BME 301
5/2/2015

"U-Cube" Intensive Physical Therapy Unit

Client: Matt Jahnke, United Cerebral Palsy of Greater Dane County

Adviser: Krishanu Saha, Dept. of Biomedical Engineering, UW-Madison

Team Members:

Jon Elicson – Team Leader, BSAC

Samantha Mešanović – Communicator

Jon Leja – BWIG

Jake Kanack – BPAG

Abstract

Every year, millions of people worldwide suffer a traumatic brain injury (TBI). Often, these injuries interfere with patients' strength and motor skills. Recently, studies have shown that intensive suit therapy has been found to increase efficiency of therapy and produce better outcomes in TBI patients. The U-Cube provides a solution for anchoring the customizable supports utilized in intensive suit physical therapy programs. The U-Cube and DLX harness are to be used in conjunction with one another in order to provide a dynamic physical therapy experience for individuals of all ages and builds. For evaluation of the U-Cube system, simulations were run in ANSYS and SAP2000. MTS testing was also performed on the materials of the U-Cube. The results of this testing showed that the U-Cube is structurally stable and safe for patient use. The U-Cube will improve upon prohibitively expensive commercial systems by providing a low cost alternative that anyone should be able to purchase and build.

Contents

Introduction

About the Client and Adviser

The Client

The client, Matt Jahnke, is currently the Adult Program Director at United Cerebral Palsy of Greater Dane County, a nonprofit organization dedicated to raising cerebral palsy awareness in Dane County, Wisconsin. His website houses many links to the various programs they offer, which provide youth resources, respite care, support services, and therapy to individuals of all ages (1). Mr. Jahnke, a UW-Madison alumnus, has been the client for several previous design projects at the university related to cerebral palsy rehabilitation and therapy. For this current design project, Mr. Jahnke requires that a device be made to therapeutically treat both traumatic brain injuries and other physical disabilities.

The Occupational Therapist

Amanda Miller is an occupational therapist at the Madison Area Rehabilitation Center. At this facility, she sees approximately 25 different patients. She would like us to design a cage that she can use in her facility to help rehabilitate her patients through the use of intensive physical therapy. She has noted that insurance does not provide much funding for disabilities after the patient has reached 21 years of age, and that there is not currently an affordable physical therapy unit she can use to help her patients improve their balance and gait. As a result, she would like us to design and manufacture a physical therapy unit that she can use at her facility.

The Patient

The patient, who will be referred to by the alias of Michael for the purposes of anonymity, is a 5’5” (1.6 m) and 150 lbs. (68 kg) Hispanic male who is in his late 50s. He was previously involved in gang related activities. He has lost a significant amount of his brain function and motor skills as the result of a gunshot wound that was inflicted approximately 30 years ago. The result was a traumatic brain injury and lasting mental and physical disabilities. His occupational therapist, Amanda Miller, used to see him weekly in order to conduct physical therapy. Unfortunately, his insurance has recently stopped paying for these visits, and as a result, he has lost his ability to walk unaided (a task he was previously able to accomplish with weekly therapy). Because of this, Amanda Miller would like use the “U-Cube” in order to help Michael regain his ability to walk.

The Adviser

Kris Saha of the Department of Biomedical Engineering at UW-Madison, holds a Ph.D. in Chemical Engineering granted to him by the University of California, Berkeley. He also has a M.Phil in Biotechnology from the University of Cambridge and a B.S in Chemical Engineering and Chemistry from Cornell University. Dr. Saha was a Postdoctoral Fellow at the Whitehead Institute for Biomedical Research at MIT/Harvard University prior to becoming an Assistant Professor at the University of Wisconsin-

Madison. Dr. Saha also is the principal investigator at his human stem cell engineering lab housed at the Wisconsin Institute for Discovery.

Background

Traumatic brain injuries, or TBIs, affected roughly 2.5 million people in the United States in 2010, and cost approximately $75 billion annually (2). A TBI can be caused by a wide range of events, from falls to assaults or car accidents as seen below in Fig. 1. There are two types of severe TBIs that a person can experience: closed or penetrating. A closed TBI would result from a concussion or fall, whereas a penetrating TBI would result from blunt force trauma to the head, such as a gunshot (2). Mild injuries result in mild symptoms, such as nausea, blurred vision, dizziness, and/or sensitivity to light and sound (2). Moderate to severe injuries, on the other hand, have more critical symptoms: loss of consciousness, seizures, extreme confusion, and/or a loss of coordination (2). Long term severe TBIs have issues extending beyond the initial injury itself. These long-term issues can impair cognitive function, emotions, sensations, and motor function. In America, there are currently 5.3 million people living with a TBI-related disability, and in 2010 it was estimated that these individuals spent a total of $76.5 billion in medical costs (2). One of the most problematic populations that suffer from TBI's in America are war veterans. Most often veterans are exposed to heavy artillery or explosive blasts that can lead to TBI and eventually loss of mobility (3). Figure 1, pictured below, shows the most common leading causes for TBIs in America, with falls accounting for 40.5% of all TBIs. Many times individuals suffering from TBI can get appropriate treatment for their condition and symptoms. However, often economically challenged individuals are unable to obtain proper treatment, and consequently their symptoms are often more intense and harsh (4). One of the main methods of treating a severe TBI and its long term issues is rehabilitation by intensive physical therapy.

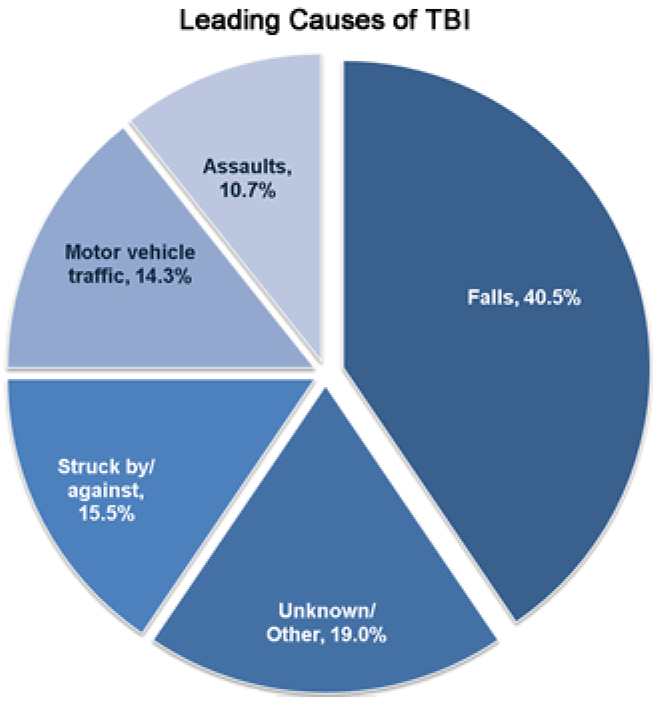


Figure 1: A figure displaying the leading causes of TBIs in America (2).

Intensive suit therapy is a rehabilitation method of physical therapy that allows a therapist to isolate different parts of an individual's body for specific exercises. The patient wears a suit which helps to support their body weight while they perform exercises that help to retrain the brain and normalize movement, making it more automatic (5). Using the suit system to support the weight of the patient so the therapist does not have to is one of the biggest benefits of intensive suit therapy (6). Integrating the suit into a rigid with suspension (like the U-Cube) also helps to support the patient, alleviating this burden from the physical therapist and allowing him or her to concentrate on the exercise itself, rather than physically supporting the patient. This intensive therapy can allow the patient to regain balance, gait train, regain muscle strength, and improve motor skills and coordination. These variables have been found to improve through intensive suit therapy (7). This form of therapy has been found to generally improve patient mobility, however there are certain variables where the suit was found to have no effect (6). However, intensive suit therapy has shown promising results and many benefits to both the patient and the therapist. There is still much research that needs to be done in this field, though, before any definitive statements can be made to the specific benefits of the therapy (3).

Motivation

TBIs can range from mild to severe, and they usually lead to decreased physical and cognitive abilities. The U-Cube in conjunction with a therapy suit is designed to act as an intensive physical therapy unit that can help these people regain mobility and motor function. The U-Cube is not only designed to treat TBIs, but it can also help patients with a variety of other diseases such as cerebral palsy and spinal stenosis. Physical therapy can strengthen muscles and improve flexibility which is an important aspect of regaining mobility and balance. The U-Cube is designed to perform all of these activities, as a means of helping to improve patients' quality of life. In addition, all of the current devices similar to the U-Cube on the market are very expensive, costing upwards of $7000 for competing designs (8); however, the U-Cube is built to be one fifth of the cost. This will allow the population to have easier access to this device. Our client, Matt. Jahnke, wants us to provide a detailed instructions manual and parts list that explains how and where to purchase all materials and put them together to fully construct the U-Cube.

In terms of all of the above, it is necessary that the design is cost effective, easy to build, and safe for all to use to help improve the quality of life for people in need of physical therapy.

Problem Statement

The purpose of this project is to create a rigid cage to suspend a patient for therapeutic purposes. Unlike previous designs, the cage must be more lightweight and portable so that it may be transported in the event that the patient or therapist wishes to relocate the device either within a specific location or between locations. It must also be made of common, inexpensive materials so that other patients may duplicate its construction. The cage should be created for use by our patient (referred to in this report under the alias "Michael"), but should able to be used with Amanda Miller's other patients. This project also requires that a suit either be purchased or fabricated and then integrated into the U-Cube through the use of elastic suspension. The suit should be capable of fitting Michael, as well as various other patients that may use it. This first prototype will then be placed at the Madison Area Rehabilitation Center. Finally, an instructions manual and parts list must be created for the U-Cube, which will then be uploaded to our client's website so that other individuals can construct it.

Previous Work

The current project is a continuation from the fall 2014 semester. Three of the current team members continued work with the project: Jon Elicson, Samantha Mešanović, and Jon Leja. The team then acquired a new member, Jake Kanack, since two of the sophomore members, Austin Gehrke and Taylor Marohl, left the project this semester. In the previous semester, the team's focus was on designing the metal cage structure which can be seen below in Figure 2.

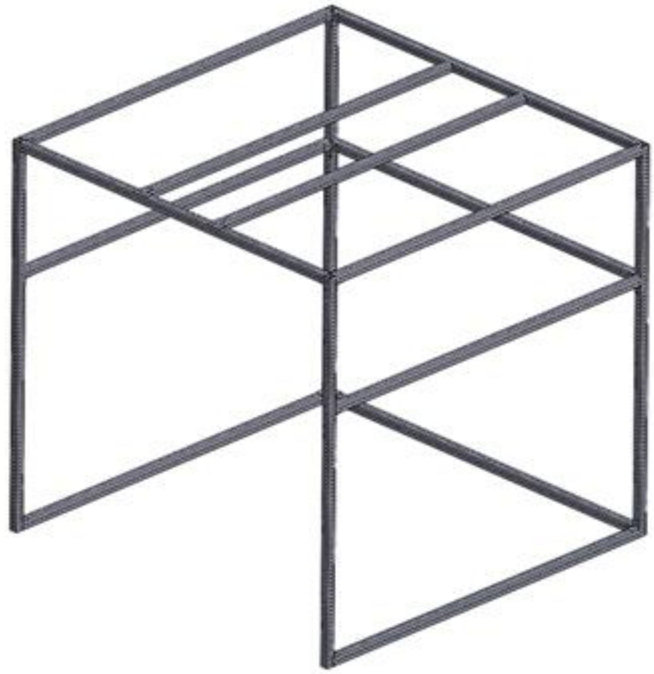


Figure 2: A 3D rendering of the U-Cube that was designed during the previous semester.

The final design was then named the U-Cube and it has a total estimated cost of approximately $1000. The structure of the cage is an eight foot cube, which is enclosed on all sides except for an open-faced front. It was important to keep the front open to allow for easy access into the cage for the physical therapist and the patient. The open-face also makes it easy for the physical therapist to bring in a variety of tools such as a treadmill, table, wheelchair, or Hoyer lift. The cage is constructed from Unistrut metal bars, which are connected with pins and joint fittings. At each corner, there is also a ninety degree fitting that helps to keep it stable, which can be seen below in Figure 3. Lastly, an important quality of the cage is that all of the materials are easily purchasable, and they can be easily put together by anyone using household tools. After the work done during the previous semester, the focus of the project shifted to making the device more stable, choosing the harness suit the user will wear, and integrating it to the metal structure.

Figure 3: An image constructed in SolidWorks of the 90 degree metal fittings that join the struts of the U-Cube.

Design Specifications

In order to facilitate intensive therapy programs, the design must allow for targetable support of specific areas of the patients' body. There must be multiple attachment points for the physical therapy bungee cord systems. The device must be capable of safely supporting the entire bodyweight of a 300 lb. (136 kg) patient. The cage must be large enough to as to accommodate common physical therapy equipment inside, namely a treadmill and a Hoyer lift. The client also requires that an instruction manual and materials list be created, which he will then upload to UCP Dane's website. This will allow for any individual who wishes to recreate this semester's design prototype to do so, thus providing an alternative to other commercially available models.

Ethical Considerations

The device must be manufactured in such a way to never endanger the safety of the individual using it. As a result, it was decided that the device should be made from commercially available, thoroughly tested materials that minimize cutting and welding on the consumer's part. Once assembled, the device should also provide enough structural support to eliminate any concern that the device should fail. The result could be catastrophic to an already disabled individual. Should the individual ever find that they are unable to detach themselves from the device or find that they are suspended in a manner that endangers their safety. Lastly, the device should be open sourced to the public without the intention of profiting from its creation or application, and ought to provide an affordable alternative to commercially available designs in order to increase the efficacy and affordability of therapy.

Design

Current Therapies

Currently, there are two common therapies that are widely available to individuals with physical disabilities. These therapies include a Spider Cage design and a design for a therapeutic full body suit. These two devices are separate therapeutic systems which are rarely used in combination with the other. Both of these therapies also have significant costs, which are associated with both the cost of the device and the cost of the professional training or supervision required to use the device safely.

Spider Cage

The Spider Cage devices that are currently used in therapy, like the Universal Exercise Unit, contain a fencing unit, which surrounds the individual. As seen in Figure 4 below, the individual then wears a harness, similar to a rock climbing harness, with bungee cords connecting it to the sides and tops of the surrounding fence (8). Inside the spider cage there can be a multitude of different devices for therapeutic applications, such as a treadmill, exercise ball, or massage table. The cage is designed for the isolation of specific muscles for intensive therapy (8). The versatility of this device allows for many different types of therapy to be implemented, and provides a way to keep therapy engaging. However, commercially available cages are prohibitively expensive, with models ranging anywhere from $5500 - $7000 (8).

Figure 4: An image that displays the spider cage being used in conjunction with a treadmill (8).

