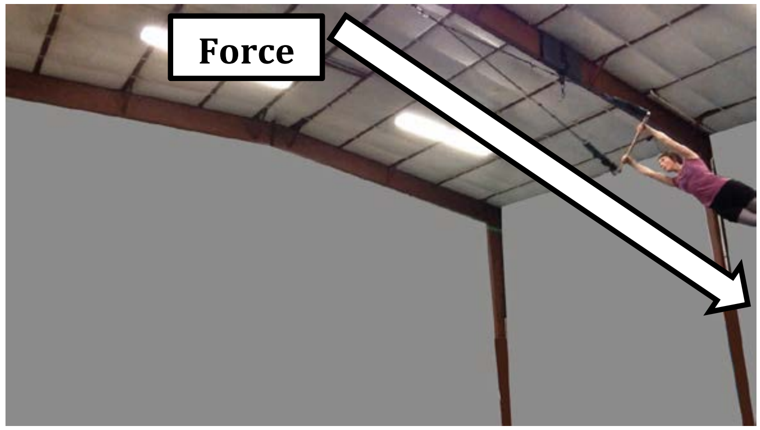

Figure 4.2 - Force in cyclical movement (i.e. *Track and Tap*)

In the example in Figure 4.2, the participant is at the apex (highest point) of a *Track and Tap*. The force in this movement has a large horizontal component.

The vertical force generated by movement directly perpendicular to the floor is essentially generated by gravity; the participant has pulled themselves up, or wound themselves up in the trapeze ropes, and is essentially 'falling down'. The force generated in the *Trap and Tap* and in the *Pegasus* not only involves the force of gravity pulling the participant down, but also the force generated by the participant as they run across the floor and then launch themselves into the air. It is interesting to note that the maximum force generated by the perpendicular movement occurs straight down, while the maximum force generated by the cyclical movements (*Track and Taps* and *Pegasus*) actually occurs out to the side at an angle. This will become important when examining different types of rigging hardware and how the hardware may need to be rated to properly accommodate these non-vertical forces.

In either case, there appears to be only a loose correlation between the participant's weight and the amount of force generated. While it might be expected that as the participant's weight increases the force they generate also increases, in fact, in many cases, a lighter participant actually generated a significantly larger amount of force. For instance, examining the max weight table/chart for *Track and Tap* for Participant 10, they weighed 136 lbs. and yet generated 255 lbs. of force, which is approximately the same amount of force as Participant 1, who weighted 155 lbs. and generated 254 lbs. of force. Another example is shown for *Free-Flight* where the participants were asked to perform any of their favorite movements on the trapeze. Participant 10 (who weighed 136 lbs.) was able to generate 637 lbs., while Participant 7 (who weighed 185 lbs.) only generated 497 lbs.

While it might be expected that a heavier person generates more force than a lighter person, in fact much of the force generated depends on both the participant's experience with aerial dance and the participant's personal style of movement. Aerialists are in general taught to move with grace and fluidity; the goal is to make the movement as smooth and effortless as possible. Therefore, much of the force loading is smoothed out by how the aerialist moves. A more experienced aerialist will potentially have a smoother, seemingly more effortless movement then a newer aerialist. Also, some aerialists naturally move with a light movement quality, while others tend to be more forceful and strong. This, combined with the different qualities of the movements themselves, makes it difficult to draw conclusions on force based solely, or even mostly, on an aerialist's weight.

4.7. Analysis of cyclical types of movements

As mentioned at the beginning of Chapter 4, the equipment not only captured the maximum force of each movement, it also captured data points at least every ten milliseconds for the entire length of the movement. A plot of this data for the entire length of Participant 7 during *Track and Tap* #2 is shown in Chart 4.4.

4.7.1. Analysis of *Track and Tap* #2 for Participant 7

This chart clearly shows the cyclical properties of the force generated during a *Track and Tap*. The force starts at 0, increases to 346 lbs. — a value greater than the participant's weight of 155 lbs. — then back down to below the participant's weight, then back up to a value of approximately 275 lbs. The force continues to cycle up and down, with the minimum and maximum force for each swing approximately the same value.

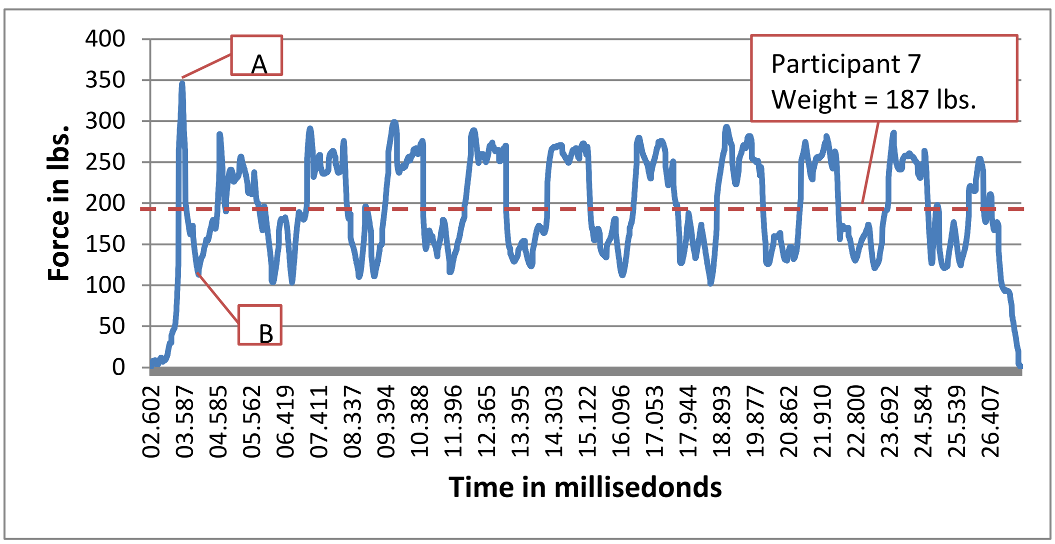

Chart 4.4 – Plot of force for Participant 7 during *Track and Tap* #2

By comparing the times recorded with the data, and the times on the video tape of each participant, it is possible to determine approximately where the maximum force occurs (the spike at the beginning of the chart). Point A in Chart 4.4 corresponds to the data in Table 4.6 and the position in Figure 4.3 which illustrates that the maximum force is 346 lbs. at time 3.548, which is just after their foot has pushed off from the floor as they begin their first *Track and Tap*.

	Time	Force (lbs.)
	00:00:03.533	337
	00:00:03.536	340
	00:00:03.539	343
	00:00:03.542	345
	00:00:03.545	346
Point A	00:00:03.548	346
	00:00:03.551	344
	00:00:03.554	341
	00:00:03.557	338
	00:00:03.560	334

Table 4.6 - Participant 7, *Track and Tap* #2, maximum force

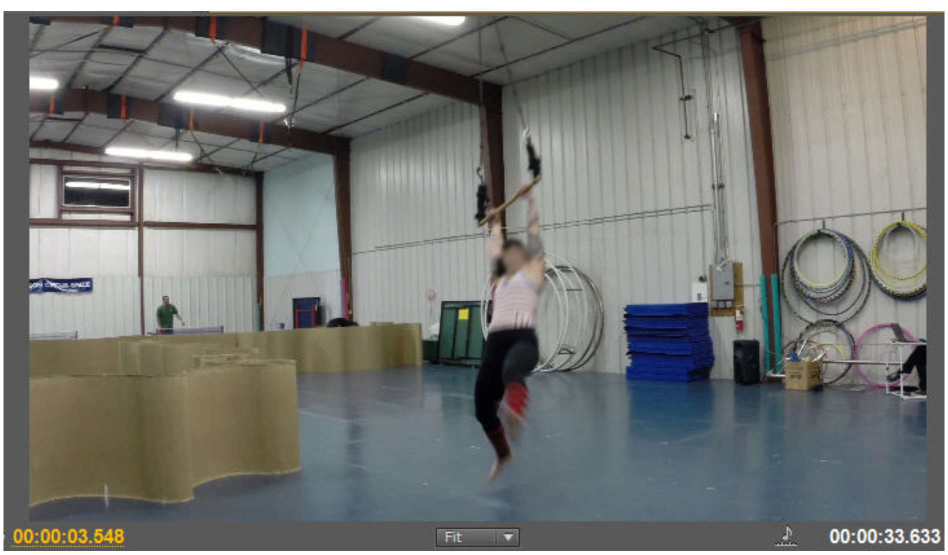

Figure 4.3 - Participant 7, *Track and Tap* #2, maximum force position

It is of interest to note that Point B in Chart 4.4 is when they were swinging through the highest point in their swing (the apex) and is when the minimum force occurred. This is illustrated in Table 4.7 and Figure 4.4. Examining the entire length of Participants 7's *Track and Tap* #2, it was consistently true that for each of the apexes the force was at a minimum amount.

	Time	Force (lbs.)
	00:00:03.990	117
	00:00:03.993	116
	00:00:03.996	115
	00:00:03.999	115
Point B	00:00:04.002	114
	00:00:04.006	114
	00:00:04.012	113
	00:00:04.063	120
	00:00:04.066	120
	00:00:04.069	121

Table 4.7 - Participant 7, *Track and Tap* #2, force at apex

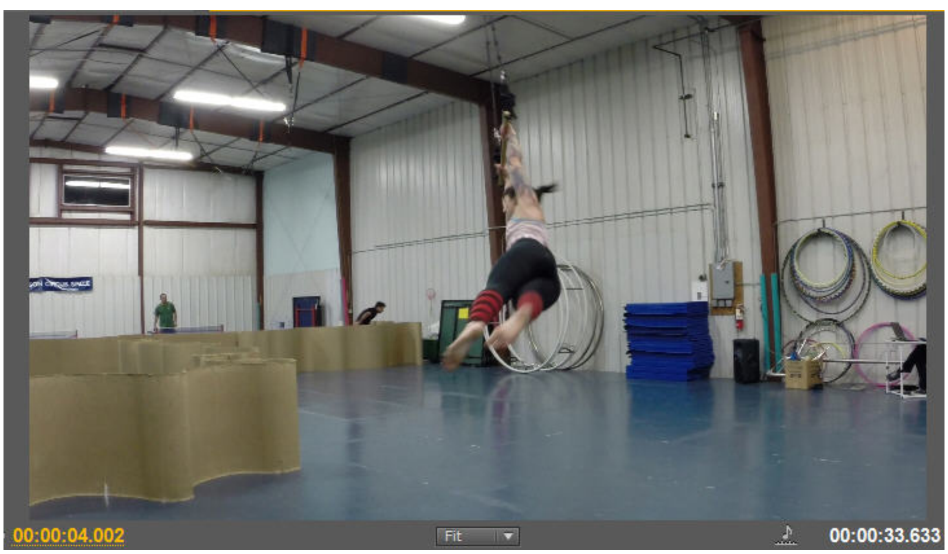

Figure 4.4 - Participant 7, *Track and Tap* #2, apex position

Other than the large spike at the beginning of data, the maximum force consistently occurred as they were swinging through the lowest point of their swing and not just after they pushed off.

4.7.2. Analysis of *Pegasus* #2 for Participant 7

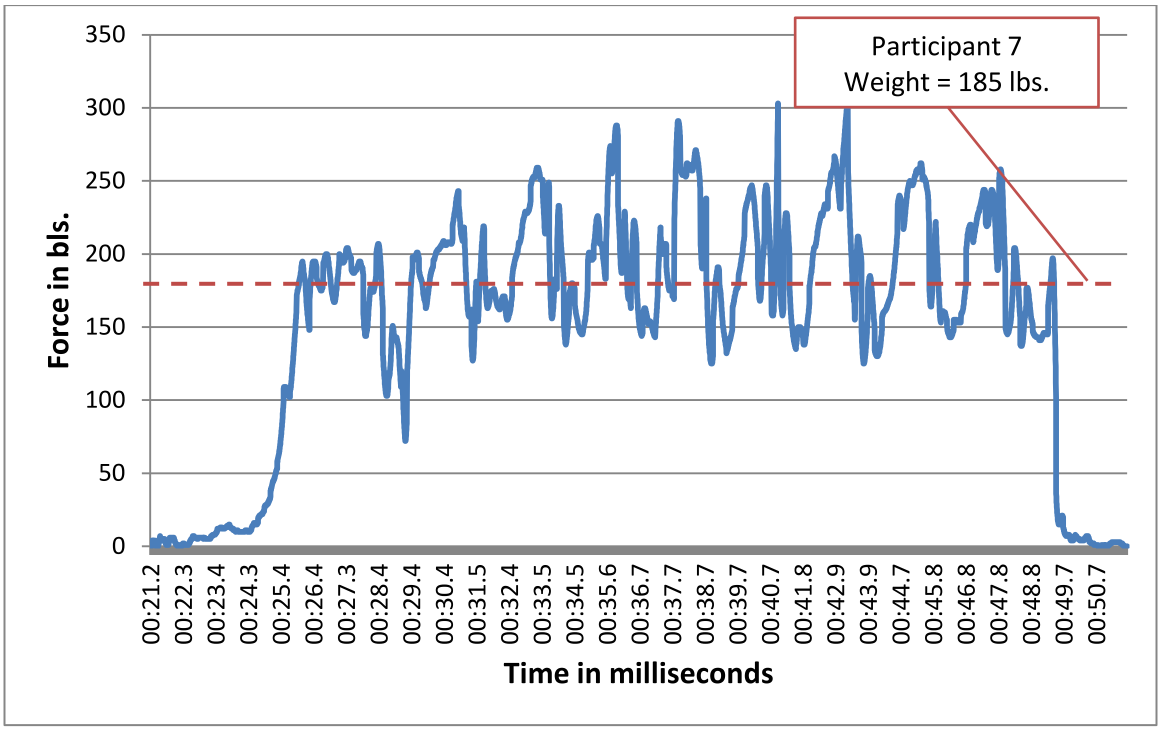

Chart 4.5 – Plot of force for Participant 7 during *Pegasus* #2

The data for a *Pegasus* for Participant 7 is shown in Chart 4.5, and demonstrates a somewhat similar cyclical pattern. Because of the more complex nature of how the participants moved during the *Pegasus*, it was more difficult to analyze the video tapes of the participant and compare them to the data captured during the research. While it cannot be conclusively proven, the data suggests that the maximum force during the *Pegasus* also occurred as they were swinging through the lowest point of their swing.

4.8. Force equation and shock Loading

In the case of the *Free-Fly* movements, much of the irregularity in data can be attributed to the fact that each participant performed a variety of movements. During the *Free-Fly*, all participants used movements that were primarily in the vertical direction, with little or no horizontal component. By analyzing the participant's movement, some insight can be gained into why a smaller participant was able to generate more force than a larger participant. For instance, Participant 10 weighed only 136 lbs. When they did a roll drop, where they rolled up in the trapeze rope, and then quickly unrolled out of it, they generated 637 lbs. This is essentially a shock loading movement, as displayed in chart 4.6. (Section 4.9.1defines Characteristic Load).

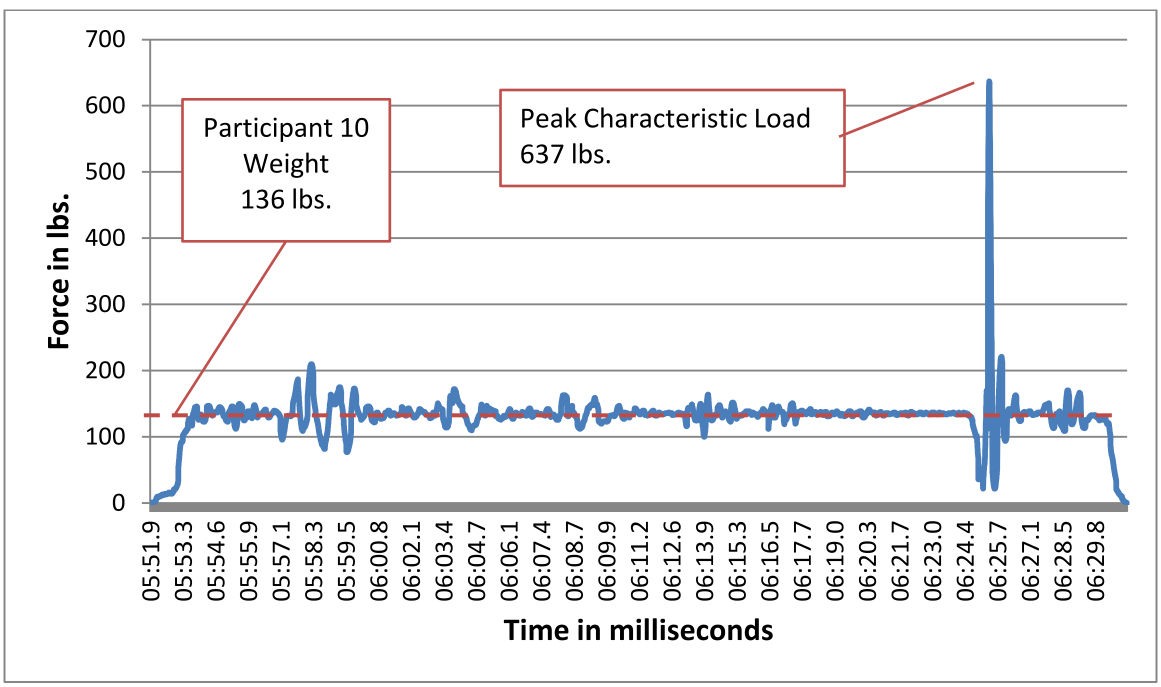

Chart 4.6 – Plot of force for Participant 10 during *Free-Fly* #2

In this example, for approximately the first 34 seconds of the movement, the participant was getting into position for the drop by rolling up into the ropes. Then, at 6:25, the participant quickly unrolled and as their roll was stopped by the trapeze bar and the ropes, they were able to generate 4.68 times their weight. This would be considered a Peak Characteristic Load. It represents a type of movement that might be choreographed on the apparatus, and the typical force it would generate. This force is generated perpendicular to the floor, and generated by gravity pulling the participant primarily straight down.

4.8.1. Theoretical peak shock load

Also to be considered is the theoretical maximum peak shock loading, which would be a calculated value instead of an actual measured value. In his article from the Theatre Design & Technology journal titled “Understanding Shock Loads”, Delbert Hall states that “Three factors determine the magnitude of the shock load: the weight of the object, the speed that the object is traveling before it starts to decelerate, and the rate of deceleration (the stopping distance)"[13]. He also provided a formula for using these three factors to calculate the shock load on the system when using fiber rope:

[13] Hall, Delbert L., “Understanding Shock Loads,” 46.

$$\text{Shock Load} = \frac{-\text{B} + \sqrt{\text{B}^2 - (4 \times \text{A} \times \text{C})}}{4 \times \text{A}}$$

Equation 4.1 - Calculating shock load on fiber rope[14]

The factors in the formula are calculated as follows:

- A = (0.005 × Rope Stretch × Rope Length)/ Rope Load
- B = - 2 × A × Load
- C = - Load × Fall Distance (in feet)
- Rope stretch: a percentage specified by the manufacturer.
- Rope length: the distance, in feet, between the load and the termination point.
- Rope load: the force, in lbs., required to achieve the manufacturer's rope stretch.
- Load: weight of object that falls.
- Fall Distance: the distance, in feet, that the load free falls.

For the rope used in this research, Sampson Trophy Braid, the values are as follows:

- Rope stretch: 2.2%[15]
  - Deflection (bending) of the wooden trapeze bar would also have a similar effect as rope stretch. As the trapeze bar bends it absorbs some percentage of the deceleration force. Calculating the value for trapeze bending is outside the scope of this thesis, however not including this value increases the load limit value, therefore moving the value in a safer direction.
  - The round sling, a green TWINTEX Spanset has an elongation factor of approximately 3%[16]. Calculating this value is out of the scope of this thesis.

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[14] Ibid., 48.
[15] "Samson."

- Rope length: the distance between the carabiner at the top of the rope, and the trapeze bar at the bottom of the rope. This distance varied depending on the participant, but the largest value was 14'.
- Rope load: 300 lbs.[17]
- Load: 60 lbs. was used for the calculation.
    - All participants weighed less than 240 lbs. Also, 240 lbs. is well above the typical weight of aerialist. This value is used as a starting point for calculations, but may be adjusted later if necessary.
    - Since there are four ropes (two per side), each rope will support ¼ of the weight. 240 lbs. /4 = 60 lbs.
    - For the purposes of this research, the peak shock load calculation will be done for one rope, and then summed for all four ropes. Note that this assumption would need to be validated before it is utilized in an installation. Validating it is outside the scope of this thesis.
- Fall Distance: 14'. This is the distance from: the peak of the triangle formed where the ropes join at the top; to the trapeze bar at the bottom. This is the theoretical maximum distance that a performer could free fall and be stopped by the trapeze bar and the ropes.