TheraSuit

The TheraSuit is the current leading design for suit therapy. It was modeled after the Russian space suit, and features a cap, shorts, vest, knee pads, as well as arm and shoe attachments. Each article of the suit is then connected by elastic bands (9). A digital rendering of the TheraSuit is pictured below in Figure 5. When worn, the TheraSuit promotes muscle normalization by loading the entire body with proportionally distributed weight (9). This suit is complex and intricate, therefore requiring an expensive training program in order to use it. Currently, the program costs $1600/week. Training takes place for a minimum of 3 weeks, rendering a total cost of $4800. (9). Furthermore, the TheraSuit is geared mostly toward children, as it only has a “one size fits all” design for adults (9).

Figure 5: A digital rendering the TheraSuit on a child (9).

Design Alternatives

This section outlines and details the three alternative suit designs that can be integrated into the U-Cube. However, the budget that was allotted this semester was unable to cover the cost of purchasing a harness to integrate with the cage prototype. As a result, the following design alternatives have been performed in order to provide a recommendation for which harness ought to be purchased for use the U-Cube. The amount of funding obtained and final prototype cost with be outlined later in the *Final Design* section of this report.

DLX Harness

The first design idea is the DLX support harness, which is manufactured by Biodex and can be seen in Figure 6. The harness features two nylon straps around the waist to secure the individual in the harness, and there is an interior padding that allows for a more comfortable fit. It does so by both distributing the pressure of the nylon straps around the waist and by creating a softer patient-suit interface. These nylon straps are capable of being adjusted from 28” to 50” (71 cm to 127 cm) (10), thus allowing for the suit to accommodate the multiple patients that Amanda Miller has in addition to Michael. The suit also provides additional straps that can be secured around the patient’s groin, thighs, and buttocks which can provide additional support as seen in Figure 7.

Figure 6: An image depicting the DLX suit with its adjustable waist straps and overhead load bearing straps (10).

Figure 7: An image detailing the additional support of the DLX harness (10).

The suit can then be integrated into to the cage by using two load bearing straps that are capable of providing both vertical and lateral suspension for patients up to 300 lbs. (139 kg) (10). These straps can be attached to bungee cords, which can, in turn, be attached to the cage in a dynamic and adjustable fashion. As a result, the DLX suit will allow for a wide range of exercises to be performed which will increase the efficacy of our cage prototype. Furthermore, these straps are also adjustable and allow for the DLX suit to accommodate multiple patients in addition to Michael (10). This ensures that the U-Cube and suit combination is as customizable as possible.

The Seat

The second design consisted of a custom fabricated "seat," pictured below in Figure 8. The frame of the seat consisted of two pieces of nylon webbing sewn together in a loin-cloth like fashion. The lower piece provides support for the groin area of the patient, and the upper piece wraps around the patient's waist in order to secure them in the harness. Nylon webbing is an ideal material for the structure of the harness, as a 3/16'' (.4 cm) thick piece has a load rating of 9,600 lbs (4354 kg) (11). The inside of the harness is lined with a soft material such as neoprene, in order to improve patient comfort. Attachment to the U-Cube is provided by steel D-rings sewn into the harness. The amount of attachment points can be customized to the client's requirements. The waist size of the harness can be adjusted via horizontal straps sewn to the waist support piece. Buckles on the adjustment straps allow for easy ingress/egress. The primary advantage of the seat design is that the device could be constructed for a fraction of the cost of commercial systems. However, the seat design provides no upper body support for the patient, which could significantly limit the utility of the harness. Additionally, this design requires custom fabrication, which could limit the accessibility of the harness to future clients.

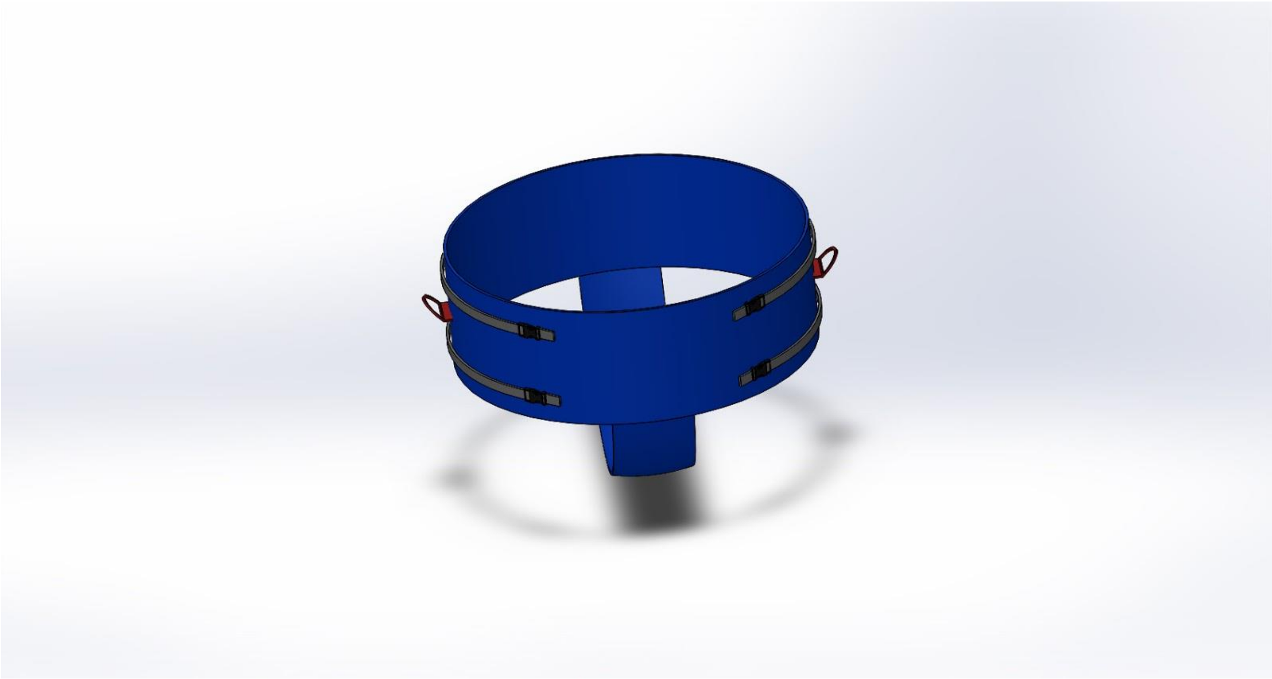


Figure 8: A 3D rendering of the seat design. Buckle models credit Tim Smith

The iHarness

The third option for the harness design is the iHarness, seen below in Figure 9. Online retailer LiteGait, a designer and distributor of various physical therapy tools and accessories, sells the iHarness for $1,500, which is the highest cost of the three design alternatives (12). One of the best qualities of this design however, is that it can create a biomechanically-appropriate posture in the patient while they wear it (12). This was one of the essential qualities that the physical therapist was looking for in a harness. It is important that the suit provides this quality because it is essential that the patients perform the therapy with appropriate posture in order to maximize the efficacy of therapy. The iHarness is also breathable, soft, and flexible (12). This is another trait the therapist was looking for since many of her patients have skin degradation problems.

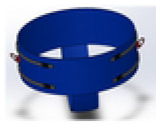
Figure 9: An image depicting the iHarness being used in conjunction with a medical lifting system (12).

The suit is also easy to clean, so that the therapist can clean it in between the uses of each patient. This is important since the cage will be placed in the Madison Rehabilitation Center and a variety of patients will be using it. This way the iHarness is able to be sanitized and cannot infect any patients. Finally, the iHarness can fit any patient up to an 84” (2.1 m) girth, which means that it will accommodate all of the patients at the Madison Rehabilitation Center (12). The iHarness also allows the patient full hip extension which is important since many patients want to focus on standing or walking, and the iHarness will not restrict their hip movement in any way while allowing them to work on this skill (12).

Design Matrix and Evaluation

The harness designs were evaluated primarily through the usage of a design matrix. The amount of physical support provided, patient comfort, and ease of use in therapy were determined to be the most important factors. As the level of physical support provided by the harness is critical to assisting with physical therapy exercises, the amount and distribution of the physical support provided by the harness was assigned the highest priority. The DLX Harness and iHarness scored the highest, as both designs provide support to the lower body, abdomen, and back of the patient. The seat design only supports the lower body of the patient, and consequently scored the lowest in the physical support category. Since the intensive therapy programs for which the U-Cube is designed consist of long therapy sessions several times per week, patient comfort in the harness was also weighted heavily. The DLX harness scored highest in this category, as the pressure exhibited by the harness is distributed in a wide area around the abdomen and back. The seat harness and iHarness were judged to be less comfortable options due to pressure applied to the lower body of the patient. The final vital category was the ease of use of the harness. The DLX harness and seat design scored the highest in this category, as both options do not restrict limb movement. The iHarness scored the lowest in this category because the harness utilizes multiple pieces that need to be attached, complicated usage.

Table 1: The design matrix that was constructed in order to evaluate the 3 design alternatives.

Design: **Criteria (weight)**	DLX 		Seat 		iHarness 	
Physical Support / Distribution of Weight (25)	4/5	20	3/5	15	4/5	20
Comfort (20)	5/5	20	3/5	12	4/5	16
Ease of Use (20)	4/5	16	4/5	16	3/5	12
Adjustability (15)	3/5	9	3/5	9	4/5	12
Safety (10)	5/5	10	2/5	4	4/5	8
Cost (10)	4/5	8	5/5	10	1/5	2
Total (100)	**83**		**66**		**70**	

Final Design

Harness Recommendation

As the design matrix shows, the DLX harness was evaluated to be the best harness option. The DLX harness scored well in every category evaluated, and should present an effective solution for the integrating the U-Cube into the gait training exercises desired by the client. Additionally, as the U-Cube plans are planned to be made publicly available, the commercial availability of the DLX harness presents a viable suspension option for future independently constructed U-Cube applications. However, at a quoted price of $499, it was determined that the provided budget would not allow for the DLX harness to be purchased. Despite this, it is still the recommendation of the design team that this is the most practical and cost effective option if a harness is to be integrated into the cage by either Amanda Miller or any other individual. As a result, the latter half of the semester focused on validating and finalizing the design of the U-Cube prototype through various physical and computational simulations while funding for the prototype was being allocated through both the UW-Madison Department of Biomedical Engineering and the UCP Bellow's Grant.

Final U-Cube Prototype Design

The final prototype design consists of a 7' (2.13 m) cube constructed as shown below in Figure 10. Telespar 2.5'' (63.5 mm) 12ga. perforated square tubing will be utilized for the construction of the cube members. The two 7' (2.13 m) tubes spanning the top of the cage (shown in green) will bear the patients weight, via movable eyebolts. As these two members support a majority of the patient's weight, they are reinforced via an additional 7' (2.13 m) long 2.25" (57.2 mm) square tubing insert. The tubes are connected by Telespar supplied brackets as shown in blue. The upper corners on all vertical faces are stabilized by ½'' (12.7 mm) thick 1.5' (.4572) eyebolt-to-eyebolt turnbuckles. All of the bracketry and turnbuckles are bolted together utilizing 3/8'' bolts and nyloc locking nuts to prevent loosening during operation. Bolted connections were utilized to facilitate assembly and increase the availability of the cage.

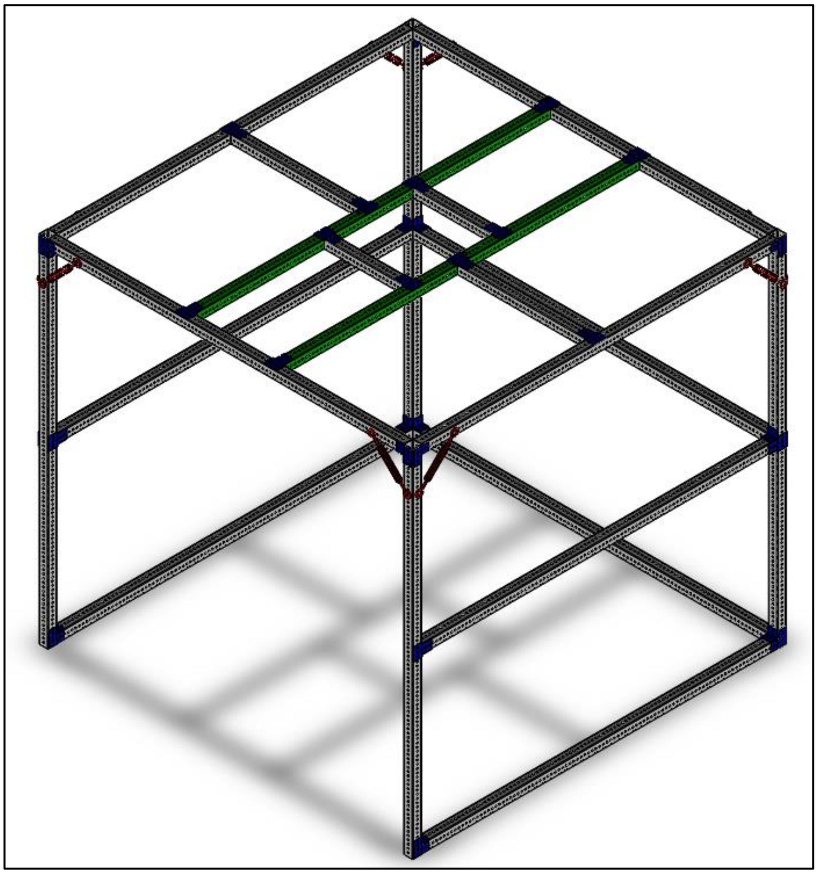


Figure 10: Depiction of the final design. Tubing is shown in gray (green if reinforced), brackets in blue, and cross braces in red.

Allocation of Funding for Final Design

$700 in funding was allocated from the United Cerebral Palsy Elsie S. Bellows Grant. This grant was created in 1995 through a $4.3 million dollar donation through a donation by Mrs. Bellows in order to provide financial assistance for individuals with various disabilities (13). The grant was first applied for in early February, upon which the application was accepted on a local level and later accepted on a national level in late April. The patient's eligibility for this grant was passed both on his physical disability and his affiliation with the client and UCP of Greater Dane County. An additional $500 in funding was applied for through the UW-Madison Department of Biomedical Engineering, which was awarded in addition to the Bellows Grant to provide a total budget of $1200 for prototype construction.

Quotations for the cage construction materials and the DLX harness were obtained from Dekker Supply Company and Biodex Medical Systems, respectively. As section VI of the Appendix shows, the materials for the cage alone came out to just under $1200. Consequently, only the materials for the cage construction were ordered.