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[16] "Spanset USA," 1.
[17] "Samson."

4.8.2. Peak Load – calculated using values from equipment used in research

Using the values from the system used in the research, the formula is used to calculate the theoretical Peak Loading that the system might experience in a worst case scenario.

- Rope stretch: 2.2%[18]
- Rope load: 300 lbs.[19]
- Load: 60 lbs. (¼ of 240 lbs.).
- Fall Distance: 14'.
- A = (0.005 × 2.2% × 14')/ 300 lbs. = 0.000513333
- B = - 2 × 0.000513333 × 60 lbs. = - -0.0616
- C = - 60 lbs. × 14' = -840

$$\text{Shock Load} = \frac{0.0616 + \sqrt{-0.0616^2 - (4\,x\,0.0616\,\text{x}\,-840)}}{4 \times 0.000513333}$$

$$\text{Shock Load} = 670 \text{ lbs x } 4 = 2680 \text{ lbs}$$

Equation 4.2 – Calculating Peak Load on system used in research

The shock load of 670 lbs. is for each rope. The force on all four ropes is transferred to the rest of the rigging hardware, and the building structure, and consequently needs to be summed; therefore the total computed Peak Load is 2680 lbs.

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[18] Ibid.
[19] Ibid.

As mentioned previously, the round sling has an elongation factor or 3%; however, I was not able to ascertain a method of calculating and adding the Peak Load of the round sling to the Peak Load of the rope. Including this value would reduce the peak load and therefore not including it will actually increase the overall margin of safety.

It is also probable that the knots in the rope will change the elongation factor for the rope; there were ten knots per side in the rope used in the research; each knot was approximately 1.5". This would potentially increase the shock loading value, but calculating this value is outside the scope of this thesis. Increasing the Peak Load value to factor in effect of the knots would be a reasonable method. Therefore, the assumption in this thesis is that the calculated total Peak Load for the system used in the research should be a value of 2700 lbs.

4.8.3. Establishing a reasonable Peak Load

An important point is that the value of 2700 lbs. would not only be applied to the equipment, but also to the aerialist; this force would probably be fatal to the aerialist.[20] OSHA standards for fall arrest systems in fact have the following limitations for fall arrest systems:[21]

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[20] Hall, Delbert L., "Understanding Shock Loads," 47.
[21] "1910.66 App C," sec. (11)(d)(1)(i–ii).

- Limit maximum arresting force on an employee to 900 pounds (4 kN) when used with a body belt;
- Limit maximum arresting force on an employee to 1,800 pounds (8 kN) when used with a body harness;

While OSHA does not address forces involved in aerial dance, it is reasonable to expect that the force on an aerialist should be limited to less than the 1,800 lbs. allowed for a fall when wearing a body harness.

From my personal experience as an aerial dancer and choreographer, it would be extremely difficult to design a fall arrest system that an aerialist could wear and still perform the choreography involved in aerial dance. Therefore, a more practical approach would be to implement policies and procedures that limit the ways in which an aerialist would interact with the trapeze. For instance, if the distance an aerialist could fall were limited by policy to only three feet, recalculating Equation 4.2 the Peak Load force would decrease to 1310 lbs., which is a more reasonable value. As an example of a policy of this type, Cycropia trains all its aerialists that free fall drops onto the trapeze bar are dangerous and should be avoided.

Note that this is for free fall drops, and would not limit choreography that might involve roll drops or other movements that would allow the aerialist to fall gradually by slowing themselves down using the rope.

4.9. Determining a Working Load Limit

After reviewing the data, determining the characteristic loading in both the horizontal and the vertical directions, and performing the Peak Shock Loading calculations, a Working Load Limit can be set using the desired design factors. The Professional Lighting and Sound Association (PLASA) has a Technical Standards Program (TSP) that is accredited by American National Standards Institute (ANSI) which sets standards for the entertainment industry. The TSP has written a draft standard for performer flying which is directed towards "devices and systems supporting people or components to which people are attached, suspended in the air that give the impression of weightlessness, floating, flying, or descending, and for acrobatic and circus performance acts. "[22]

4.9.1. TSP definitions of different types of loads

The TSP standard defines the following terms that are relevant to this thesis:

- Characteristic Load: The maximum force applied to the performer flying system resulting from normal intended operating conditions while the system is at rest or in motion. This includes the working load limit (WLL), self-weight including that due to load carrying devices and lifting media, and forces due to inertia and dynamics in normal use.[23]
- Peak Load: The maximum force applied to the performer flying system resulting from abnormal conditions, or irregular operation (e.g., effects of emergency stops, uncontrolled stops, drive electronics or power failure, stalling of the actuation equipment, extreme environmental conditions).[24]

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[22] "DRAFT - BSR E1.43-201x, Entertainment Technology—Live Performer Flying Systems," 1.
[23] Ibid., 2.
[24] Ibid., 3.

- Risk Assessment / Risk Reduction (RA/RR): The cyclical process of identifying risk, mitigating risk, evaluation of residual risk, and repeating the process until the risk has been reduced to an acceptable level.
- Working load limit (WLL): The maximum weight as defined by the Flying System Designer that a User is allowed to apply to a lifting medium in the performer flying system.[25]
- Design factor: A ratio of the design load limit to the ultimate load carrying capacity of a material or component.[26]
- Flexible lifting media (e.g., rope, chain, band, webbing) shall be designed with a minimum design factor of 10X WLL, 6X characteristic load and 3X peak load.[27]
- Ultimate load carrying capacity: The maximum load a component may support without fracture, buckling or crushing as determined by nationally recognized construction standards appropriate for the given material.[28]

4.9.2. Peak Loading

Peak Loading is an important criterion to consider in rigging system design because it is always expected to be higher than (or equal to) any of the characteristic loads. Therefore, it will most likely be the limiting value that is used to select the rigging components for the system. In the case of single point aerial dance, Peak Loading will generally be due to gravity and be downwards in a vertical direction. Because this is the peak load that can be applied to the system, and is a calculated value that is a theoretical maximum, the design factors can be lower for this value. For the purpose of this thesis, the design factor for Peak Loading is three, which is the value from the TSP

[25] Ibid., 4.
[26] Ibid., 7.
[27] Ibid., sec. 4.8.4.1.
[28] Ibid., 4.

standards. Recalculating the formula based on a 3' drop, the Peak Loading value becomes 1310 lbs., which when multiplied by the design factor of three results in a Peak Loading for the system of 3930 lbs.

4.9.3. Characteristic loading for drops and falls (Vertical)

While movements that are drops and falls are less typical that the cyclical movements, they still occur often enough that they are considered characteristic for an aerial dance system and design limits would need to be set for them. In the case of single point aerial dance, this value will primarily be straight down and will be less than the peak shock loading, since free fall drops are not a characteristic movement and are in fact something that aerialists are trained to avoid. The research in this thesis shows that typical values for a *Roll Drop* can be as high as five times the performer's weight, which was the highest characteristic load that was observed. Using the 240 lbs. that was previously set as the maximum performer weight, the Characteristic Load for drops and falls would be 240 lbs. x 5 = 1200 lbs.

For the purpose of this thesis, the design factor (DF) for Characteristic Loading in the vertical direction is six, which is the value from the TSP standards. Therefore, the design Characteristic Load for drops and falls would be 1200 lbs. x 6 = 7200 lbs.

4.9.4. Characteristic loading for cyclical movement (Horizontal)

Typical characteristic loading during the cyclical aerial dance movements needs to be considered separately from drops and falls because these movements occur in the horizontal plane and therefore loads the system differently. The research in this thesis shows that the horizontal force can potentially be twice the aerialist's weight and can be at angles as high as 45 degrees. For the purpose of this thesis, the design factor for Characteristic Loading in the vertical direction is six, which is the value from the TSP standards. The Characteristic Load for cyclical movement (Horizontal) can be calculated using the following values:

- 240 lbs.: maximum allowed aerialist's weight
- 2: multiplication factor based on the research
- 6: design factor from the TSP standard

Therefore, the design Characteristic Load for cyclical movement would be

- 240 lbs. x 2 x 6 = 2880 lbs.

4.9.5. Summary of design load limits

Three design load limits were calculated for the system:

- Peak Load Limit: 3930 lbs.; based on a 240 lb. aerialist falling 3' and being stopped by the rope. DF: 3 (reduced by RA/RR from 8100 lbs. for a 14' fall)
- Vertical Characteristic Load Limit: 7200 lbs.; based on a 240 lb. aerialist performing a *Roll Drop* and generating a force of five times their weight. DF: 6
- Horizontal Characteristic Load Limit: 2880 lbs.; based on a 240 lb. aerialist performing a *Track and Tap* and generating a force of twice their weight. DF: 6

4.9.6. Equipment used in research

The equipment used in this research represents equipment that would be used in a typical single point aerial dance installation. It includes the following hardware, starting at the top with the connection to the building I-beam:

- *SpanSet* E60 TwinTex Endless Sling
  - Green Polyester Round Sling
  - Two were used in parallel with each other
  - Wrapped around the I-beam, which was padded with thick rubber-backed carpet; then passed through itself to form a choker.
  - WLL 4,200 lbs. choker each, 8,400 lbs. total
- *Black Diamond* Twist Lock Carabiner
  - 24 kN (5395 lbs.) ultimate breaking strength
  - Two carabiners are used, one above and one below the swivel
- Sterling Rope SR Swivel
  - 36kN (8093 lbs.) ultimate breaking strength
- Sampson 3/8" Trophy Braid Rope
  - 3,000 lbs. average breaking strength
  - There are four total lines used in the trapeze rope, two per side.
  - Each side has several overhand knots tied in them to provide gripping points for the aerialist. Any one overhand knot decreases the strength of the rope to 50% (.5)[29] of its total strength; this value is non-additive.
  - 3000 lbs. x 4 ropes x .5 = 6000 lbs. average breaking strength
- Trapeze bar
  - Birch 1-1/4" wooden dowel
  - 28" long

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[29] Carter and Carter, *Backstage Handbook*, 88.

4.9.7. Determining Working Load Limit

Reviewing the load ratings for the equipment used in the research and comparing it to the three Design Load Limits (Section 4.9.5), it is obvious that some of the equipment does not have a high enough load rating for the Peak Load. Specifically, neither the carabiners (5,395 lbs.) nor the rope (6,000 lbs.) meet the desired Vertical Characteristic Load Limit rating of 7,200 lbs.

To resolve these issues, the components could be replaced with ones that have a higher load rating. For example a Fusion Tacoma-TK carabiner, which has a load rating of 50kN (11,240 lbs. ultimate strength), could be used. Increasing the size of the rope to ½" would increase its breaking strength to 12,000 lbs.; while this would also in fact increase the Peak Load value to 5,400 lbs. that would still be under its breaking strength. Another technical solution may be to change the knots from overhand knots (50% strength reduction) to figure eight knots (36% strength reduction)[30] which would provide a breaking strength of 7680 lbs. for all four ropes combined. However, changing the knot may be undesirable from either the choreography or visibility standpoint, as a figure eight knot is slightly larger than an overhand knot.

Another possibility is to limit the allowable weight for aerialists for certain types of movements. If a limit of 180 lbs. were set for vertical *Roll Drops*, the vertical Peak

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[30] Donovan, *Entertainment Rigging*, chap. 7, page 29.

Load would be reduced to 5400 lbs., which is under the ultimate strength of the 3/8" rope that was used in this research.

Based on the calculations above and the equipment used in this research, I would recommend a WWL for the system of 240 lbs. for all movements except *Roll Drops*; I would set a WLL of 180 lbs. for *Roll Drops*; I would set a limit of three feet on any free fall drops.

Chapter 5

Rigging considerations and options

5.1. Introduction

The research and information in this thesis can assist a rigger to make safe, informed decisions when utilizing aerial dance equipment, specifically single point aerial dance trapeze. Since each installation is unique, with different building structure, differences in the height of the rig point, different types of apparatus, and varying choreography needs, this thesis can only provide general suggestions on what to consider when installing aerial dance equipment. Additionally, before installing any equipment, the overall building design needs to be carefully evaluated to ensure that it can adequately support the additional dynamic load generated when single point aerial dance is performed. If necessary, a structural engineer should be consulted to determine load considerations for the building.

5.1.1. Site considerations

To properly evaluate the building structure, the specific rig point for the equipment installation will need to be determined. When considering the specific rig point, the rigger will need to know information about the expected use for the equipment, including information about the choreography. Some items to consider are:

- how much height and width will be needed;
- how many aerialists will be using the equipment;
- whether the expected load will be mostly in the vertical direction or whether there will be significant horizontal movement;
- how long the installation will be utilized, and how often (is it a temporary installation for a single performance, or will it be utilized for regular rehearsals);
- what obstructions might be in the space;
- access to the rig point (will the apparatus need to be changed out on a regular basis;
- how will maintenance be done on the rig point/equipment).

This information would then be provided to the structural engineer allowing them to make more informed calculations determining how the load of the aerial equipment will affect the building structure.

5.2. Connecting equipment to the building structure

Once the installation rig point has been determined and the building structure has been evaluated, the rigger would need to determine how to connect the equipment to the building. From my personal observations, the three most widely used methods are beam clamps, eye bolts, and round slings. Each of these methods has benefits and drawbacks. Before using any of these methods, some factors to consider are the load that will be applied, what direction that load may be applied in, the manufacturers load ratings and recommendations for the device, the frequency of use, and how long the equipment will be in the location. One very important factor to consider when selecting a connection to the building is how the rating factor is affected by loads not in line with the device. Because of the probability of a horizontal component in aerial dance movements, side loading and off axis side loading need to be carefully considered. Finally, cost must be considered; in general, eye bolts are the least expensive option, round slings are more expensive then eye bolts, and beam clamps are the most expensive option.

5.2.1. Beam clamps

When there is an available I-beam, beam clamps are often utilized. This is especially true if access around the entire beam is not possible. Almost none of the beam clamps researched is rated for overhead lifting of people, and many manufacturers and vendors in fact specifically state "Do Not lift people or lift loads over people". Additionally, most of the load ratings on the beam clamps researched are maximum load; accordingly a design factor will need to be supplied to determine a WLL.

Also, most beam clamps (and eye bolts) are load rated for vertical loads, and some de-rating design factor should be applied for use in aerial dance because of the probability of side loading due to horizontal forces generated in aerial dance. Some beam clamps either are rated for side loading, or have a de-rating factor based upon the angle of the side load; however, that side load rating may be only for loads in the same plane as the eye/beam clamp, as shown in Figure 5.1. Loads that are not in the same plane as the eye/beam clamp do not have any rating at all, and some manufactures specifically state that loads are not allowed in that direction.

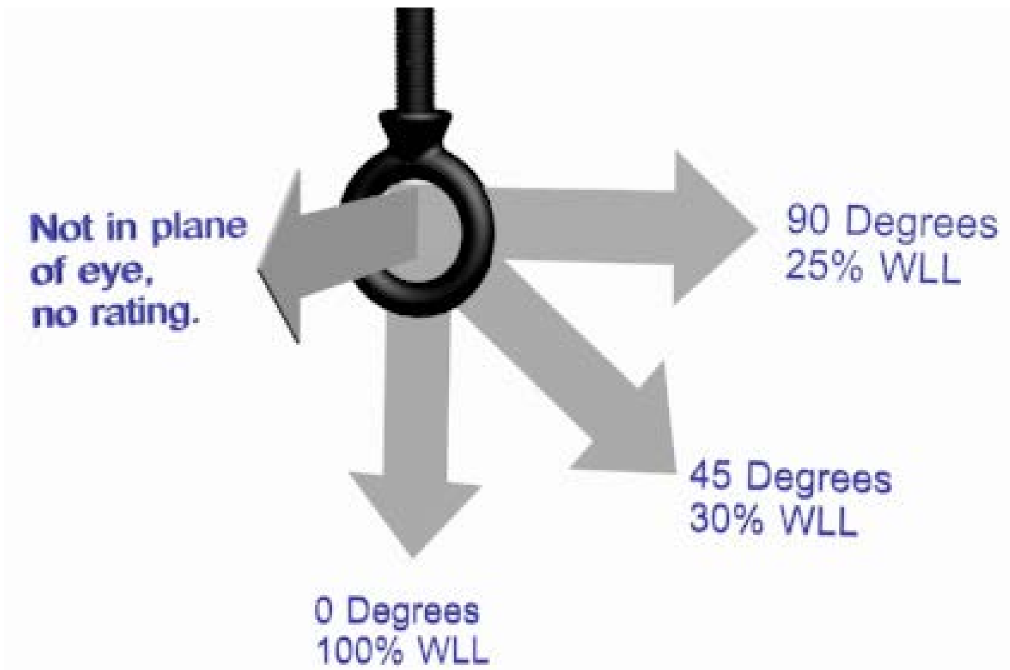

Figure 5.1 – Side loading and off axis side loading of eye bolts/beam clamps

There are numerous different styles of beam clamps available that might be applicable to aerial dance rigging, some of which are discussed in the following sections.

The type of beam clamp that I have often observed being used in aerial fabric installations is shown in Figure 5.2. These come in different capacities based upon both the size of the I-beam and the expected load. Note that the documentation from

Harrington specifically states "Clamp is intended only for vertical lifting services or freely suspend unguided loads. Do **<u>not</u>** use clamp for loads that are not lifted vertically, loads that are not freely suspended, or loads that are guided."[31](Bold underline is from original document). Based on this warning, devices of this type do not seem appropriate for single point aerial dance trapeze rigging, which generates significant non-vertical loads.

Figure 5.2 – 2 ton Harrington universal beam clamp[32]

Another style occasionally utilized is shown in Figure 5.3. These are most frequently used by gymnastics clubs for attaching ceiling hung rings, climbing ropes and spotting rigs to I-beams. This style is sized by the width of the flange of the I-beam and seldom includes a load rating. As has been demonstrated through this research, the loading for aerial dance can be much higher than the weight of the aerialist. If the gymnastics beam clamps are not load rated, it is difficult to evaluate them for use as rigging hardware for aerial dance.

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[31] "Universal Beam Clamp Owners Manual," 3.
[32] "Certified Slings and Rigging Store."

Figure 5.3 –Gymnastic beam clamp[33]

Another style of beam clamp is the model shown in Figure 5.4 that is designed for threaded hanger rod. It will fit beams up to 5" and is load rated for a maximum load of 8000 lbs., depending on beam size. I personally have never seen these used for aerial dance rigging and would want to perform a thorough RA/RR analysis to determine if they would safely hold both the vertical and horizontal load of aerial dance.

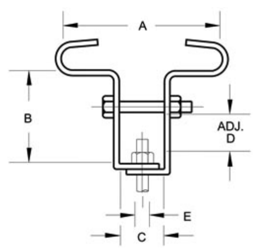

Figure 5.4 – Hanger rod beam clamp[34]

Often in building construction, two steel beams will need to be connected securely together without welding and there are specific clamps designed for such purposes. Shown in Figure 5.5 is such a clamp, but instead of a beam to beam connection, the manufacturer, LNA Solutions, uses the clamps to hold a plate with a shackle mounted on it. Other manufactures have similar solutions. The shackle has a

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[33] "American Gymnast," I–Beam–Clamp–P212.aspx.
[34] "Stainless Fasteners," nless–steel–beam–clamps–stainless–steel–beam–clamp.

side load rating up to 45 degrees, and moves freely on its pivot allowing it to adjust somewhat to horizontal side loads. However, with very fast movements, it may be possible to cause the shackle to bind and not move freely.

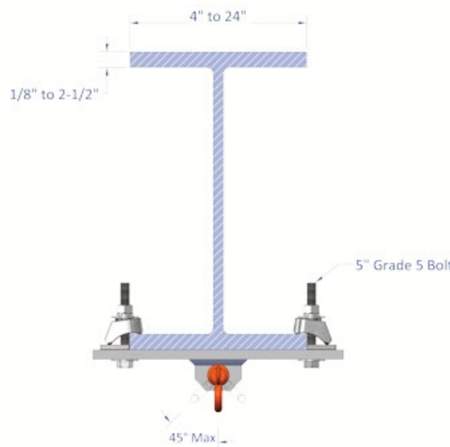

Figure 5.5 – Steel to steel beam clamp [35]

A beam clamp that has recently become available is shown in Figure 5.6. Based on an email from the vendor, the eye swivels 360 degrees, and can be loaded up to 45 degrees.[36] It is available in one and two ton models. Because of the maximum angle of 45 degrees, it may not be appropriate for single point aerial dance trapeze installations.