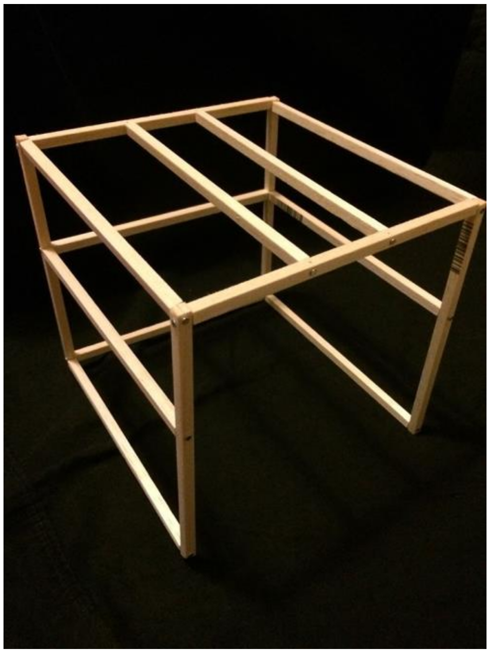
Testing & Results

Testing & Results: Physical

Balsa Wood Modeling and Results

In order to initially infer how structural changes to the U-Cube's tentative structure affected it's overall stability and load bearing qualities, several 1:12 scale balsa wood models were created of the cage with differing overhead truss organization and cross bracing possibilities. It should be noted that these balsa wood models have not been used to justify the structural properties of the U-Cube prototype, but rather to provide a crude and initial inference of which cage structures would minimize cage deflection and maximize load bearing in later computer simulations. Finally, the initial motivation for these balsa wood models was an inability to initially secure funding. These models provided a practical and cost effective method for which to construct initial prototype models in order to obtain an elementary understanding how structural changes affected cage stability.

Seen below in Figure 11 are two of the 1:12 scale models used to initially model prototype structures. The model on the left features no cross bracing and only two overhead beams. The model on the right features a more complex overhead truss system as well as the addition of cross braces. Each model was then loaded with 1 lb. (4.45 N) that bisected the longest overhead beam in order to determine how different truss structures affected the resulting deflections. The longest overhead beams were chosen since they represent the weakest points of the cage truss system due to their lengths. Once loaded, the resulting images below in Figure 12 were obtained.



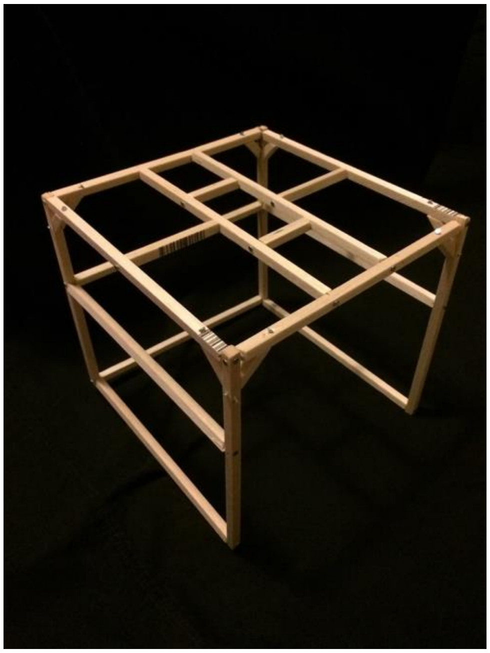


Figure 11: (Left) 1:12 scale balsa wood model featuring no cross braces and two single overhead beams and (right) 1:12 scale 6 member truss system.

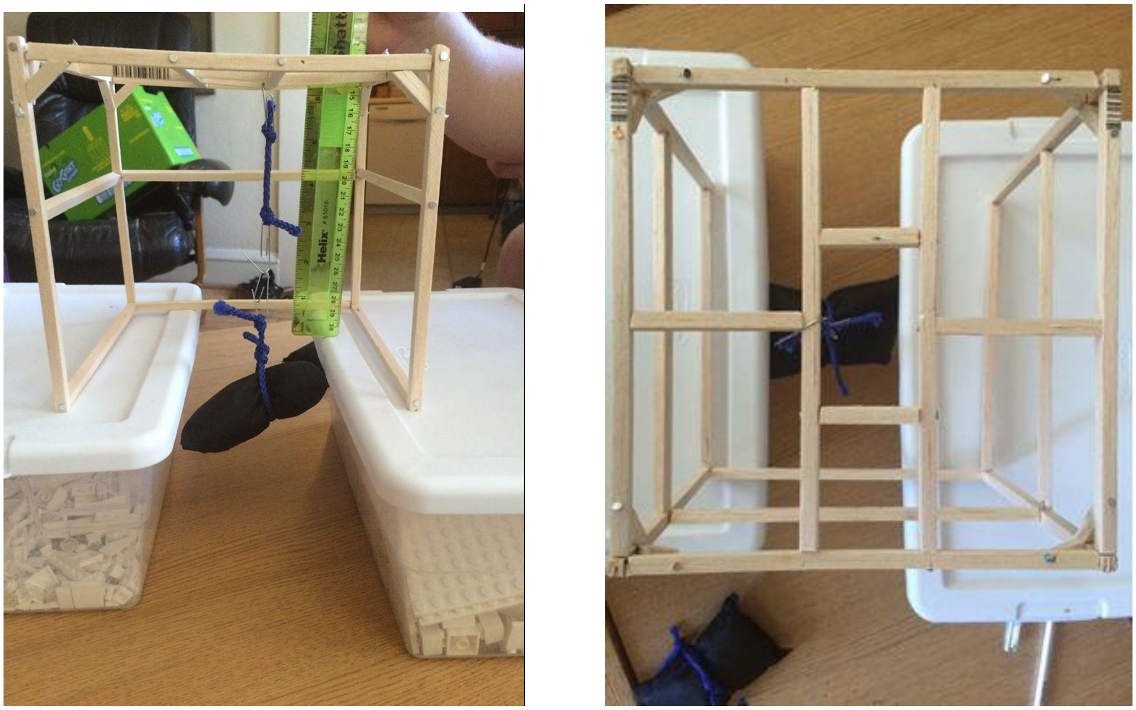


Figure 12: (Left) 6 members truss system being loaded with a 1 lb. (4.45 N) at overhead beam bisection and (right) overhead view of 6 member truss loading case.

The table seen below was then obtained by recording the distance between the top of the loaded beam to the bottom of the cage in order to determine how much each overhead beam deflected in the different truss systems. After these deflections were recorded, the loaded height of each overhead beam was then subtracted to their respective unloaded heights. These values were then divided by their corresponding unloaded heights in order to determine the percentage each overhead beam deflected with respect to the cages unloaded height as seen by the equation in Equation (1) below. A 0% deflection corresponds to no deflection, whereas a 100% deflection would correspond to a beam that has deflected from its initial position to the bottom of the cage which is not experimentally possible.

$$\% \text{ Deflection} = (H_{\text{unloaded}} - H_{\text{loaded}}) / H_{\text{unloaded}} \qquad (1)$$

Table 2 below corresponds to these calculated deflections. Equation (1) was used to calculate the percent of deflection each overhead member exerted under a 1 lb. (4.45 N) load.

Table 2: A table detailing the initial height, loaded height, and percent deflection of overhead beams with respect to total cage height

Single Member Truss System			
	Initial Height (cm)	**Loaded height (cm)**	**% Deflection**
Trial 1	17.3	16.5	4.6
Trial 2	17.3	16.5	4.6
Six Member Truss System			

	Initial Height (cm)	Loaded height (cm)	% Deflection
Trial 1	16.8	16.3	2.9
Trial 2	16.8	16.4	2.4

From the experimentally obtained data, it was inferred that the 6 member overhead truss system significantly reduced deflection when compared to a single member overhead truss system. This data was used in order to provide experimental data to provide initial inferences on overhead truss stability. It should be noted that these calculations have in no way been used to provide justification of the final cage prototype and exhibit many possible sources of error and inaccuracy (i.e experimental set up, material properties, joint properties). Rather, they were used in order to determine what truss systems may or may not provide additional structural stability in SAP and ANSYS computational modeling, and provided initial insight into possible truss designs.

MTS Testing and Results

After securing two 3' (0.91 m) samples of perforated square 12 gauge (.105", .27 cm) steel tubing, MTS testing was conducted. The first sample was 2.5" (63.5 mm) in cross sectional area (CA) and the second sample was 2.25" (57.15 mm) in CA. Using a drop saw, each sample was cut down to three 1' (0.31 m) segments. Using a 10,000 lb. (44.5 kN) SinTech MTS machine, each of the three samples were tested in three point bending. The samples can be seen bellow in Figure 13 being cut to size in the UW-Madison College of Engineering Student Shop.

Figure 13: Image depicting the use of a drop saw used to cut Telespar samples for MTS testing.

The purpose of the three point bending test was to measure the deflection of a beam under a known load. In order to accurately measure the deflection of the specimens, the machine's compliance number needed to be obtained. The compliance number is a measure of how much of the movement and deflection being measured is due to the screws in the machine as opposed to purely beam deflection, since the deflection is so small. In order to obtain the compliance number, a beam of solid steel was loaded to the maximum capabilities of the MTS machine. The deflection that was measured during this test was considered to be the compliance number, as the steel beam was assumed to be so rigid that it wouldn't deflect under the given load. The compliance number was found to be 0.0035” (0.089 mm). This number was subtracted from the measured deflection of each specimen to yield a more accurate result.

As seen below in Figure 14, the samples were centered on two specimen stands. The crosshead was lowered, the load zeroed on the computer, and the samples were tested under a known load. Each sample was loaded to the yield point, or until plastic deformation began to occur, which happened around 6,000 lbs. (27 kN).

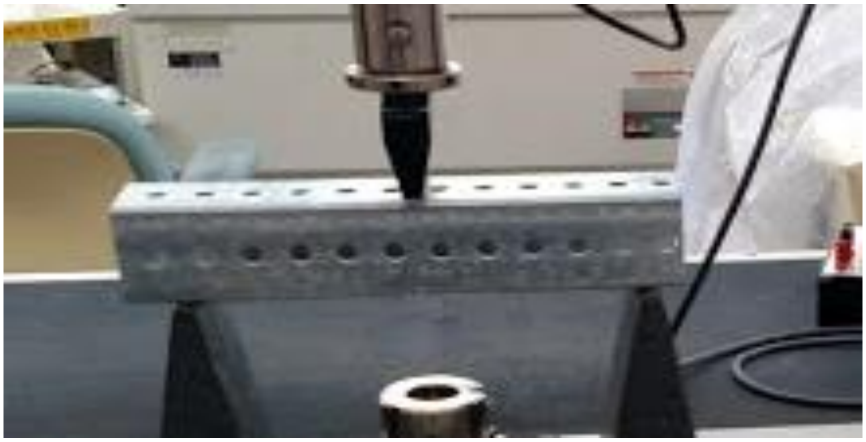


Figure 14: A sample being tested in three point bending on a Sintech 10,000 lb. MTS machine.

For each of the trials, a force versus displacement curve was constructed in MATLAB. The MTS testing results were compared to three point bending analysis done in SAP 2000 seen below in Figure 15. At a load of 320 lbs. (1.4 kN), the measured deflection from MTS testing was 0.0039 in (0.098 mm). The SAP 2000 results were approximately 30.1 % smaller than the MTS results. In order to accommodate this, the SAP 2000 simulation was rerun with an additional 30% load, resulting in a 400 lb. (1.8 kN) run. A plot of deformation versus force can been seen below in Figure 16 for both the MTS and SAP 3 point bending trials.

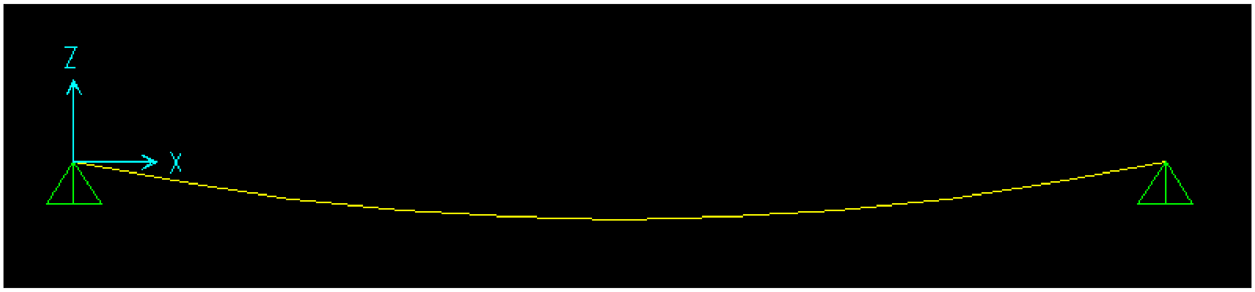


Figure 15: Image detailing a computational replication in SAP 2000 of Telespar 3 point bending.

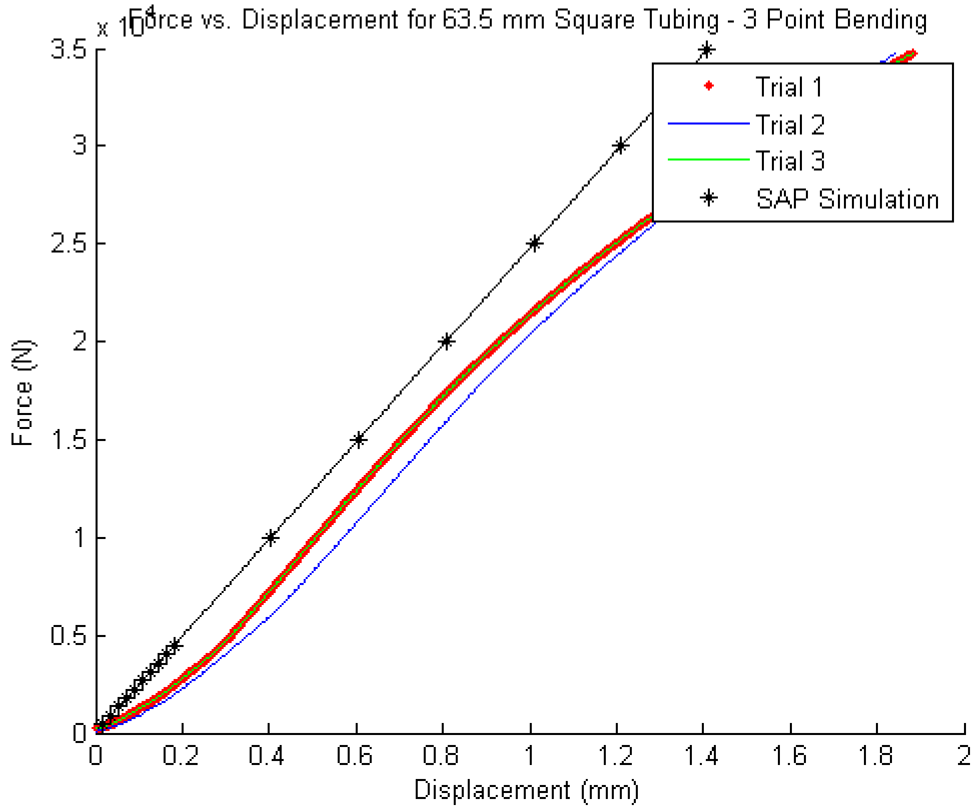


Figure 16: Force vs Displacement curve for the three trials and SAP 2000 results of beams in three point bending.