Figure 5.6 – Beam clamp with swivel eye[37]

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[35] "LNA Solutions," beamclamp–rigging–clamps–krc062.
[36] "Machinery Eye Bolts."
[37] "Beam Clamps."

Another newer beam clamp is the ClimbTech I-beam anchor, shown in Figure 5.7. It is designed primarily "for fall protections, rope access and work positioning".[38] Unfortunately, according to the manufacturer, this clamp is designed to slide along the beam, which may make it inappropriate for use in single point aerial dance trapeze installations because the horizontal loads may cause it to slide along the I-beam.

Figure 5.7 – ClimbTech safety beam clamp with swivel eye[39]

5.2.2. Eye Bolts

Eye bolts are primarily designed for vertical load applications, and some de-rating must be applied if the load is at an angle (refer to Figure 5.1); only shoulder eye bolts should be used for angular lifts. A shoulder eye bolt is shown in Figure 5.1. At 45 degrees, the WLL needs to be adjusted to 30% of the rated WLL; at 90 degrees, 25% of the rated WLL.[40] Eye bolts must be aligned in the direction of the load, as shown in Figure 5.1[41] Because of the probability of horizontal loads in aerial dance, and because of the manufacturer's recommendation against off axis side loading; a very thorough RA/RR analysis should be made before using them in aerial dance.

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[38] "ClimbTech Beam Clamp."
[39] Ibid.
[40] Donovan, *Entertainment Rigging*, chap. 7, pages 12–13.
[41] Ibid., fig. 4.30.

5.2.3. Round Slings

Round slings present a good solution for attaching to I-beam and other building members where access completely around the building structural member is possible. Round slings are industry standards in arena rigging and have load ratings in an acceptable range for aerial dance installations.

There are two important installation considerations for round slings: how tightly they are choked and the angle of the load on the choke. If the choke is left fairly loose the round sling tends to slide along the beam as the aerialist performs movements like a *Pegasus*, which loads the sling with horizontal force. A rigger may have be a tendency to choke the sling as tightly as possible, to prevent it from sliding on the beam. However, if the choke is made too tight, causing the angle between the two legs to become greater than 120 degrees, the force on the round sling will increase significantly. As the angle approaches 180 degrees, the force can easily exceed the load rating of the sling. This is essentially the same issue that is faced with very tight basket hitches and also bridle angles.[42] A better solution than tightening the choke too tightly is to take an extra wrap around the structural member. [43]

A second issue, also related to the horizontal loading, is the angle of the load to the choke. This may become an issue when the aerialist flies up at a high angle in a

[42] Ibid., chap. 1, page 7.
[43] Ibid., chap. 1, page 10.

direction that bends the sling back over itself at a small angle. Donovan and many of the sling manufacturers provide the following values for the load rating of choked slings:[44]

120° - 180°	100%
90° - 119°	87%
60° - 89°	74%
30° - 59°	62%
0° - 29°	49%

Table 5.1 - Choker hitch angle adjustment

The values that are in the table are the percent of load rating remaining. Note that the WLL of a green round sling is 4,200 lbs. when used in a choke, with a manufacturer's DF of 5:1. Therefore its ultimate breaking strength is 21,000 lbs. When applying the DF of 6:1 used in this thesis, its WLL is 3,400 lbs., which at a 0 degree angle, is reduced to 49% (of 3,400 lbs.), which is 1,666 lbs. This is still well over the maximum horizontal loads measured in this thesis.

5.2.4. Custom design

One possible solution to address the issues with horizontal loading forces would be to mount a swivel hoist ring onto a custom beam clamp plate, as shown in Figure 5.8. This solution would probably require a certified engineer to determine load ratings.

[44] Ibid., chap. 1, page 7.

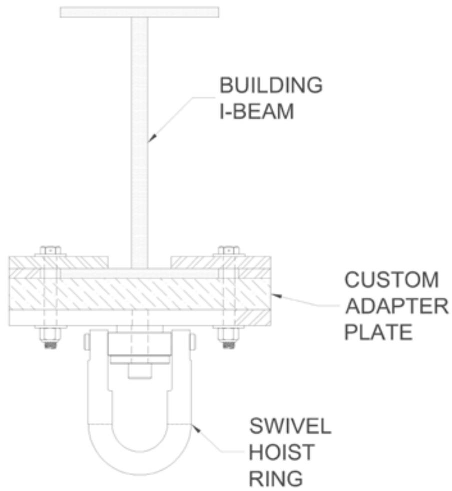

Figure 5.8 - Custom beam clamp with swivel hoist ring

Another possible solution, suggested in discussions of this issue with colleagues at UW-Madison and ZFX Flying Effects, would be to build a support structure that supports the horizontal loading and to use it in conjunction with a beam clamp or eye bolt that supports the vertical loading, as shown in Figure 5.9.

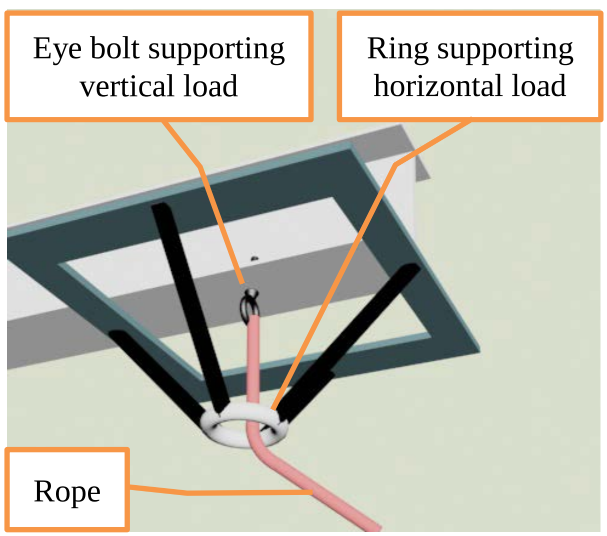

Figure 5.9 - Concept drawing of horizontal support bracket

5.3. Rigging summary

There are many industries that use rigging hardware that can be utilized for aerial dance, including entertainment, climbing, arborist, circus, safety and industrial rigging. Little of this equipment is rated for lifting people, nor specifically for aerial dance. A thorough RA/RR should be taken to ensure appropriate Working Load Limits are determined, and proper de-rating is applied, when utilizing equipment from other industries.

Chapter 6

Summary

When I first approached my advisor on the topic for my thesis, it was fairly simple – "What is the maximum force generated by a single point aerial dance trapeze?" This question was based on my belief that the aerial groups I was working with were sometimes using components that were rated well above the value they needed. I also wondered if we were using eyebolts as rigs points above their rated capacity. More importantly, I wanted to have a better understanding of what factors to consider when determining rigging hardware for aerial dance.

Early in my process for determining how to measure the maximum force in aerial dance, 'scope creep' began to occur. This 'scope creep' started out when I began to conduct the actual measurements and to document the research data. I added a video camera, to document the movement of the aerialists on the trapeze. I decided to add "and what is optimal rigging hardware for single point aerial dance trapeze" to my thesis statement. But the biggest amount of 'scope creep' came in when I decided that to include determining the directionality of the force. I decided that it was important to not only analyze the maximum force, but also to analyze the data to determine the following: at what point in the aerialists' movement did this maximum force occur; at what point did the minimum force occur; how much force was there that was more horizontal than vertical; how much horizontal side loading was there on the rig point?

I have been able to provide answers to many of these questions. Based on my research, the maximum characteristic force occurs when a aerialist is performing drops on the trapeze, and can be as almost five times their weight; this force is primarily vertically applied, straight down. I was also able to determine that some of the hardware that we currently use, especially the 3/8" Trophy Braid Rope, may not have a high enough rating for how we are currently using it.

Another important conclusion I made was that there is a significant horizontal component to the forces in single point aerial dance trapeze movement which is approximately twice the aerialist's weight. While these horizontal forces are not the overall limiting factor in system design, they may in fact be higher than the rated capacity of some equipment typically used in single point aerial dance trapeze rigging, for instance, eyebolts and beam clamps. Use of this equipment for single point aerial dance trapeze rigging may be contrary to the manufacturers' recommendations and a very thorough RA/RR analysis should be made before using them.

I was able to determine design load limits for the typical aerial dance systems that I most often work with:

- Peak Load Limit: 3930 lbs.; based on a 240 lb. aerialist falling 3' and being stopped by the rope. DF: 3 (reduced by RA/RR from 8100 lbs. for a 14' fall)
- Vertical Characteristic Load Limit: 7200 lbs.; based on a 240 lb. aerialist performing a *Roll Drop* and generating a force of five times their weight. DF: 6
- Horizontal Characteristic Load Limit: 2880 lbs.; based on a 240 lb. aerialist performing a *Track and Tap* and generating a force of twice their weight. DF: 6

However, one of the most interesting questions is left only partially answered: What is the peak loading factor on the equipment? The research has in fact generated more questions: How do knots in the rope, the use of multiple ropes, the bending of the trapeze bar, and the stretch of the round sling factor into the calculations for this peak loading? Is the value of 8100 lbs.? which I originally calculated for Peak Loading a reasonable value? Is the value of 3930 lbs. from the RA/RR analysis valid?

Answers to these questions will require further research. Next steps might be to measure the actual peak loading on the components used in the research: start off with a small amount of weight, and a small falling distance; gradually increase both the weight, and the distance, recording the force; then try to develop an equation for calculating the peak force; or develop guidelines on how knots in the rope, multiple ropes, and different types of elongation (ropes and round slings and trapeze bars together) all effect the peak loading.

Further research could also seek to explore and more accurately define the horizontal component in aerial dance. One of the regrets I have is that I did not provide for a more accurate method of syncing the video to the data. The experience I had trying to match a certain point in the video to the same point in the data suggests better syncing was critical to a good analysis of the data. It would have been good to set the time clocks of the Beckhoff CPU and the video camera to the same time; then, include the time code on the video as it was recorded. Additionally, I wish that I had developed a method to sync the aerialist's position and horizontal angle with the video and the data. A more perpendicular alignment between the camera and the path of the aerialist would have helped to determine the angle. Multiple cameras, one above the aerialist, and several around the aerialist, would have provided even more accurate position information. By providing more complete syncing between the different recording devices, it would have been possible to more accurately determine what the horizontal component in aerial dance really is.