Testing & Results: Computational

ANSYS Structural Analysis Software Testing and Results

A finite element analysis program, ANSYS Workbench 14.5, was utilized to perform preliminary analysis on the overhead beams that will support the patient's body weight. Two different types of square perforated Tubing were compared under a 337.21 lb (1500 N) static load: 2.5'' Tubing Telespar tubing, and 2'' Telestrut tubing. Both tubing types are manufactured by UNISTRUT Corporation, and are widely available at a national scale. The tubing sizes tested are the largest size commercially available. The ANSYS testing showed that a truss structure constructed of the larger Telespar tubing showed a 61% lower deflection than the Telestrut tubing, under a 337.21 lb. (1500 N) load. Figures 17 and 18 below outline ANSYS tests.

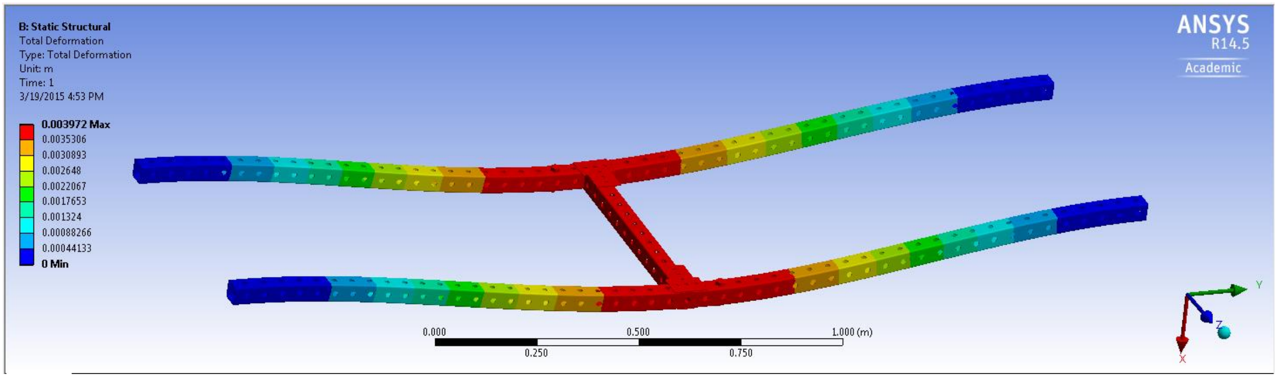


Figure 17: ANSYS simulation performed on truss structure constructed of 2in Telestrut tubing. The simulation showed a 3.972 mm deflection under a 350 lb. static load.

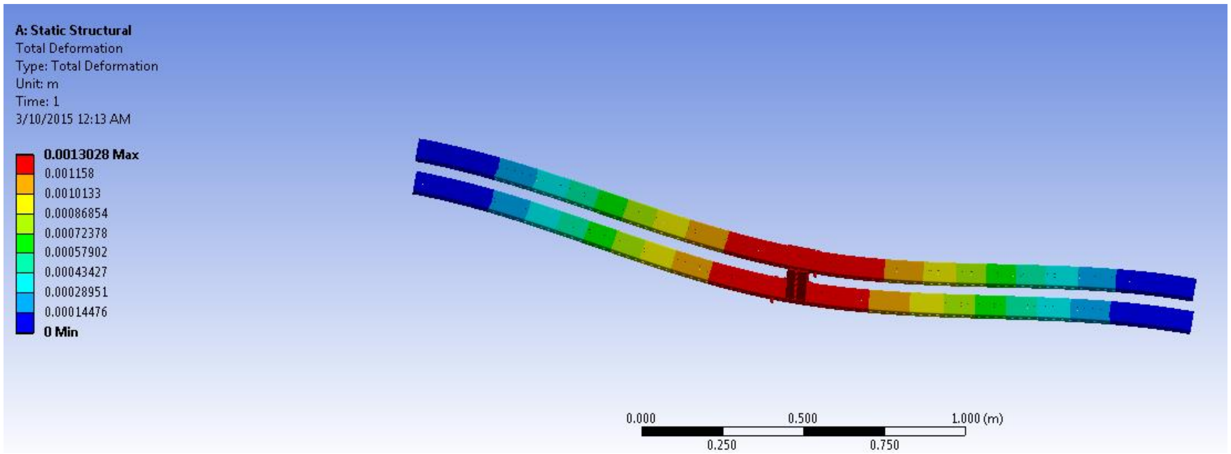


Figure 18: ANSYS Simulation conducted on 2.5'' Telespar Tubing. Simulation conditions were identical to Telestrut Simulation. The Telespar tubing showed a deflection of .13 mm, which was 60% lower than the Telestrut simulation.\

SAP 2000 Structural Analysis Software Testing and Results

A grid was generated in SAP with 9 lines spaced 1' (.31 m) apart in the X, Y, and Z directions in order to define the space that the prototype models would be constructed in. SAP then provides two windows for viewing: one that can be defined with respect to a 2 dimensional plane and one that encompasses the 3 dimensional space of the model as seen below in Figure 19. From here, a previously existing material was used that closely replicated that of the ASTM 1011 grade 50 steel that the Telespar sections are fabricated out of and had its properties modified in order to match that of Telespar. This material was used to model both the Telespar sections as well as the turnbuckle cross braces. After this material was defined, section properties were then created for both the Telespar members as well as the turnbuckles. These section properties can be seen below in Figure 20.

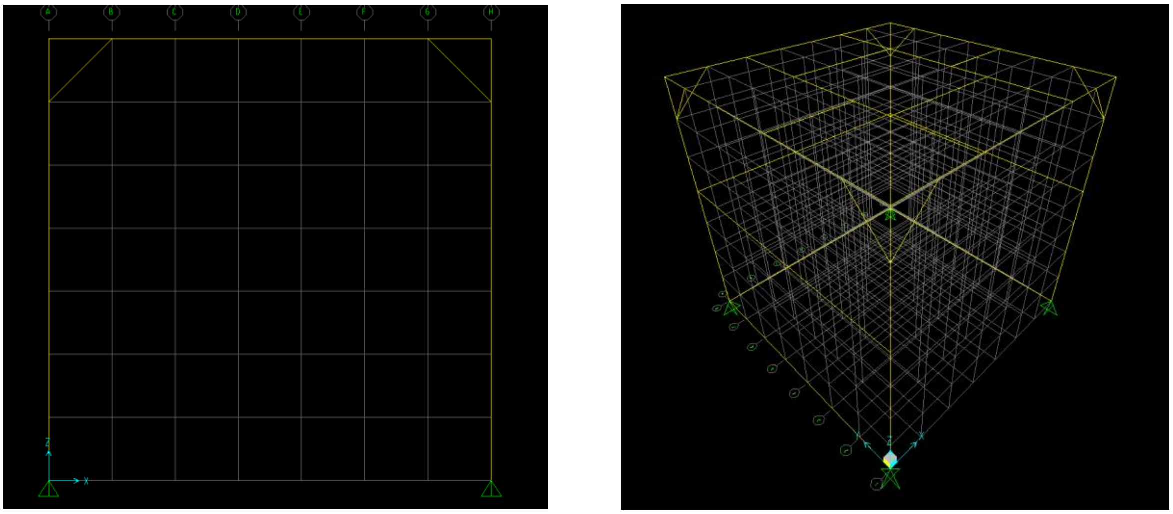


Figure 19: (Left) two dimensional representation of the open face of the cage prototype in the XY (Z=0) plane and (right) representation of cage prototype modeled in 3 dimensional space.

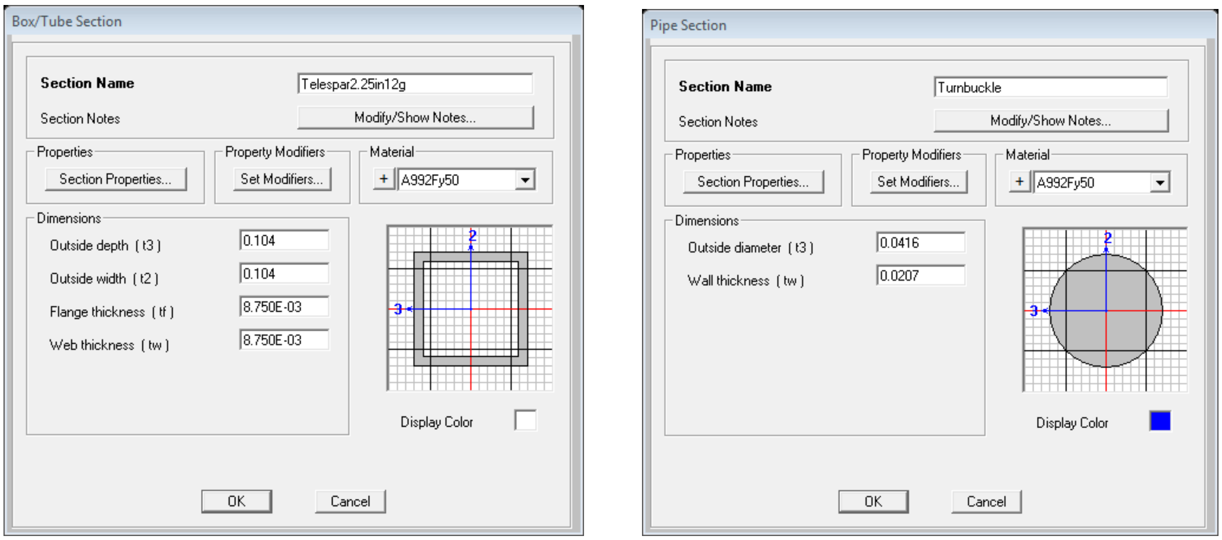


Figure 20: (Top) SAP properties window outlining Telespar sectional properties and (bottom) SAP window outlining turnbuckle sectional properties.

After all of the cage members had been defined in 3 dimensional space, they then had to be constrained with respect to one another as well as with respect to the floor (the XY plane at Z=0). The four corners of the XY plane (Z=0) were constrained with respect to the XY plane, but allowed to translate in the X and Y directions. This constraint was performed in order to effectively allow the cage to translate and deflect in the X and Y directions, but not in the Z direction, and can be seen below in Figure 21. This effectively modeled the floor upon which the prototype would be constructed. The entire cage was then meshed in order to define the different members of the cage as being rigidly connected to one another, rather than individual beams that only exist in space without any physical constraint. The resulting cage model can be seen below.

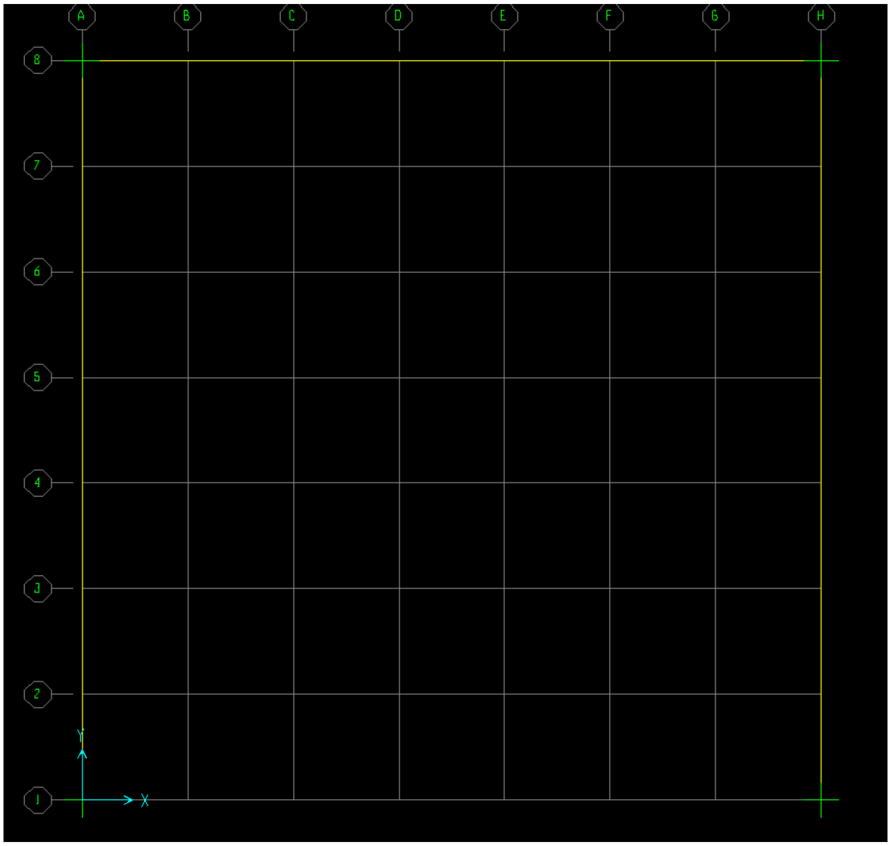


Figure 21: An image depicting the bottom of the modeled cage in the XY plane at Z=0. In each corner a green "+" marks where the cage has been constrained within the XY plane.

Various load patterns were then able to be defined by first assigning these loads to different members of the cage. This provided the dynamic ability for the cage to be loaded under multiple scenarios, and as a result, theoretical data was able to be produced with respect to the axial forces, moments, shear forces, and deflection that the cage sustained under each of these unique loading scenarios. These scenarios and their respective results will be defined in the upcoming testing and results section.

In order to validate the cage prototype's stability in a severe loading case, both a vertical (400 lb., 1780 N) and lateral (150 lb., 668 N) live load were applied to different members of the cage as seen below in Figure 22. This loading scenario provides insight into how the cage will deform under the unlikely and recommended circumstance that an individual is completely suspended on the weakest beam of the cage due to its overhead span. The cage's exaggerated deflection under these simultaneous loading scenarios can be seen below in Figure 23. This image should not warrant unnecessary concern over what may first seem like an unacceptable deformation incapable of supporting an individual safely. Instead, it is only an exaggerated depiction of cage deformation that provides the engineer with a better understand of how members deflect under various loading scenarios.