What I believe I have provided for myself, and for others, is: a better understanding of the complexities in safely determining load ratings for components used in aerial dance rigging; what factors to consider when calculating the peak load on the aerial dance rigging and building structure; and some criteria to consider when selecting equipment used in aerial dance rigging. Furthermore, I hopefully have provided references and information which riggers can use to provide answers to some of these considerations. Finally, I believe I have provided a methodology for continuing to research the forces in aerial dance, to provide more accurate methods for selecting rigging equipment for aerial dance. Most important for me, I believe that I can provide more accurate and reliable advice for the many rigging questions that I am asked and that I will be able to continue to provide safe rigging solutions for the aerialists that I work with.

Notes

- Unless otherwise noted, all figures, charts and tables were developed by the author and are the property of the author.
- Unless otherwise noted, all photographs were photographed by the author and are the property of the author.
- All photographs and drawing of beam clamps in Section 5.2.1 were copied from the cited references.
- An interesting source for more information on circus rigging in general is the Simply Circus site at http://www.simplycircus.com/Equipment_and_Rigging.
- I highly recommend the following books as reference material for aerial dance riggers:

  - Bernasconi, Jayne, and Nancy Smith. Aerial Dance, 2008. ISBN: 0-7360-7396-5
  - Carter, Paul Douglas, and Sally Friedman Carter. Backstage Handbook: An Illustrated Almanac of Technical Information. Shelter Island, N.Y.: Broadway Press, 1994. ISBN: 091174729X
  - Donovan, Harry. Entertainment Rigging: A Practical Guide for Riggers, Designers, and Managers. Seattle, Wash: H.M. Donovan, 2002. ISBN: 097233811X
  - Glerum, Jay O. Stage Rigging Handbook. 3rd ed. Carbondale: Southern Illinois University Press, 2007. ISBN: 9780809327416
  - Hall, Delbert L. "Understanding Shock Loads." Theatre Design & Technology 49, no. 2 (Spring 2013): 46–51. http://tdt.usitt.org/
  - PLASA. DRAFT - BSR E1.43-201x, Entertainment Technology—Live Performer Flying Systems. PLASA, n.d. http://tsp.plasa.org/tsp/documents/docs/BSR%20E1-43_201x.pdf.
  - Santos, Steven. Introduction to rigging: aerial fabrics. [S.l.]: Steven A. Santos II. ISBN: 9781304764034
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Appendix A - Research Participant Information and Consent Form

Research Participant Information and Consent Form

UNIVERSITY OF WISCONSIN-MADISON

Research Participant Information and Consent Form

Title of the Study: Forces involved in Single Point Aerial Dance

Principal Investigator: James Vogel (phone: 608-265-4799) (email: james.vogel@em.wisc.edu)

DESCRIPTION OF THE RESEARCH

You are invited to participate in a research study about the forces generated when flying on a single point aerial dance trapeze.

You have been asked to participate because you have previous training and experience on single point aerial dance trapeze in general and specifically on the following dance movements: track and taps; one-handed circles into Pegasus; mounting/dismounting from the trapeze.

The purpose of the research is to determine the actual maximum force generated when performing certain movements on a single point aerial dance trapeze.

This study will include trained aerialists who have experience in single point aerial dance trapeze.

Videos will be made of your participation. James Vogel, the primary researcher, will retain ownership of the videos, which will be kept for one year before they are destroyed.

WHAT WILL MY PARTICIPATION INVOLVE?

If you decide to participate in this research you will be asked to do the following on a single point aerial dance trapeze:

1. Mount the bar to a sitting position, using your desired method of mounting; sit on the bar for approximately 30 seconds; dismount from the bar using your desired method. - repeat 3 times
2. Do a 'track and tap' movement on the bar for at least 5 swings (out and back is considered one swing), trying to safely achieve the maximum height at the end of each swing. - repeat 3 times
3. Run in a circle while holding the trapeze in one hand, complete 3 circles and then move into a 'Pegasus' movement, completing at least 3 additional circles and trying to safely achieve the maximum height. - repeat 3 times
4. Interact with the trapeze for approximately 3 minutes, using your desired movements.

Your participation will last approximately 1 hour per session and will require 1 session.

ARE THERE ANY RISKS TO ME?

We do not foresee any risks or discomfort from your participation in the research. Please ensure that all movement on the trapeze is performed in a safe manner, without exceeding your own personal skill level.

ARE THERE ANY BENEFITS TO ME?

We don't expect any direct benefits to you from participation in this study. Results of the study will be shared with participants if they desire.

HOW WILL MY CONFIDENTIALITY BE PROTECTED?

This study is anonymous. Neither your name nor any other identifiable information will be recorded except for the video as previously mentioned.

WHOM SHOULD I CONTACT IF I HAVE QUESTIONS?

You may ask any questions about the research at any time. If you have questions about the research after you leave today you should contact the Principal Investigator James Vogel at 608-265-4799.

If you are not satisfied with the response of the research team, have more questions, or want to talk with someone about your rights as a research participant, you should contact the Education and Social/Behavioral Science IRB Office at 608-263-2320.

Your participation is completely voluntary. If you begin participation and change your mind you may end your participation at any time without penalty.

Your signature indicates that you have read this consent form, had an opportunity to ask any questions about your participation in this research and voluntarily consent to participate. You will receive a copy of this form for your records.

Name of Participant (please print):____________________________

________________________________ ___________

Signature Date

Appendix B - Waiver

ACKNOWLEDGEMENT OF RISK, WAIVER AND RELEASE OF CLAIMS

PLEASE READ THIS ACKNOWLEDGMENT OF RISK, WAIVER, AND RELEASE OF CLAIMS (THIS “RELEASE”) CAREFULLY. BY SIGNING THIS RELEASE, YOU WILL GIVE UP CERTAIN LEGAL RIGHTS. IF YOU DO NOT UNDERSTAND ANYTHING IN THIS RELEASE, YOU SHOULD SEEK THE ADVICE OF YOUR LEGAL COUNSEL BEFORE SIGNING BELOW. The undersigned (“you”) agrees that when participating in the Research Thesis titled "Forces involved in Single Point Aerial Dance " conducted by James Vogel you hereby agree to the following:

Acknowledgement of Risk: You acknowledge there is an inherent risk in the use of the equipment (trapeze, ropes, rigging hardware, etc) utilized for this research thesis (collectively, the "Equipment"). You further acknowledge that such risk includes, but is not limited to physical injury, illness, death, or damage to personal property. You acknowledge that the risks inherent in the use of the "Equipment" are always present and that such risks are increased when the "Equipment" is used incorrectly or unsafely. You represent and warrant that you have all of the necessary and proper training and knowledge for any and all uses (collectively "Your Use") of the "Equipment" and that you will never intentionally engage in unsafe or improper use of said "Equipment". You assume all risk of any injury, damage or loss. This Release applies to all use of the "Equipment" regardless of your authorization for such use.

Waiver and Release Claims: You waive, relinquish, discharge, release, and covenant not to sue James Vogel from any and all rights, claims, demands, causes of action, damages, liabilities or losses, that you, your employer, your assigns, your family members or kin may have or could have had that may arise from or are related to "Your Use" (INCLUDING NEGLIGENCE BUT NOT INTENTIONAL OR RECKLESS MISCONDUCT BY A WAIVED PARTY).

Disclaimer of Liability: In no event shall any waived party be liable for any direct, indirect, incidental, special, exemplary, punitive or consequential damages, however caused and on any theory of liability, whether, of liability, whether in contract, strict liability of tort (INCLUDING NEGLIGENCE BUT NOT INTENTIONAL OR RECKLESS MISCONDUCT BY A WAIVER PARTY) arising in any way out of Your Use, even if such Waived Party has been advised of the possibility of such damage. This disclaimer of liability applies to any damages, injuries or losses including, without limitation, personal injury, death or property damage, under any cause of action.

Additional Representations: You acknowledge you have had an opportunity to object to any or all the terms described herein and, after careful consideration, fully understand the extent of the waiver represented by such terms in their aggregate and waive any right to bargain for different terms. You understand that if you later learn that any fact you believed to be true at the time you signed this Release is later found to be incorrect, you nevertheless are bound by this Release. YOU HAVE READ THIS RELEASE THOROUGHLY. YOU SIGN THIS RELEASE VOLUNTARILY ON BEHALF OF YOURSELF, YOUR HEIRS, NEXT OF KIN, ASSIGNS, PERSONAL REPRESENTATIVES AND RELATED INDIVIDUALS. NO ONE HAS MADE ANY REPRESENTATIONS, STATEMENTS OR INDUCEMENTS THAT CHANGE OR MODIFY ANYTHING WRITTEN IN THIS RELEASE.

The undersigned has agreed to and acknowledged the forgoing as of ______________________, 20________
Signature: ______________________________________ Minor Name: _________________________________
Printed Name: __________________________________ (If applicable)

Appendix C – Calibration Certificates

CAPITOL SCALE COMPANY 2744 Pearl Court Sun Prairie, WI 53590

Precision Measurement / Industrial Automation

(608) 837-4848 (888) 953-5333 Fax: (608) 837-4830

REPORT OF INSPECTION AND CALIBRATION

Page (___) of (___)

CUSTOMER NAME:	JAMES VOGEL	All Test Standards Traceable To NIST
STREET ADDRESS:	452 N. SHERMAN AVE.	
CITY, STATE ZIP:	MADISON, WI	
PURCHASE ORDER #:		

MODEL	MANUFACTURER	SERIAL #	I.D. #	CAPACITY	LOCATION	TEST LOAD USED	TEST RESULTS AS FOUND	Accepted	Rejected	AS LEFT	Accepted	Rejected
LAPTOP	PC	UNKNOWN	NONE	2000	PORTABLE	1000	0	X		0	X	

REMARKS / RECOMMENDATIONS:

Serial #	I.D. #	Remarks
		TESTED LOAD CELL AT 50,100 AND 1000 POUNDS WITH NO ERROR

Were the above Remarks and Possible Solutions discussed with the Customer? _______ With JAMES

Requested Action by the Office: None

NOTIFICATION OF NONCOMPLIANCE

I understand this report does not comply with ISO/IEC 17025 requirements, accept services as performed, and this report as written.