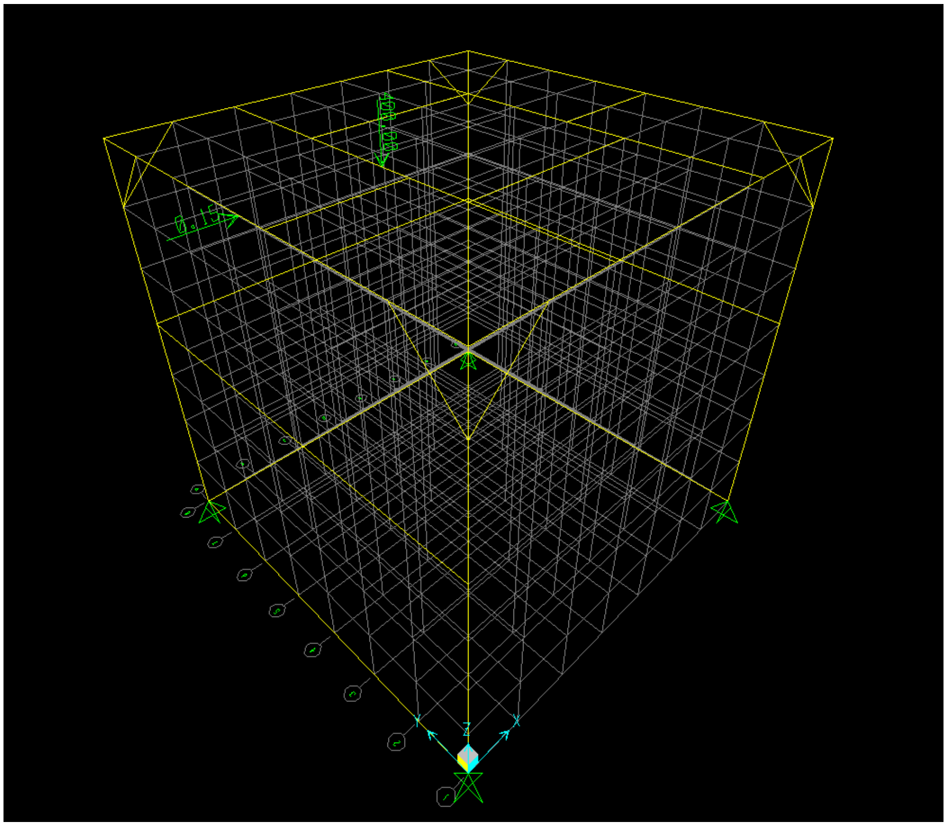


Figure 22: (Above) SAP modeled cage prototype with 150 lb. (668 N) lateral load and 400 lb. (1780 N) vertical load. It should be noted that these have been applied in the above image with units of kips rather than lb. (1000 lb. = 1 kip).

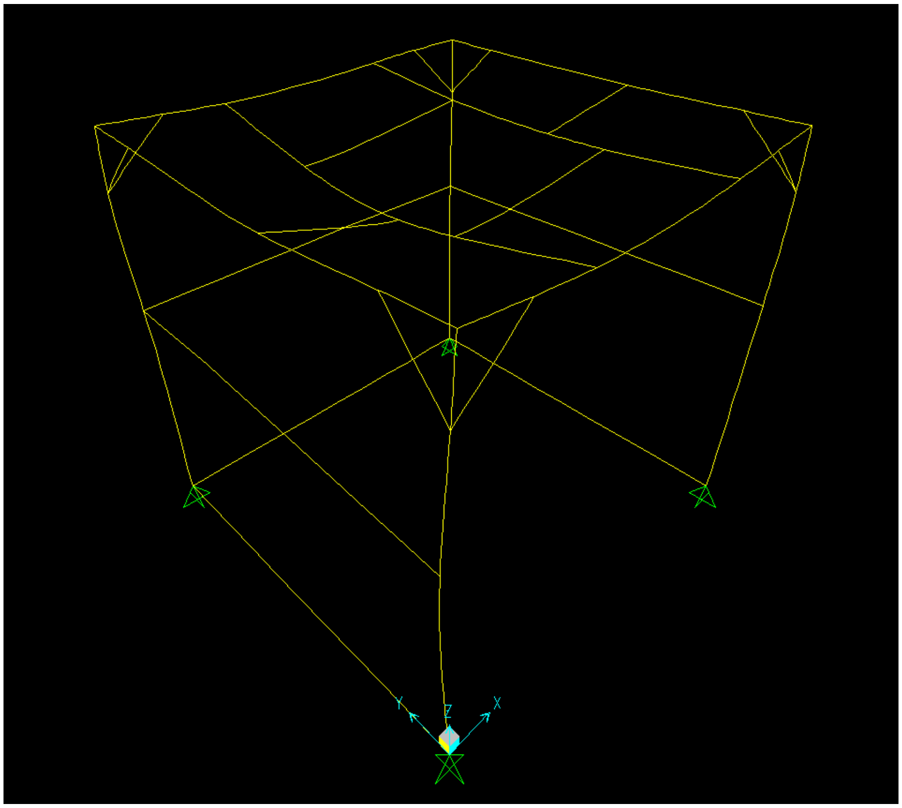


Figure 23: An image depicting the exaggerated deflection that was experience by the cage under the previously described loading scenario.

Once these loading scenarios were applied, SAP was used to determine both the deflections and forces present in different members of the cage. Most importantly, these variables were examined on the loaded overhead beam and on the open face axial beams that make up the front of the cage, since they do not provide a ground level connecting member to prevent them from "buckling" inwards or outwards. The resulting SAP generated diagrams for both of these members can be seen below in Figures 24 and 25.

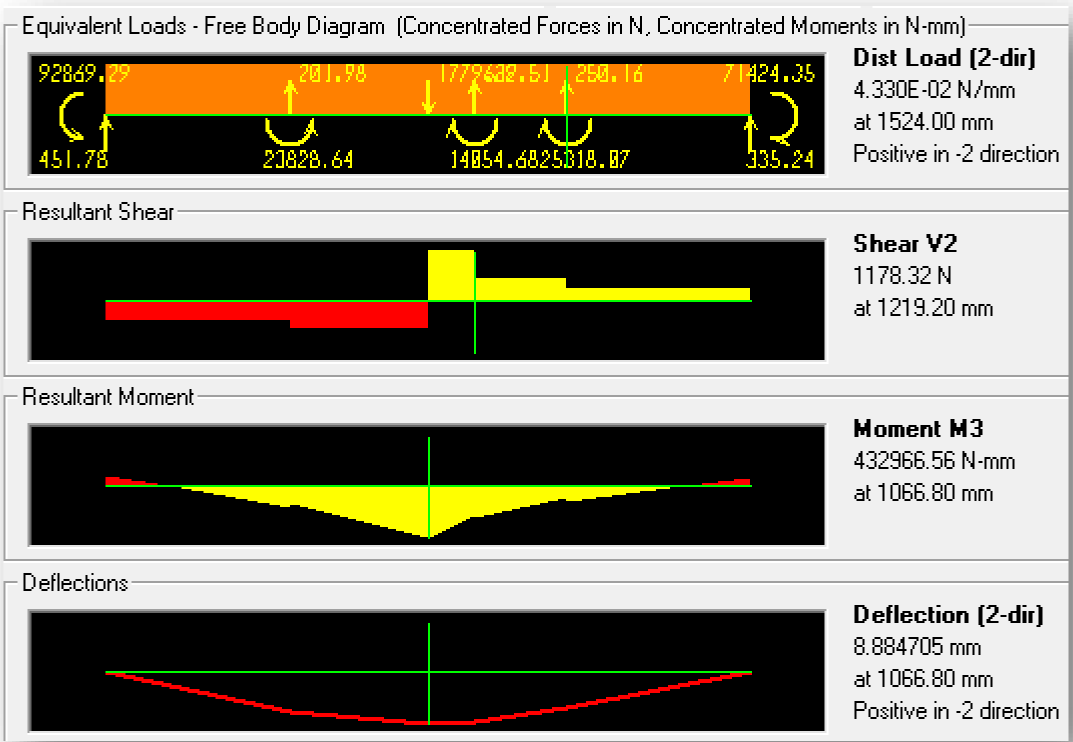


Figure 24: (Above) window depicting the how an overhead beam was affected by a 400 lb. (1780 N) load.

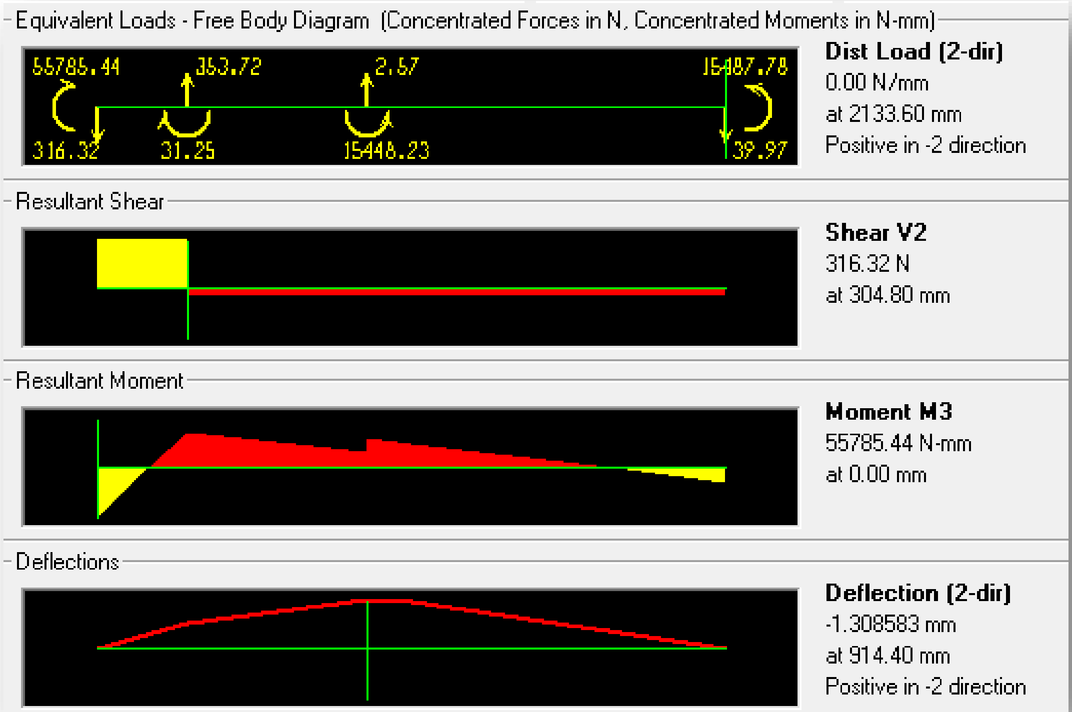


Figure 25: Window depicting how an open face axial beam was affected by the aforementioned 150 lb. (668 N) load.

The resulting deflections of this severe loading case had a maximum value of 8.84 mm in the -Z direction and 1.3 mm in the Y direction for both a 7' (2.13 m) overhead beam and 7' (2.13 m) vertical open face beam. These values were then cross referenced against Telespar cited values and it was determined that not only was the cage well within the cited maximum allowable load, but that the cage did not exhibit perceptible deflection according to the Telespar cited values, with 8.9 mm being the threshold for perceptible deflection at a 1/240 span. In addition to this loading scenario, various other loading scenarios were performed on the cage which can be seen in section V of the Appendix. The conclusion was that these additional loading scenarios supported that the cage exhibited sufficient stability and minimal deflection under other loading scenarios.

Potential Sources of Error in SAP and ANSYS

When evaluating the computer simulation results, it is important to recognize the limitations of the software. Finite element analysis programs such as SAP2000 and ANSYS rely on analyzing a "mesh" of individual nodes. The behavior of the entire system can then be predicted by numerically solving linear differential equations applied to the individual elements. (14) As the mesh is an approximation of the homogenous components it is modelling, error can be introduced into finite element analysis software from this approximation, known as "Discretization error" (15). Additionally, both simulation modalities utilized fixed boundary conditions. For FEA, fixed conditions are assumed to exhibit no displacement. However, true fixed conditions do not exist in the real world, which may increase defection seen in physical testing. (16).

Discussion

Prototype Impact

The final prototype will have many important implications. The largest benefit of the U-Cube will be that it serves as a physical therapy device that can accommodate people of all ages, sizes, and diseases. The main focus of the cage was to help a patient who suffered from a TBI to regain mobility through gait training; however people suffering from cerebral palsy, stroke, and many others can perform physical therapy activities with the U-Cube. In regards to the Madison area alone, fifty-five patients at the Madison Area Rehabilitation Center will be gaining access to this new physical therapy device. This is important because many of these patients are not covered for this kind of therapy so the U-Cube will provide them with access to it. It was seen earlier that in underserved populations that cannot get access to appropriate therapy, intensive suit therapy can have huge benefits in relieving these patients of their symptoms (Meagher). The therapy that the cage will provide will help these patients regain mobility through physical therapy, and by regaining their mobility their quality of life will greatly improve.

The U-Cube was also designed to be built by anyone, and with easily acquired parts directly from a supplier, the cost of the cage is greatly reduced. Another implication of the U-Cube is that physical therapists will be able to perform their jobs easier. One of the main functions of the device is to support the weight of the patient so the therapist does not have to do this. Since the therapist can then expand more energy on the therapy, the treatment is more effective for the patient and easier for the therapist to perform. This should greatly decrease the stress on the therapist, while possibly allowing the patient to get more out of their time in therapy.

In conclusion, the U-Cube prototype provides an alternative to commercially available models at 1/5 the cost ($1200 compared to $7000). Thus, once an instructions manual is created an uploaded to UCP Dane’s website, individuals suffering from TBIs and other physical ailments will be able to have a more diverse range of physical therapy options at their disposal. Thus, the U-Cube allows for a cost effective alternative to current therapy systems that provides a mechanism for which an individual can increase their overall quality of life.

Conclusion

In summary, the purpose of creating the U-Cube prototype was to create an affordable therapy system when compared to competing commercial design while not sacrificing a large amount of functionality. This was done by creating a prototype out of inexpensive, yet structurally sound materials that are capable of providing both a dynamic assembly that can be altered by a therapist as well as the ability to provide dynamic attachments for elastic suspension. Unfortunately, the budget this semester was unable to cover to the cost of both an elastic suspension system and harness, but the design team was able to create a design matrix and recommend the Biodex DLX harness for use with the U-Cube prototype.

Through multiple forms of computational analysis and physical modeling, the U-Cube prototype was ultimately found to be structurally stable. Initially, balsa wood models were created to create a crude model of overhead truss designs. From these models, it was inferred that the 6 member overhead truss system provided additional stability when compared to both a single overhead truss system. From here, additional calculations were run in ANSYS to provide computational evidence that this conclusion was also true, and to provide additional justification for the final overhead truss design. Once completed, Telespar samples were obtained and tested in an MTS machine to compare experimental 3 point bending tests with the Telespar data sheet (III, Appendix) and SAP 2000 3 point bending tests. However, it was found that the 3 point bending tests conducted in the MTS machine were significantly higher than the SAP tests, but still closely replicated that data provided in the Telespar data sheet. As a result, the loads that were applied in SAP were increased to compensate for this discrepancy. Lastly, the complete prototype was modeled in SAP where various loads were applied, and it was ultimately determined that the U-Cube prototype was structurally stable, thus providing the final justification that our prototype was stable.

Future Work

During the upcoming weeks several steps will be taken in order to construct the U-Cube prototype as well as experimentally validate its design and structural stability. Most notably, parts have been ordered and will be arriving within the next 4-5 weeks from the date provided on this report. Once the materials are obtained, the prototype will first be constructed on campus in order to determine how an instructions manual will be created. After the U-Cube's construction, this instruction manual will then be loaded onto the client's website: www.UCPdane.org. After the methods and tools required for prototype construction have been determined and an instructions manual has been created, the design team will seek to experimentally validate both prototype structure and functionality through a series of experimental tests. Testing procedures will be determined during the upcoming weeks and upon the arrival of materials, and will consist of applying different loading scenarios to the cage in order to analyze experimental results against computational results with respect to member deflection. Additionally, the functionality of the cage will be conferred and validated through a series of therapy activities that will be performed in cage upon construction.

Once the stability and functionality of the cage have been validated, it will be disassembled and delivered to Amanda Miller's office located and the Madison Area Rehabilitation Center (MARC). In order to do so, a commercial vehicle will be obtained from UW-Madison through the sponsorship of our design team by UW-Madison's Department of Biomedical Engineering. The prototype will then be constructed at MARC where it will be available for use by Amanda Miller, her patient Michael, and any other individual with which she determines would benefit from the prototype's application. Lastly, feedback from both Amanda Miller, our client Mr. Jahnke, and Micheal can be sent to Sam Mesanovic (mesanovic@wisc.edu), and any additional structural modifications that are either required or desired will be taken into consideration. Provided that funding is available, any additional changes that are required will be made to the cage up to but not exceeding 6 months after the submission date of this report provided on the title page (5/6/2015).

Works Cited

1. (n.d.). Retrieved February 19, 2015, from http://ucpdane.org/

2. Traumatic Brain Injury in the United States: Fact Sheet. (n.d.). Retrieved February 19, 2015, from http://www.cdc.gov/traumaticbraininjury/get_the_facts.html

3. Scherer, M. (2007). Gait rehabilitation with body weight-supported treadmill training for a blast injury survivor with traumatic brain injury. *Brain Injury,* (1), 93-100.

4. Meagher, A., Beadles, C., Doorey, J., & Charles, A. (2015). Racial and ethnic disparities in discharge to rehabilitation following traumatic brain injury.*Journal of Neurosurgery.* (3), 595-601.

5. Intensive Suit Therapy – the most powerful and innovative therapy method for Cerebral Palsy and Brain Injury. (n.d.). Retrieved February 24, 2015, from http://www.revivo.ca/suittherapy/

6. Ko, M., Lee, J., Kang, S., & Jeon, H. (2014). Effect of Adeli suit treatment on gait in a child with cerebral palsy: a single-subject report. *Physiotherapy Theory and Practice. 30,* 1-8.

7. Bailes, A., Greve, K., & Schmitt, L. (2010). Changes in Two Children with Cerebral Palsy After Intensive Suit Therapy: A Case Report. *Pediatric Physical Therapy*, 22, 76-85.

8. Universal Exercise Unit. (n.d.). Retrieved October 8, 2014, from http://www.believetherapy.com/cage/

9. TheraSuit Method. (n.d.). Retrieved October 8, 2014, from http://www.suittherapy.com/

10. Support Harness DLX. (n.d.). Retrieved February 19, 2015, from http://www.biodex.com/physical-medicine/products/harnesses/standard-support-harness

11. (n.d). Retrieved Febuary 19, 2015, from http://www.hanessupply.com/webcatalog/Documents%2fNylon_Slings_Technical_Information.pdf

12. IHarness. (n.d.). Retrieved February 19, 2015, from https://www.litegait.com/products/iharness

13. Bellows Fund. (n.d.). Retrieved May 5, 2015, from http://www.ucpnb.org/about-us/bellows-fund

14. Pointer, J. (2004). Understanding Accuracy and Discretization Error in an FEA Model. In ANSYS 7.1, 2004 Conference, Woodward Governor Company.

15. Shah, C. (2002). Mesh Discretization Error and Criteria for Accuracy of Finite Element Solutions. In Proceedings of International ANSYS Conference (Vol. 2002).

16. Errors Arising in FEA. (n.d.). Retrieved May 3, 2015, from http://www.tech.plym.ac.uk/sme/mech335/feaerrors.htm

Appendix

I. Product Design Specifications

Team Members: Jon Elicson, Jon Leja, Samantha Mešanović, Jake Kanack
Date: March 3, 2015

Function

A spider cage is a device used by therapists to work with people (usually children) who have physical disabilities. Spider cages provide targeted support to an area of the patient's body through bungee cords connected to a suit, harness, or band, and assist with intensive physical therapy programs. The support provided by the bungee cords is adjusted by changing the strength and attachment locations of the cords. Spider cage devices are available commercially, but are prohibitively expensive. The desired product must be relatively inexpensive, collapsible for transport, and created utilizing off-the-shelf components for widespread applications.

Client Requirements

- The device must work for a variety of individuals of varying weight, age, and height in addition to Michael.
- The device must include some apparatus to connect the individual to the cage. This apparatus will most likely take the form of elastic suspension bands of varying length and resistance.
- The device must cost less than the commercially made devices priced at $5500.
- The device must have a simple fabrication process using easily obtainable tools and materials.
- The device must include a detailed instruction manual and parts list to assist in assembly that will be uploaded to UCPdane.org.

Design Requirements

1. **Physical and Operational Characteristics**
    a. ***Performance requirements:*** The device should be able to withstand day to day use, and be durable and light enough to be disassembled and transported. The spider cage should provide enough room to allow for the individual to translocate around the cage in each direction. It should provide attachment locations for the necessary elastic straps, and allow these straps to attached or detached to the individual using the cage. This device should allow for an able-bodied individual to facilitate therapy without a trained professional if they so choose.
    b. ***Safety:*** The spider cage should be strong and stable enough to allow for rapid movement and loads that will exceed the normal weight of the individual.
    c. ***Accuracy*:** The support provided by the suspension system must be adjustable to target therapy relevant sections of the patient (eg, a specific limb). The strength of the support provided by the suspension system must be adjustable.

d. ***Life in Service:*** The device must be able to be used for 2 hour long therapy sessions 5 times per week without wear. The device should also be stored in a temperature controlled environment, and away from excessively humid or dry air.
e. ***Operating environment:*** The device is intended for use in the individual's home or in a physical therapist's facility. The device should be capable of being tailored to a specific individual for extended periods of use, but have the capability to be adjusted to accommodate another individual. The targeted use is for patients of all ages, placing an emphasis on the ability of the cage to accommodate small children.
f. ***Ergonomics:*** The elastic bands must be reachable and easily adjustable.
g. ***Size:*** The cage must be tall and wide enough to accommodate anyone. Different attachments must be small enough so that they can be handled easily.
h. ***Weight:*** The device should be transportable.
i. ***Materials:*** (To be further discussed and determined): Material for the cage itself should not be sharp. Materials that are resistant to corrosion and rust should be used.
j. ***Aesthetics, Appearance, and Finish:*** The device should look professionally assembled. Elastic bands should be color coded or labeled in another way in order to identify different strength bungee cords for ease of use.

2. Production Characteristics:

a. ***Quantity:*** Plans and an instruction manual for the unit will be uploaded to ucpdane.org, with the intention of creating a device that could be readily produced by future patients or patient care providers. Accordingly, the device must be constructed utilizing parts and tools that are commercially available. However, the first prototype will be placed at the Madison Area Rehabilitation Center for use by an occupational therapist.
b. ***Target:*** Current research has found that a similar device would cost about $5500. The product can most likely be mass produced, however current manufacturers only custom produce each product. The client would like the device to be as inexpensive as possible without there being an exception to the device's safety and functionality.

3. Miscellaneous:

a. ***Standards and Specifications:*** The device must include a materials list and an instructions manual so it can be uploaded online on the United Cerebral Palsy of Greater Dane County's website for fabrication by other individuals. The cage will not be required to be approved by the FDA for use, but will need to have a finite element analysis performed on it to ensure a reasonable factor of safety for personal use after construction by a third party who does not necessarily have professional training.
b. ***Customer:*** The customer is Matt Jahnke from United Cerebral Palsy of Greater Dane County. There is currently no specific client for which this cage will be designed, instead, Mr. Jahnke requires that a cage prototype be constructed for which an instruction manual and parts list will be created. These lists will then be uploaded to ucpdane.org, thus allowing any individual to download and construct the cage prototype. Mr. Jahnke has designated that this cage design will be marketed on his website only as a therapy device for cerebral palsy, and will not be marketed as a therapy device for any other purpose. The cage will also likely be constructed in a residential environment in the absence of

commercial tools. As a result, the cage should be able to be assembled using common household tools and hardware.

c. ***Patient-Related Concerns:*** It is recommended that the patient be supervised and assisted during therapy sessions that utilize the cage prototype. The device should be able to be operated by individuals with varying degrees of cerebral palsy with relative ease.

d. ***Competition:*** There is no commercial competition in the price range desired by the client. There are several models on the internet for approximately $5500.

II. MATLAB Code for MTS Processing

Load the Data

```
%ask = uigetfile('*.txt','Select the file to open');
data = load('largesample3EditedForMatlab.txt');
data2 = load('largesample2EditedForMatlab.txt');
data3 = load('largesample3EditedForMatlab.txt');
```

Add in the Correction Factor of -.0889mm

```
datab = data(:,3);
AdjData = datab-.0889;
datab2 = data2(:,3);
AdjData2 = datab2-.0889;
datab3 = data3(:,3);
AdjData3 = datab3-.0889;
```

Convert lbf to N

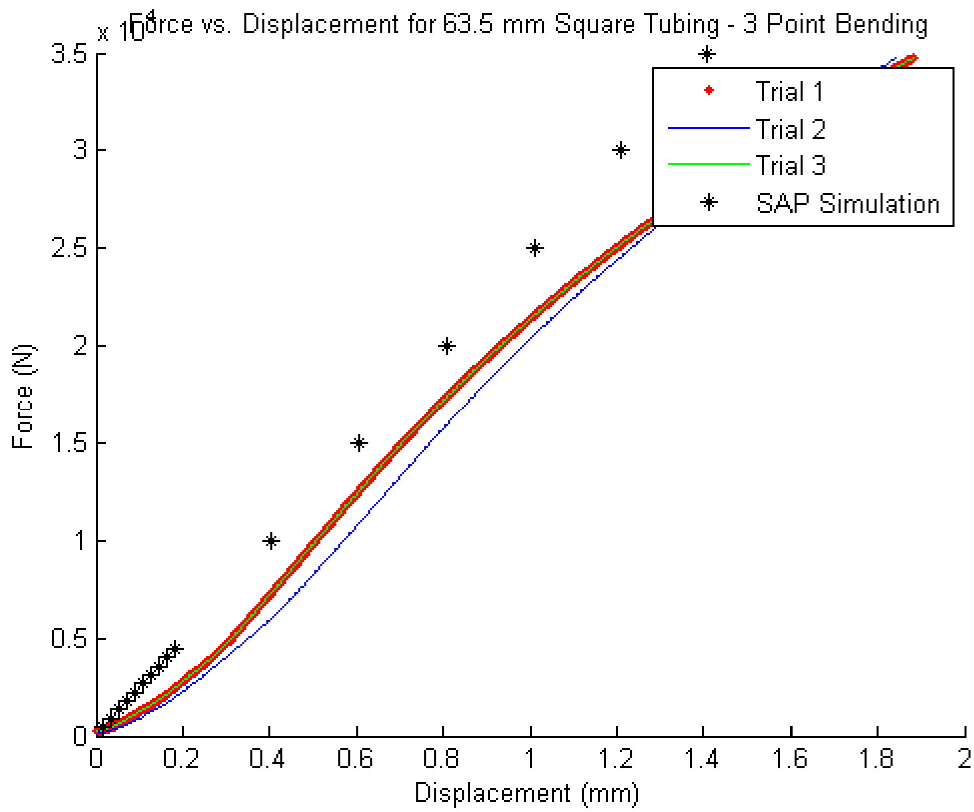
```
ForceN = data(:,1).*4.44822162;
ForceN2 = data2(:,1).*4.44822162;
ForceN3 = data3(:,1).*4.44822162;
Trial_1 = data;
Trial_2 = data2;
Trial_3 = data3;
```

Enter SAP Data

```
SAPForce = [450,895.78,1340.6,1785.42,2230.24,2675.06,3119.88,3564.7,4009.54,4454.36,1e4,1.5e4,2e4,2.5e4,3e4,3.5e4];
SAPDisp = [.018,.036,.054,.072,.089,.108,.126,.144,.162,.18,.403,.606,.808,1.01,1.21,1.41];
```

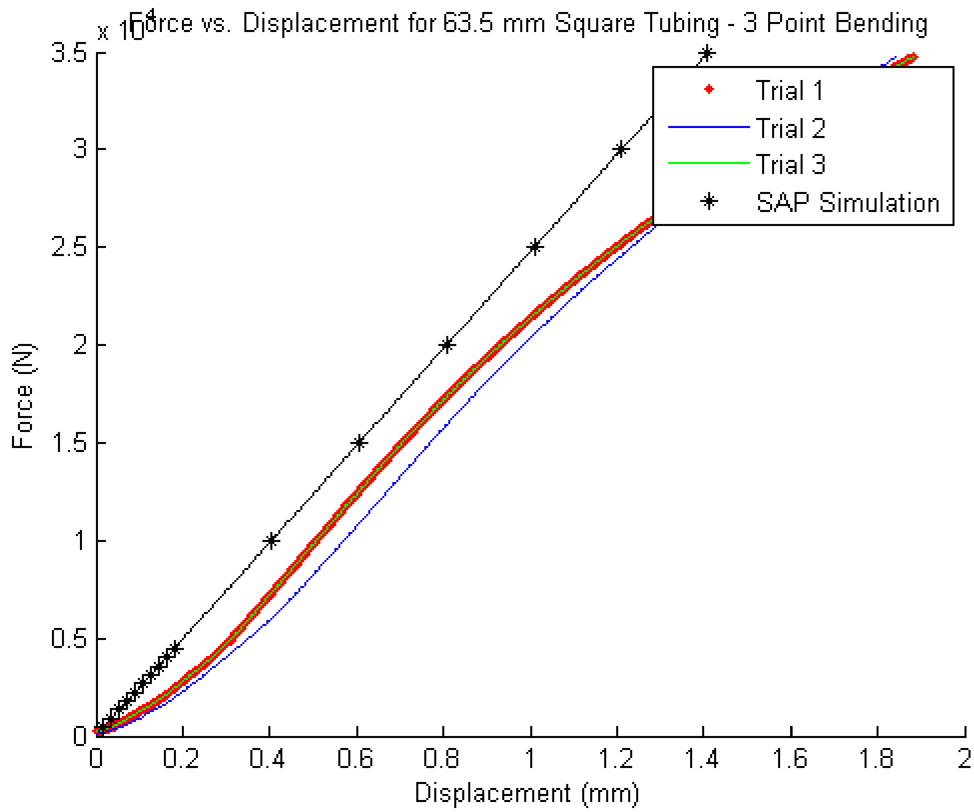
Plot Data

```
figure
hold on
xlabel('Displacement (mm)')
ylabel('Force (N)')
title('Force vs. Displacement for 63.5 mm Square Tubing - 3 Point Bending')
plot(Trial_1(:,3),ForceN,'r.')
plot(Trial_2(:,3),ForceN2,'b')
plot(Trial_3(:,3),ForceN3,'g')
plot(SAPDisp,SAPForce,'k*')
legend('Trial 1','Trial 2','Trial 3','SAP Simulation')
```