Services provided herein were performed in accordance with Capitol Scale Co. Level (3) quality procedures; as discussed.

Jeff Playter — Signature of Technician

11/21/2013 — Date

Thanks James — Signature of Customer Representative

Revision # O CAPITOL SCALE CO. - QUALITY PROCEDURE MANUAL - CONTROLLED DOCUMENT Report # R-510L3/4RIC (File # 5.10.e)

State of Wisconsin
Governor Scott Walker

Department of Agriculture, Trade and Consumer Protection

Ben Brancel, Secretary
Wisconsin Weights and Measures Laboratory

Calibration Certificate

Date Received:	June 20, 2013	State Test No.:	W13-132
Date of Test:	June 21, 2013	Item(s) Submitted:	Cast Weight
		Manufacturer:	Rice Lake, Webb, Fair
		Condition:	Good
		Tolerance Class:	NIST Class F
Customer:	CAPITOL SCALE COMPANY LLC	Kit Serial #:	
Address:	2744 PEARL CT	Balance ID#:	8
	SUN PRAIRIE, WI 53590	Procedure Used:	NIST SOP 8 (2012)
Contact:	JEFF	Temperature:	20.0°C
Phone:	(608) 837-4848	Relative Humidity:	59.6%
PO Number:		Pressure:	740.8 mmHg

Nominal Mass	Mass Unit	Serial No.	Corrected Balance Readings (mg)		NIST Class F		Uncertainty, (mg)
			As Found	As Left	As Found	As Left	(k=2)
50	lb	CSC-C08	-3,400	521	*Fail*	Pass	120
50	lb	CSC-C07	-2,360	761	*Fail*	Pass	120
50	lb	CSC-C02	-4,590	1,051	*Fail*	Pass	120
50	lb	CSC-C19	-7,320	921	*Fail*	Pass	120
50	lb	38	-4,640	1,161	*Fail*	Pass	120
50	lb	30	-29,570	721	*Fail*	Pass	120
50	lb	37	-41,570	131	*Fail*	Pass	120

r Weight has been rejected for calibration (please see enclosed letter for details).
The following standard(s) were used: 25 lb: W25LB, 50 lb: W50LB

The standards used by the Wisconsin State laboratory are traceable to the International System of Units (SI) through the National Institute of Standards and Technology (NIST). Participation in NIST's Measurement Assurance Program ensures continued accuracy and traceability within the level of uncertainty reported by this laboratory. The State Standards are traceable to the SI unit for mass, the kilogram, and to the SI unit for volume, the cubic meter. This report may not be reproduced, except in full, without the written approval of this laboratory.

Jeffrey T. Houser, Chief Metrologist

State of Wisconsin
Governor Scott Walker

Department of Agriculture, Trade and Consumer Protection

Ben Brancel, Secretary
Wisconsin Weights and Measures Laboratory

Calibration Certificate

Date Received: June 20, 2013
Date of Test: June 21, 2013

Customer: CAPITOL SCALE COMPANY LLC
Address: 2744 PEARL CT
SUN PRAIRIE, WI 53590
Contact: JEFF
Phone: (608) 837-4848
PO Number:

State Test No.: W13-132
Item(s) Submitted: Cast Weight
Manufacturer: Rice Lake
Condition: Good
Tolerance Class: NIST Class F
Kit Serial #:
Balance ID#: 10
Procedure Used: NIST SOP 8 (2012)
Temperature: 19.9°C
Relative Humidity: 58.9%
Pressure: 740.8 mmHg

Nominal Mass	Mass Unit	Serial No.	Corrected Balance Readings (mg) As Found	Corrected Balance Readings (mg) As Left	NIST Class F As Found	NIST Class F As Left	Uncertainty, (mg) (k=2)
500	lb	CS-B04	-7,715	-7,715	Pass	Pass	1600
500	lb	CS-B03	-12,315	-12,315	Pass	Pass	1600
500	lb	CS-B01	1,685	1,685	Pass	Pass	1600
500	lb	CS-B02	14,085	14,085	Pass	Pass	1600
1000	lb	17	38,310	38,310	Pass	Pass	4900
1000	lb	18	9,110	9,110	Pass	Pass	4900
1000	lb	14	11,110	11,110	Pass	Pass	4900
1000	lb	10	15,810	15,810	Pass	Pass	4900
1000	lb	15	-16,190	-16,190	Pass	Pass	4900
1000	lb	16	13,310	13,310	Pass	Pass	4900
1000	lb	03	18,110	18,110	Pass	Pass	4900
1000	lb	05	-9,890	-9,890	Pass	Pass	4900
1000	lb	04	8,910	8,910	Pass	Pass	4900
1000	lb	06	-2,890	-2,890	Pass	Pass	4900
1000	lb	12	-8,790	-8,790	Pass	Pass	4900
1000	lb	07	12,310	12,310	Pass	Pass	4900
1000	lb	08	3,710	3,710	Pass	Pass	4900
1000	lb	09	-22,590	-22,590	Pass	Pass	4900
1000	lb	01	-37,990	-37,990	Pass	Pass	4900
1000	lb	02	18,410	18,410	Pass	Pass	4900
1000	lb	13	14,710	14,710	Pass	Pass	4900
1000	lb	11	15,210	15,210	Pass	Pass	4900

The following standard(s) were used: 500 lb: 90499, 1000 lb: 392

The standards used by the Wisconsin State laboratory are traceable to the International System of Units (SI) through the National Institute of Standards and Technology (NIST). Participation in NIST's Measurement Assurance Program ensures continued accuracy and traceability within the level of uncertainty reported by this laboratory. The State Standards are traceable to the SI unit for mass, the kilogram, and to the SI unit for volume, the cubic meter. This report may not be reproduced, except in full, without the written approval of this laboratory.

Jeffrey T. Houser, Chief Metrologist

3601 Galleon Run • Madison, WI 53718 • (608) 224-4910

Appendix D – Structured Text program

```
PROGRAM MAIN
VAR
	(* process data OUT*)
	wControl AT %Q*:WORD;
	(* process data IN*)
	wStatus AT %I*:WORD;
	rValue_REAL AT %I*:REAL;
	nValue_DINT AT %I*:DINT;
	nValue_Supply AT %I*:DINT;		(*only for voltage measurement, change PDO settings"*)
	nValue_Bridge AT %I*:DINT;		(*only for voltage measurement, change PDO settings"*)
	stEcSlaveAmsNetAdr AT %I*:ST_AmsAddr;
	bWcState AT %I*:BOOL;
	wState AT %I*:WORD;

	(* commands *)
	bStartManualCalib:BOOL;
	bDisableCalibration:BOOL;
	bInputFreeze:BOOL;
	bSampleMode:BOOL;
	bTara:BOOL;
	bCmd_FullCalibration:BOOL;
	bCmd_ZeroCalibration:BOOL;
	bCmd_Tara:BOOL;
	bCmd_TaraEEProm:BOOL;

	sEcSlaveAmsNetAdr:T_AmsNetId;
	rValue:REAL;
	bOverrange, bDataInvalid, bError, bCalibrationInProgress, bSteadyState:BOOL;
	bTxPDOToggle, bSyncError:BOOL;
	sfFullCalibration:R_TRIG;
	sfZeroCalibration:R_TRIG;
	sfTara:R_TRIG;
	sfTaraEEProm:R_TRIG;
	fbCoE:FB_EcCoESdoWrite;
	wCoeData:WORD;
	sStatus, sSampleMode:STRING(100);
	bTermError:BOOL;
	nCntCalibrations:UDINT;
	sfCalibInProgress:R_TRIG;

	rValueDiff, rValueL:REAL;
	bActivateAutoInputFreeze:BOOL;
	rInputFreezeTreshold:REAL:=10;
	tofInputFreeze:TOF;
	tInputFreeze:TIME:=t#50ms;
	sfCntInputFreeze:R_TRIG;
	nCntInputFreeze:UDINT;
	rLastMax:REAL := 0;
```

```
	bCmd_MaxReset: BOOL:=FALSE;

(* File *)
	bWrite			: BOOL := FALSE;(* Rising edge starts program execution *)
	sNetId			: T_AmsNetId := '192.168.137.50.1.1';	(* TwinCAT system network
address *)
	sUserName		:T_MaxString := ''; (* Current flyer, used as file name *)
	sFilePath		: T_MaxString := 'C:\Users\James\Dropbox\MFA\Thesis\Data\';(*
CSV destination file path *)
	sFileExt		: T_MaxString := '.csv';(* CSV destination extension *)
	sFileName		: T_MaxString := '';(* CSV destination file path + file name + file
extension*)
	sCSVLine		: T_MaxString := '';(* Single CSV text line (row, record), we are using
string as record buffer (your are able to see created fields) *)
	sCSVField		: T_MaxString := '';(* Single CSV field value (column, record field) *)
	bBusy			: BOOL;
	bFileError		: BOOL;
	nErrId			: UDINT;
	nRow			: UDINT		:= 0;(* Row number (record) *)
	nColumn			: UDINT		:= 0;(* Column number (record field) *)
	hFile			: UINT		:= 0;(* File handle of the source file *)
	step			: DWORD		:= 0;
	fbFileOpen		: FB_FileOpen;(* Opens file *)
	fbFileClose		: FB_FileClose;(* Closes file *)
	fbFilePuts		: FB_FilePuts;(* Writes one record (line) *)
	fbWriter		: FB_CSVMemBufferWriter;(* Helper function block used to create CSV data
bytes (single record line) *)

		MAX_CSV_ROWS			: UDINT := 264000;
		MAX_CSV_COLUMNS		: UDINT := 2;
		MAX_CSV_FIELD_LENGTH	: UDINT := 100;


	fbGetSystemTime		: GETSYSTEMTIME;
	fileTime		: T_FILETIME;

(* END FILE  *)
	bWriting: BOOL := FALSE;
END_VAR
VAR_OUTPUT
END_VAR
(* @END_DECLARATION := '0' *)
	(*example program for EL3356(-0010)
	this demo is designed only for load cell connection, not for 2channel voltage measurement*)

	(*get terminal information*)
bOverrange := wStatus.1;
bDataInvalid := wStatus.3;
bError := wStatus.6;
bCalibrationInProgress := wStatus.7;
bSteadyState := wStatus.8;
bSyncError := wStatus.13;
bTxPDOToggle := wStatus.15;
	(*triggers*)
```

```
sfZeroCalibration(CLK:=bCmd_ZeroCalibration);
sfFullCalibration(CLK:=bCmd_FullCalibration);
sfTara(CLK:=bCmd_Tara);
sfTaraEEProm(CLK:=bCmd_TaraEEProm);

        (*value: Integer or Real value*)
IF (rValue_REAL <> 0) THEN    (*select currently used input data*)
        rValue := rValue_REAL;
ELSIF (nValue_DINT <> 0) THEN
        rValue := DINT_TO_REAL(nValue_DINT);
ELSE
        rValue := 0;
END_IF


IF ABS( rValue)>ABS(rLastMax) THEN
    rLastMax := rValue;
END_IF;
IF bCmd_MaxReset THEN
    rLastMax := 0;
bCmd_MaxReset := TRUE;
END_IF;


        (*status*)
IF bWcState THEN
        sStatus := 'Wc fail';
        bTermError := TRUE;
ELSIF NOT (wState.3) THEN
        sStatus := 'Slave not in OP';
        bTermError := TRUE;
ELSIF bDataInvalid THEN
        sStatus := 'DataInvalid';
        bTermError := TRUE;
ELSIF bError THEN
        sStatus := 'Channel Error';
        bTermError := TRUE;
ELSIF bOverrange THEN
        sStatus := 'Overrange';
        bTermError := TRUE;
ELSE
        sStatus := 'ok';
        bTermError := FALSE;
END_IF

        (*sample mode 0/1*)
sSampleMode := SEL(bSampleMode, '0', '1');

        (*count calibrations*)
sfCalibInProgress(CLK:= bCalibrationInProgress, Q=> );
nCntCalibrations := SEL(sfCalibInProgress.Q , nCntCalibrations, nCntCalibrations+ 1);

        (*Coe parameter administration*)
sEcSlaveAmsNetAdr := F_CreateAmsNetId(nIds:=stEcSlaveAmsNetAdr.netId );
```

```
	(*test input freeze
this lines are for a small demonstration of Input freeze: when difference of loadvalue, compared to
last PLC cycle, is over rInputFreezeTreshold
then InputFreeze is activated by tofInputFreeze for some time. See screenshot in documentation for
further explanations*)
rValueDiff := rValue - rValueL;
rValueL := rValue;
tofInputFreeze(IN:= bActivateAutoInputFreeze AND (ABS(rValueDiff) >rInputFreezeTreshold) , PT:=
tInputFreeze, Q=> , ET=> );
sfCntInputFreeze(CLK:= tofInputFreeze.Q , Q=> );
nCntInputFreeze := SEL(sfCntInputFreeze.Q , nCntInputFreeze, nCntInputFreeze+ 1);

(* START FILE *)

	DEFAULT_CSV_FIELD_SEP := 16#2C;(* Comma ASCII code *)
CASE step OF
	0:	(* Wait for rising edge at bWrite variable *)
		IF bWrite THEN
			bBusy		:= TRUE;
			bWriting			:= TRUE;
			bFileError			:= FALSE;
			nErrId		:= 0;
			hFile		:= 0;
			nRow		:= 0;
			nColumn		:= 0;
			step		:= 1;
			IF sUserName = '' THEN
				sUserName := 'default';
			END_IF
			sFileName := CONCAT (sFilePath, sUserName);
			sFileName := CONCAT (sFileName, sFileExt);
		END_IF

	1:	(* Open source file *)
		fbFileOpen(  bExecute := FALSE  );
		fbFileOpen(	sNetId := sNetId, sPathName := sFileName, nMode :=
FOPEN_MODEWRITE OR FOPEN_MODETEXT,(* Open file in TEXT mode! *)
						ePath := PATH_GENERIC, bExecute := TRUE );
		step := 2;

	2:(* Wait until open not busy *)
		fbFileOpen( bExecute := FALSE, bError => bFileError, nErrID => nErrID, hFile =>
hFile );
		IF NOT fbFileOpen.bBusy THEN
			IF NOT fbFileOpen.bError THEN
				step := 3;
			ELSE(* Error: file not found? *)
				step := 100;
			END_IF
		END_IF

	3:(* Convert one PLC record to CSV format *)
		sCSVLine := '';
```

```
                    fbWriter.eCmd := eEnumCmd_First;(* Write first field value *)
                    IF nRow <= MAX_CSV_ROWS AND bWrite THEN

                            (* FOR nColumn := 0 TO MAX_CSV_COLUMNS BY 1 DO *)

                                    fbGetSystemTime(timeLoDW=>fileTime.dwLowDateTime,
timeHiDW=>fileTime.dwHighDateTime );
                                    sCSVField := SYSTEMTIME_TO_STRING(
FILETIME_TO_SYSTEMTIME( fileTime ) );(* TODO: Get field value from your application *)

                                    (* Add new field to the record buffer *)
                                    fbWriter(        pBuffer := ADR( sCSVLine ), cbBuffer := SIZEOF(
sCSVLine ) - 1, putValue := sCSVField, pValue := 0, cbValue := 0,
                                                        bCRLF := (FALSE ) );(* bCRLF == TRUE =>
Write CRLF after the last field value *)
                                    IF fbWriter.bOk THEN
                                            fbWriter.eCmd := eEnumCmd_Next;(* Write next field value
*)
                                    ELSE(* Error *)
                                            step := 100;
                                            RETURN;
                                    END_IF

                                    sCSVField := LREAL_TO_FMTSTR( rValueL, 0,  FALSE );;(* TODO:
Get field value from your application *)

                                    (* Add new field to the record buffer *)
                                    fbWriter(        pBuffer := ADR( sCSVLine ), cbBuffer := SIZEOF(
sCSVLine ) - 1, putValue := sCSVField, pValue := 0, cbValue := 0,
                                                        bCRLF := (TRUE) );(* bCRLF == TRUE =>
Write CRLF after the last field value *)
                                    IF fbWriter.bOk THEN
                                            fbWriter.eCmd := eEnumCmd_Next;(* Write next field value
*)
                                    ELSE(* Error *)
                                            step := 100;
                                            RETURN;
                                    END_IF

                             (* END_FOR *)(* FOR nColumn := 0... *)

                            (* FB_FilePuts adds allready CR (carriage return) to the written line.
                            We have to replace the $R$L characters with $L character to avoid double
CR. *)
                            IF RIGHT( sCSVLine, 2 ) = '$R$L' THEN
                                    sCSVLine := REPLACE( sCSVLine, '$L', 2, LEN( sCSVLine ) - 1 );
                            END_IF

                            nRow := nRow + 1;(* Increment number of created records (rows) *)
                            step := 4;(* Write record to the file *)

                    ELSE(* All rows written OR "Save Data" button no longer pressed => Close file *)
                            step := 10;
                    END_IF
```

```
        4:      (* Write single text line *)
                fbFilePuts( bExecute := FALSE );
                fbFilePuts( sNetId := sNetId, hFile := hFile, sLine := sCSVLine, bExecute := TRUE );
                step := 5;

        5:(* Wait until write not busy *)
                fbFilePuts( bExecute := FALSE, BError => bFileError, nErrID => nErrID );
                IF NOT fbFilePuts.bBusy THEN
                        IF NOT fbFilePuts.bError THEN
                                step := 3;(* Write next record *)
                        ELSE(* Error *)
                                step := 100;
                        END_IF
                END_IF

        10:     (* Close source file *)
                fbFileClose( bExecute := FALSE );
                fbFileClose( sNetId := sNetId, hFile := hFile, bExecute := TRUE );
                step := 11;

        11:(* Wait until close not busy *)
                fbFileClose( bExecute := FALSE, bError => bFileError, nErrID => nErrID );
                IF ( NOT fbFileClose.bBusy ) THEN
                        hFile := 0;
                        step := 100;
                END_IF

        100: (* Error or ready step => cleanup *)
                IF ( hFile <> 0 ) THEN
                        step := 10; (* Close the source file *)
                ELSE
                        bBusy := FALSE;
                         bWrite         := FALSE;
                        bWriting                := FALSE;
                        step := 0;      (* Ready *)
                END_IF

END_CASE

(* STOP FILE *)


(*++++++++++++++ CoE communication +++++++++++++++++++++*)
wCoeData := 16#0101; (* Command zerocalibration*)
fbCoE(
        sNetId          := sEcSlaveAmsNetAdr,
        nSlaveAddr      := stEcSlaveAmsNetAdr.port,
        nSubIndex       := 16#01,
        nIndex          := 16#FB00,
        pSrcBuf         := ADR(wCoeData),
        cbBufLen        := SIZEOF(wCoeData),
        bExecute        := sfZeroCalibration.Q,
        tTimeout        := t#5s
```

```
);

wCoeData := 16#0102; (* calibration*)
fbCoE(
        sNetId          := sEcSlaveAmsNetAdr,
        nSlaveAddr      := stEcSlaveAmsNetAdr.port,
        nSubIndex       := 16#01,
        nIndex          := 16#FB00,
        pSrcBuf         := ADR(wCoeData),
        cbBufLen        := SIZEOF(wCoeData),
        bExecute        := sfFullCalibration.Q,
        tTimeout        := t#5s
);

wCoeData := 16#0001; (* tara*)
fbCoE(
        sNetId          := sEcSlaveAmsNetAdr,
        nSlaveAddr      := stEcSlaveAmsNetAdr.port,
        nSubIndex       := 16#01,
        nIndex          := 16#FB00,
        pSrcBuf         := ADR(wCoeData),
        cbBufLen        := SIZEOF(wCoeData),
        bExecute        := sfTara.Q,
        tTimeout        := t#5s
);

wCoeData := 16#0002; (* tara EEProm*)
fbCoE(
        sNetId          := sEcSlaveAmsNetAdr,
        nSlaveAddr      := stEcSlaveAmsNetAdr.port,
        nSubIndex       := 16#01,
        nIndex          := 16#FB00,
        pSrcBuf         := ADR(wCoeData),
        cbBufLen        := SIZEOF(wCoeData),
        bExecute        := sfTaraEEProm.Q,
        tTimeout        := t#5s
);

        (*output data to terminal*)
wControl.0 := bStartManualCalib;
wControl.1 := bDisableCalibration;
wControl.2 := bInputFreeze OR tofInputFreeze.Q ;
wControl.3 := bSampleMode;
wControl.4 := bTara;

END_PROGRAM
```