Best Fit Line SAP

```
coeffs = polyfit(SAPDisp,SAPForce,1);
Fitx = linspace(min(SAPDisp),max(SAPDisp),200);
Fity = polyval(coeffs,Fitx);
plot(Fitx,Fity,'k')
```



Determine Yield at Lim Force

```
Displacement = [0,0,0];
r = 1;
g = 1;
g2 = 1;
g3 = 1;
Lim = 1779.3;
while r < length(data)
   F = ForceN(r,1);
   if r <= length(data2)
   F2 = ForceN2(r,1);
   end
   if r <= length(data3)
   F3 = ForceN3(r,1);
   end
   if F >= Lim
      give(1,g) = AdjData(r,1);
       if r <= length(F2)
         if F2 >= Lim
         give2(1,g2) = AdjData2(r,1);
             g2 = g2+1;
         if F3 >= Lim
           give3 = AdjData3(r,1);
```

```
            g3 = g3+1;
          end
          end
        end
      r = r+1;
      g = g+1;
    elseif F2 >= Lim
      give2(1,g) = AdjData2(r,1);
      g2 = g2+1;
      if F3 >= Lim
          give3(1,g3) = AdjData3(r,1);
          g3 = g3+1;
      end
      r = r+1;
    elseif F3 >= Lim
      give3(1,g3) = AdjData3(r,1);
      g3 = g3+1;
      r = r+1;
    else
      r=r+1;
    end
end
```

Data Processing

```
Displacement(3) = give(3);
Displacement(1) = give(1);
Displacement(2) = give(2);
AvgDisplacement = mean(Displacement);
StdDevDisplacement = std(Displacement);
```

Published with MATLAB® R2014a

III. Telespar Data Sheet

UNISTRUT®

TELESPAR® TELESCOPING SQUARE TUBING
for Industrial & OEM Applications

VERSATILE, REUSABLE, ECONOMICAL

Use the Telespar System to fill your building needs in almost any application: racks, shelving, ceiling grids, conveyor systems, interior partitions, adjustable platforms, material handling devices, scaffolds, strapping machines, hangers, support members, protective railings, sign supports, etc. No special welding, tools or assembly procedures are necessary with the Telespar System.

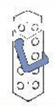
One of the secrets to Telespar's versatility is its ability to telescope. Smaller sizes fit smoothly and snugly into the next larger size. This is made possible by the latest in high-speed roll-forming technology with high-frequency resistance welding. This produces smooth corner welds within very close tolerances, reducing your fabrication costs.

Telespar standard perforated tubing comes in eight sizes, from 1" to 2½" square, in 10 and 12 gauge. Perforated holes are 7/16" spaced on 1" centers, except for 1" and 1¼" which have 11/32" holes on 1" centers. Sections without holes are available in all sizes.

Telespar comes in two standard finishes: Pre-Galv Plus™ and plain (lightly oiled) surface. The Telespar System includes a complete line of zinc-electroplated fittings, fasteners and accessories for splicing, extending and reinforcing.

COMPONENTS

FITTINGS DIMENSIONS

Fittings*	Tube Size	Cutting Dimensions**	Fittings*	Tube Size	Cutting Dimensions**
TL015† T-Fitting 	1½" sq. 1¾" sq. 2" sq. 2¼" sq. 2½" sq.	1 3/16" 1 1/16" 15/16" 13/16" 11/16"	TL020 90° Offset Fitting 	1½" sq. 1¾" sq. 2" sq. 2¼" sq. 2½" sq.	1 3/16" 1 1/16" 15/16" 13/16" 11/16"
TL016† L-Fitting 	1½" sq. 1¾" sq. 2" sq. 2¼" sq. 2½" sq.	1 3/16" 1 1/16" 15/16" 13/16" 11/16"	TL090 TL092 TL094 Lock Pin 	1½" sq. 1¾" sq. 2" sq. 2¼" sq. 2½" sq.	N/A
TL018 Straight Fitting 	1½" sq. 1¾" sq. 2" sq. 2¼" sq. 2½" sq.	N/A	TL017 Anti-Rotation Fitting 	1½" sq. 1¾" sq. 2" sq. 2¼" sq. 2½" sq.	1" 1" 1" 1" 1"

* Standard Unistrut® channel fittings will not work on Telespar.®
** Distance from end of tube to center of first hole.
† Both tubes must be same size.

CONNECTING BOLTS

Part No.	Description	Use with Tube Sizes
TLCB516S	Corner Bolt	1½", 1¾", 2"
TLCB516M	Corner Bolt	2¼", 2½"
TLJNH516	5/16" Heavy Hex Jam Nut	All
TL090EG	5/16" Lock Pin	1", 1½", 1¾"
TL092EG	3/8" Lock Pin	1½", 1¾", 2"
TL094EG	3/8" Lock Pin	2¼", 2½"
TLXDR3878	Drive Rivet	All

Tubing holes are 7/16" diameter, one inch on center, which accommodates standard 5/16" or 3/8" bolts. All corner bolts are 5/16" diameter.

ELEMENTS OF SECTION

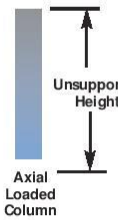
I-Moment of Inertia S-Section Modulus r-Radius of Gyration K-Torsional Factor

	Non-Perforated									Perforated						
Tube Size	Wall Thickness U.S. Std. Gauge	Part No.	Area Sq. In.	Wt./Ft. Lbs.	I In.4	S In.3	r In.	K	Allowable Moment in Lbs.	Part No.	Area Sq. In.	Wt./Ft. Lbs.	I In.4	S In.3	r In.	Allowable Moment in Lbs.
1" x 1"	12 (.105)	11F10	0.354	1.203	0.040	0.080	0.336	0.075	2,634	11F12	0.210	1.070	0.026	0.052	0.352	1,712
1¼" X 1¼"	12 (.105)	12F10	0.459	1.560	0.093	0.148	0.450	0.158	4,874	12F12	0.315	1.427	0.070	0.112	0.472	3,688
1½" x 1½"	12 (.105)	14F10	0.564	1.917	0.175	0.234	0.557	0.285	7,706	14F12	0.380	1.702	0.129	0.172	0.582	5,664
1¾" x 1¾"	12 (.105)	16F10	0.669	2.274	0.294	0.336	0.663	0.467	11,065	16F12	0.485	2.060	0.231	0.264	0.690	8,694
2" x 2"	12 (.105)	20F10	0.774	2.631	0.456	0.456	0.768	0.715	15,018	20F12	0.590	2.416	0.372	0.372	0.794	12,251
2¼" x 2¼"	12 (.105)	22F10	0.879	2.988	0.668	0.594	0.872	1.036	19,563	22F12	0.695	2.773	0.561	0.499	0.898	16,434
2½" x 2½"	12 (.105)	24F10	0.987	3.356	0.937	0.749	0.974	1.443	24,667	24F12	0.803	3.141	0.804	0.643	1.001	21,176
2" x 3"	12 (.105)	2030F10	0.987	3.356	MAJOR AXIS 1.217	.811	1.110	1.319	20,709	2030F12	.711	3.034	MAJOR AXIS .976	.651	1.172	21,440
					MINOR AXIS .647	.647	.810	1.319	21,308				MINOR AXIS .480	.480	.822	15,808
2 3/16" x 2 3/16"	10 (.135)	21H10	1.077	3.662	0.731	0.668	0.824	1.167	22,000	21H12	0.841	3.432	0.605	0.590	0.848	19,431
2½" x 2½"	10 (.135)	24H10	1.248	4.236	1.146	0.917	0.959	1.786	30,200	24H12	1.010	4.006	0.979	0.783	0.985	25,787

TELESPAR® TELESCOPING SQUARE TUBING

CALCULATION OF TELESCOPED BEAM LOADING

When consecutive size tubes are telescoped one inside another, beam loads from charts on pages 5 –7 are additive. Deflections for spans 5 feet and over will be approximately the same as for the larger tube. Deflections for shorter spans will show a slight increase.

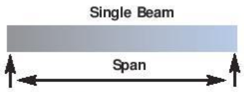


Beam Loads: Allowable uniformly distributed loads are listed for various simple spans (beam on two supports). If load is concentrated at center of span, multiply load from table by 0.5 and corresponding deflection by 0.8

Allowable Loads— Calculated per the American Iron and Steel Institute " Specification for the Design of Cold-Formed Steel Structural Members" , 1989 addendum.

Deflection 1/240 Span— Recommended for use where the amount of deflection is required to be imperceptible.

Column Loads: Column loadings are for allowable axial loads for the unsupported heights listed. Eccentric loads should be reduced according to standard practice.



Example: 12 Gauge Tubing

	Size	Span Feet	Uniform Beam Load- Lbs.	Deflection Inches
Tubing with perforation	1½" Sq.	8	59	
	1¾" Sq.	8	913	1.54
	1½" & 1¾" telescoped	8	1511	1.54
Tubing with no perforation	1½" Sq.	10	647	
	1¾" Sq.	10	930	
	2" Sq.	10	1262	2.11
& 2" Sq.	1½" & 1¾" telescoped	10	2839	2.11

BEAM & COLUMN DATA - 10 GAUGE [.135] WALL THICKNESS

		Non-Perforated				Perforated			
Beam Span or Column Unsupported Height	Tube Size	Maximum Allowable Uniform Load Pounds	Deflection at Uniform Load Inches	Uniform Load @ Max. Defl. 1/240 Span	Maximum Column Load	Maximum Allowable Uniform Load Pounds	Deflection at Uniform Load Inches	Uniform Load @ Max. Defl. 1/240 Span	Maximum Column Load
18"	2 3/16" x 2 3/16""	9,734	0.03	-	20,200	8,591	0.03	-	15,800
18"	2½" x 2½"	13,361	0.03	-	23,600	11,403	0.03	-	19,200
24"	2 3/16" x 2 3/16"	7,305	0.06	-	19,800	6,450	0.06	-	15,500
24"	2½" x 2½"	10,023	0.05	-	23,200	8,552	0.05	-	18,800
30"	2 3/16" x 2 3/16"	5,832	0.10	-	19,300	5,163	0.10	-	15,100
30"	2½" x 2½"	8,014	0.09	-	22,800	6,844	0.09	-	18,500
36"	2 3/16" x 2 3/16"	4,861	0.14	-	18,700	4,295	0.15	-	14,700
36"	2½" x 2½"	6,674	0.12	-	22,200	5,701	0.12	-	18,000
42"	2 3/16" x 2 3/16"	4,165	0.18	3,912	18,200	3,678	0.20	3,240	14,200
42"	2½" x 2½"	5,728	0.17	-	21,700	4,887	0.17	-	17,600
48"	2 3/16" x 2 3/16"	3,652	0.24	2,995	17,600	3,218	0.26	2,480	13,800
48"	2½" x 2½"	5,005	0.21	4,695	21,100	4,283	0.21	4,010	17,200
60"	2 3/16" x 2 3/16"	2,916	0.38	1,916	16,200	2,575	0.40	1,590	12,700
60"	2½" x 2½"	4,007	0.33	3,005	19,800	3,416	0.33	2,570	16,200
72"	2 3/16" x 2 3/16"	2,431	0.55	1,330	14,700	2,154	0.58	1,100	11,700
72"	2½" x 2½"	3,336	0.48	2,090	18,500	2,850	0.48	1,780	15,200
84"	2 3/16" x 2 3/16"	2,089	0.75	980	13,100	1,839	0.79	810	10,500
84"	2½" x 2½"	2,864	0.65	1,530	16,900	2,444	0.65	1,310	14,000
96"	2 3/16" x 2 3/16"	1,826	0.97	750	11,200	1,616	1.04	620	9,100
96"	2½" x 2½"	2,509	0.85	1,170	15,400	2,141	0.85	1,000	12,800
108"	2 3/16" x 2 3/16"	1,616	1.23	590	9,300	1,432	1.31	490	7,700
108"	2½" x 2½"	2,220	1.08	930	13,600	1,905	1.08	790	11,300
120"	2 3/16" x 2 3/16"	1,458	1.52	480	7,500	1,288	1.62	400	6,200
120"	2½" x 2½"	2,010	1.33	750	11,800	1,708	1.33	640	9,900

BEAM & COLUMN DATA - 12 GAUGE [.105] WALL THICKNESS

		Non-Perforated				Perforated			
Beam Span or Column Unsupported Height	Tube Size	Maximum Allowable Uniform Load Pounds	Deflection at Uniform Load Inches	Uniform Load @ Max. Defl. 1/240 Span	Maximum Column Load	Maximum Allowable Uniform Load Pounds	Deflection at Uniform Load Inches	Uniform Load @ Max. Defl. 1/240 Span	Maximum Column Load
18"	1" x 1"	1,182	0.07	1,160	5,905	768	0.07	760	-
18"	1¼" x 1¼"	2,178	0.06	-	8,130	1,634	0.06	-	-
18"	1½" x 1½"	3,439	0.05	-	10,255	2,537	0.05	-	6,950
18"	1¾" x1¾"	4,954	0.04	-	12,365	3,891	0.04	-	9,000
18"	2" x 2"	6,719	0.04	-	14,480	5,485	0.04	-	11,070
18"	2¼" x 2¼"	8,751	0.03	-	16,595	7,344	0.03	-	13,155
18"	2½" x 2½"	11,036	0.03	-	18,780	9,469	0.03	-	15,200
24"	1" x 1"	890	0.14	650	5,365	578	0.14	425	-
24"	1¼" x 1¼"	1,634	0.10	1,530	7,655	1,226	0.10	1,150	-
24"	1½" x 1½"	2,590	0.09	-	9,830	1,899	0.09	-	6,680
24"	1¾" x1¾"	3,705	0.08	-	11,990	2,922	0.08	-	8,750
24"	2" x 2"	5,033	0.06	-	14,120	4,103	0.06	-	10,800
24"	2¼" x 2¼"	6,560	0.06	-	16,245	5,511	0.06	-	12,890
24"	2½" x 2½"	8,274	0.06	-	18,420	7,105	0.06	-	14,970

TELESPAR® TELESCOPING SQUARE TUBI

AM & COLUMN DATA - 12 GAUGE [.105] WALL THICKNESS

		Non-Perforated				Perforated			
Beam Span or Column Unsupported Height	Tube Size	Maximum Allowable Uniform Load Pounds	Deflection at Uniform Load Inches	Uniform Load @ Max. Defl. 1/240 Span	Maximum Column Load	Maximum Allowable Uniform Load Pounds	Deflection at Uniform Load Inches	Uniform Load @ Max. Defl. 1/240 Span	Maximum Column Load
30"	1" x 1"	704	0.21	420	4,755	458	0.21	275	-
30"	1¼" x 1¼"	1,302	0.17	975	7,165	977	0.17	735	-
30"	1½" x 1½"	2,072	0.14	1,840	9,410	1,514	0.14	1,350	6,400
30"	1¾" x1¾"	2,974	0.12	-	11,570	2,338	0.12	-	8,450
30"	2" x 2"	4,024	0.10	-	13,710	3,294	0.10	-	10,530
30"	2¼" x 2¼"	5,246	0.10	-	15,920	4,409	0.10	-	12,590
30"	2½" x 2½"	6,614	0.08	-	18,060	5,684	0.09	-	14,690
36"	1" x 1"	584	0.30	290	4,070	379	0.30	190	-
36"	1¼" x 1¼"	1,089	0.24	680	6,620	817	0.24	510	-
36"	1½" x 1½"	1,726	0.20	1,275	8,900	1,262	0.20	940	6,090
36"	1¾" x1¾"	2,470	0.18	2,140	11,105	1,939	0.18	1,680	8,130
36"	2" x 2"	3,360	0.15	3,320	13,330	2,736	0.15	2,710	10,200
36"	2¼" x 2¼"	4,369	0.14	-	15,500	3,678	0.14	-	12,300
36"	2½" x 2½"	5,511	0.12	-	17,690	4,741	0.12	-	14,380
42"	1" x 1"	505	0.42	210	3,350	328	0.42	140	-
42"	1¼" x 1¼"	930	0.33	500	5,980	698	0.33	375	-
42"	1½" x 1½"	1,474	0.27	940	8,350	1,089	0.27	690	5,760
42"	1¾" x1¾"	2,125	0.23	1,570	10,610	1,660	0.23	1,240	7,820
42"	2" x 2"	2,882	0.21	2,440	12,850	2,350	0.21	1,990	9,890
42"	2¼" x 2¼"	3,745	0.18	3,575	15,060	3,147	0.18	3,000	11,970
42"	2½" x 2½"	4,728	0.17	-	17,270	4,064	0.17	-	14,060
48"	1" x 1"	438	0.54	160	2,580	285	0.54	105	-
48"	1¼" x 1¼"	823	0.43	380	5,330	618	0.43	285	-
48"	1½" x 1½"	1,288	0.36	720	7,750	956	0.36	530	5,370
48"	1¾" x1¾"	1,859	0.31	1,200	10,080	1,461	0.31	950	7,440
48"	2" x 2"	2,523	0.27	1,870	12,350	2,058	0.27	1,520	9,510
48"	2¼" x 2¼"	3,280	0.24	2,735	14,590	2,762	0.24	2,300	11,600
48"	2½" x 2½"	4,130	0.22	3,840	16,850	3,546	0.22	3,290	13,710
60"	1" x 1"	358	0.86	100	1,650	233	0.86	70	-
60"	1¼" x 1¼"	650	0.66	240	3,820	488	0.66	185	-
60"	1½" x 1½"	1,036	0.56	460	6,490	757	0.56	340	4,580
60"	1¾" x1¾"	1,487	0.48	770	8,920	1,169	0.48	610	6,660
60"	2" x 2"	2,018	0.42	1,200	11,230	1,646	0.42	980	8,730
60"	2¼" x 2¼"	2,630	0.38	1,750	13,560	2,205	0.38	1,470	10,850
60"	2½" x 2½"	3,306	0.34	2,460	15,820	2,842	0.34	2,110	12,960
72"	1" x 1"	292	1.20	70	-	190	1.20	50	-
72"	1¼" x 1¼"	545	0.96	170	2,680	409	0.96	125	-
72"	1½" x 1½"	863	0.81	320	4,980	638	0.82	230	3,640
72"	1¾" x1¾"	1,235	0.69	540	7,615	970	0.69	420	5,740
72"	2" x 2"	1,674	0.60	830	10,080	1,368	0.61	680	7,870
72"	2¼" x 2¼"	2,191	0.54	1,220	12,420	1,833	0.54	1,020	9,950
72"	2½" x 2½"	2,762	0.49	1,710	14,740	2,364	0.48	1,460	12,130
84"	1" x 1"	252	1.65	50	-	163	1.65	35	-
84"	1¼" x 1¼"	465	1.30	120	1,960	349	1.31	95	-
84"	1½" x 1½"	744	1.11	230	3,690	545	1.10	170	2,740
84"	1¾" x1¾"	1,062	0.94	390	6,170	837	0.94	310	4,770
84"	2" x 2"	1,434	0.82	610	8,720	1,169	0.82	500	6,920
84"	2¼" x 2¼"	1,873	0.74	890	11,260	1,580	0.74	750	9,050
84"	2½" x 2½"	2,363	0.66	1,250	13,660	2,032	0.66	1,080	11,220
96"	1" x 1"	226	2.20	40	-	146	2.20	25	-
96"	1¼" x 1¼"	412	1.73	100	-	310	1.74	70	-
96"	1½" x 1½"	650	1.45	180	2,810	478	1.45	130	2,090
96"	1¾" x1¾"	930	1.23	300	4,750	730	1.23	240	3,750
96"	2" x 2"	1,262	1.08	470	7,330	1,029	1.08	380	5,880
96"	2¼" x 2¼"	1,646	0.96	680	9,900	1,383	0.96	570	8,070
96"	2½" x 2½"	2,071	0.86	960	12,325	1,779	0.86	820	10,250
108"	1" x 1"	199	2.77	30	-	129	2.77	20	-
108"	1¼" x 1¼"	358	2.14	80	-	269	2.14	55	-
108"	1½" x 1½"	571	1.81	140	2,240	425	1.83	100	1,660
108"	1¾" x1¾"	823	1.55	240	3,760	650	1.56	190	2,940
108"	2" x 2"	1,115	1.36	370	5,810	916	1.37	300	4,760
108"	2¼" x 2¼"	1,461	1.22	540	8,430	1,222	1.21	450	7,010
108"	2½" x 2½"	1,833	1.09	760	11,000	1,580	1.09	650	9,200
120"	1" x 1"	173	3.29	30	-	112	3.29	15	-
120"	1¼" x 1¼"	332	2.72	60	-	250	2.72	45	-
120"	1½" x 1½"	518	2.26	110	-	385	2.27	80	-
120"	1¾" x1¾"	744	1.93	190	3,050	584	1.93	150	2,390
120"	2" x 2"	1,010	1.69	300	4,850	823	1.69	240	3,810
120"	2¼" x 2¼"	1,314	1.50	440	6,890	1,102	1.50	370	5,780
120"	2½" x 2½"	1,660	1.35	610	9,590	1,421	1.34	530	8,070

UNISTRUT® TELESPAR® TELESCOPING SQUARE TUBING

SPECIFICATIONS

Tubing shall be TELESPAR® tubing conforming to manufacturers' standards. Tubing shall be corner welded by high-frequency resistance welding and externally scarfed to agree with corner radii.

MATERIALS

Tubing with plain finish is roll formed from 10 gauge (.135) and 12 gauge (.105 U.S.S. Gauge) hot rolled steel, ASTM Des. A-1011 Grade 50, pickled and oiled. Galvanized finish, roll formed from 10 gauge (.135) and 12 gauge (.105 U.S.S. Gauge) hot rolled steel, galvanized material ASTM A-653 Grade 50. Average minimum yield strength after cold forming is 60,000 PSI.

STANDARD FINISHES

Plain – Material has oiled finish as the material comes from the rolling mills. Tubes must be thoroughly cleaned before protective finishes are applied.

Pre-Galv Plus™ – Galvanized conforming to ASTM specification A-653 des. G-90. Corner weld is zinc coated after scarfing operation. Tubing then receives a conversion coating and a clear organic polymer topcoat.

SQUARENESS OF SIDES AND TWIST

Nominal Outside Dimension, Inches	Squareness Tolerance, Inch*	Twist Permissible in 3 Ft., inch†
1" x 1"	± .006	.050
1¼" x 1¼"	± .007	.050
1½" x 1½"	± .009	.050
1¾" x 1¾"	± .010	.062
2" x 2"	± .012	.062
2 3/16" x 2 3/16"	± .014	.062
2¼" x 2¼"	± .014	.062
2½" x 2½"	± .015	.075
2" x 3"	± .018	.075

* TELESPAR tubing may have its sides failing to be 90° to each other by the tolerance listed.

† Twist is measured by holding down the edge of one end of a square tube on a surface plate with the bottom side of the tube parallel to the surface plate and noting the height that either corner on the opposite end of the bottom side is above the surface plate.

TOLERANCES

Tolerance on size

Nominal Outside Dimension, Inches	Outside Tolerance for All Sides at Corners, Inch
1" x 1"	± .005
1¼" x 1¼"	± .006
1½" x 1½"	± .006
1¾" x 1¾"	± .008
2" x 2"	± .008
2 3/16" x 2 3/16"	± .010
2¼" x 2¼"	± .010
2½" x 2½"	± .010
2" x 3"	± .010

Wall thickness tolerance – Permissible variation in wall thickness is + .011, -.005 inches.

Convexity and concavity – Measured in the center of the flat side, tolerance is ± .010 inch applied to the specific size determined at the corner.

Straightness tolerance – Permissible variation in straightness is 1/16" in 3 feet.

Corner radii – Standard corner radius is 5/32" ± 1/64".

Weld Flash – Weld flash on corner welded square tubing shall permit 9/64" radius gauge to be placed in the corner.

Telescoping – Using 10 gauge (.135) or 12 gauge (.105) square tube, consecutive size tubes shall telescope freely for ten feet.

Length tolerance – To allow for subsequent cutting – tubes without holes – standard length members are 3/8" ± 1/8" longer. Tubes with holes – standard length members are 2" ± 1/8" longer. Tubes can be furnished in special lengths. Standard pre-galvanized lengths are 20' and 24', standard plain finish length is 24'.

Hole tolerance – Tolerance on hole size is ± 1/64" on a 7/16" hole size. Tolerance on hole spacing ± 1/8" in 10 feet.

START SOLVING PRODUCT DESIGN AND IN-PLANT CONSTRUCTION PROBLEMS TODAY...

Telespar Telescopic Tubing is among the world's best known and most trusted engineering support systems...and for good reason. It's a complete system, designed and manufactured to exacting quality standards. For more information call your nearest Telespar tubing representative.

tyco Electrical & Metal Products

CUSTOMER SERVICE
Unistrut Service Company
Cleveland, OH
800-694-9274
www.UnistrutOhio.com

Printed in U.S.A. 06/03 TSP-2

APPROVED UNISTRUT NO SUBSTITUTIONS

IV. Final Quote

Decker Supply Co Inc.
1115 O'Neill Ave
PO Box 8008
Madison WI 53708

QUOTATION

Quote Number: 470091
Quote Date: 04/13/15
Page: 1
Customer Phone: 262-5690
Customer Fax:

BILL
UNIV. OF WI-MADISON
ACCOUNTS PAYABLE
21 NORTH PARK, STE 5301
MADISON, WI 53715-1218

SHIP
UNIV. OF WI-MADISON
ACCOUNTS PAYABLE
21 NORTH PARK, STE 5301
MADISON, WI 53715-1218
ATTN: PO# BA36035 023962

Entered By: MIKE
Location:
Account Cd: UWMADIS
Salesperson: 0

RFQ Number: EMAIL JAKE
Ship Via: UPS/SDS
Taxable: Y
Pmt Terms: NET 30

Line	Order Qty	Part Number	Description	Price	UM	Ext Price	Est Ship
1	20.00	PS25084H12G	8"X 2-1/2" SQ.TUBE 4-H 12GA	$35.8500	EA	$717.00	04/13/15
2	2.00	PS22584H12G	8" X 2-1/4" SQ.TUBE 4-H 12GA	$28.1000	EA	$56.20	04/13/15
3	25.00	TL016-Z	L-FITTING FOR TELESPAR	$4.1600	EA	$104.00	04/13/15
4	25.00	TL015-Z	T-FITTING FOR TELESPAR	$4.1600	EA	$104.00	04/13/15
5	25.00	TL020	SIGN BRACKET 90 DEGREE	$1.9600	EA	$49.00	04/13/15
6	120.00	3/8X3-1/4 BHEX	3/8 X 3-1/4 HEX BOLT (GALV.) (FOR STATE PROJECTS)	$0.9000	EA	$108.00	04/13/15
7	120.00	3/8 LOCK NUT	3/8" TRI-LOCK NUT (GALV.) (FOR STATE PROJECTS)	$0.2500	EA	$30.00	04/13/15
8	120.00	WASHER 3/8FEND	STEEL WASHER 3/8X1-1/4X1/16 GALVANIZED (STATE SPEC)	$0.1500	EA	$18.00	04/13/15
			CUSTOMER PICK UP - SALESPERSON:MIKE				

V. Additional SAP Testing

Additional Simulations Performed In Order To Confer Structural Stability of Cage Prototype		
Loading Scenarios	**Axial deflection of open face beam in Y direction (mm)**	**Overhead deflection of loaded beam in Z direction (mm)**
2x 200 lb. (890 N) loads on each 7' (2.13 m) overhead span and 150 lb (668 N) lateral load as depicted in Figure 23	1.5	6.26
400 lb. (1780 N) load centered on span connecting center 2 7' (2.13 m) beams and 150 lb. (668 N) lateral load as depicted in Figure 23	2.5	2.78
150 lb. (668 N) lateral load as depicted in Figure 23 and 200 lb (890 N) lateral bisecting load on left vertical open face member	20	NA
2x 200 lb (890 N) load placed in order to trisect 7' (2.13 m) overhead beam and 150 lb (668 N) lateral load as depicted in Figure 23	1.09	5.27

VI. Itemized Parts List

Qty	Size	Part	Cost
18	7' (2.13 m)	2.5'' (63.5 mm) 12 Ga. Perforated Tubing	717
2	7' (2.13 m)	2.25'' (57.15mm) 12 Ga. Perforated Tubing	56.2
120	7/16'' (50.8 mm)	Bolts (Grade 8+)	104
120	7.16'' (50.8 mm)	Nyloc Nuts	104
120	7.16'' (50.8 mm)	Fender Washers	49
25	-	L brackets	108
25	-	T brackets	30
25	-	90 degree brackets	18
8	9'' (203.2 mm)	1/2'' Eye/Eye Turnbuckle	9
6	7/16'' (50.8mm)	Eyebolt	3
Total Cost		**$1,198.20**	

Table: itemized and total costs for both the final cage prototype and harness recommendation.