Tubing Analysis and Selection Process for the Frame of the IXA Walker

by

Lucas Cummings

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Signature of Author..
Department of Mechanical Engineering
May 7, 2010

Certified by ....
Warren P. Seering
Weber-Shaughness Professor of Mechanical Engineering
Thesis Supervisor

Accepted by ....
Professor John H. Lienhard V
Collins Professor of Mechanical Engineering
Chairman, Undergraduate Thesis Committee

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ABSTRACT

A thorough analysis and test of the frame for a walker was conducted in order to select the optimal size tubing for the walker. Initially a rough first order bending analysis was completed to make an initial decision on tubing size. Finite element analysis was done on the tubing selected to confirm the theory of the first order analytical model, and to determine the expected deflection. A test rig was then built with a 1:1 scale frame in order to test the actual deflection of the frame. Weights were used to measure the deflection for masses varying from 0 lbs to 150 lbs. The results of the complete analysis and testing show that a 1.5" outer diameter by 1.26" inner diameter tube will optimally meet the deflection and weight requirements of the walker. The experimental results are within 5% error of the expected deflection from the finite element analysis, while the quick first order analysis was within 7% of the results from the finite element analysis.

Thesis Supervisor: Warren Seering
Title: Weber-Shaughness Professor of Mechanical Engineering

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Introduction

Project Overview and Background

As an undergraduate mechanical engineering student at MIT you are required to take 2.009, Product Development Engineering, in order to graduate. In teams of 15 students, you are tasked with brainstorming and developing an alpha prototype of a product under a certain theme. For the fall of 2009 the theme was Emergency. After much deliberation and hard work our team built the alpha prototype of the IXA Walker (figure 1), a walker designed to help users rise from any seated position independently.

Figure 1: *Solid Model of IXA Walker*

There are two major modules of this design- the frame, made up almost entirely of aluminum tubing, and the joint which connects the two parts of the frame. The joint allows the walker to rotate from an upright walking position to a down position that is used to help the user rise independently from any seated position. The handles in the down position act similarly to the way armrests on a chair can be used when trying to stand up. This allows the user to help themselves up.

One major concern for the walker is the sturdiness and usability of the frame. According to our market and user research, the frame must be able to withstand 300 lbs of force, deflect less than 1 cm (only the deflection due to the frame bending, not the joint), and the total weight of the frames tubing must be under 6 lbs in order to be competitive. This left us with tight constraints to work with.

Original Frame Design Process

The original frame design for the IXA Walker was haphazardly thrown together at the last minute due to time constraints in the course. We spent countless hours figuring out the perfect geometry for the frame that would allow for the greatest variety in the size of the user, but neglected doing the work on what type of tubing should be used in order to meet the requirements of our user contract for force applied, deflection, and weight of the walker. Since nearly all other walkers were made from a nearly standard 1" outer diameter 6061-T6 aluminum tubing, we assumed that would also work for ours. This was a poor decision, since our walker was obviously not like any other walker.

Frame Geometry

The first prototype of our walker ended up having many design flaws. One of those flaws was the design of the frame. This paper will describe the proper analysis needed for the design of a working used to build a walker with the specified original geometry. Figure 2 shows a side view of the walker with the original geometry. Since geometry was not an issue in the first prototype, the focus for improvement of the frame was on the size of the tubing, not the shape of the frame.

Figure 2: *Side View of Walker in Up and Down Positions*

First Order Analytical Analysis

Purpose

The purpose of the first order analytical analysis is to gain a quick understanding of the frame. From this analysis we expect to gain a rough idea of whether or not the project will succeed. This analysis also provides a starting point for further in depth analysis and testing. Most importantly it saves a significant amount of time and money.

Diagram of Simplified Frame

The walker will likely see the greatest stress from the user in the down position when the user puts their full force on the walker in order to rise. It is important that the frame is able to withstand 300 lbs of total weight while not deflecting more than 1 cm in this position. Analyzing only the frame, a simplified diagram can be made of the frame. This simplified diagram is made using the assumptions that there will be some deflection and that there will not be any deflection along the lower rear leg that is resting flat on the ground. The fact that there will not be any deflection in the lower leg allows us to ignore it in the simplified diagram and model. The frame does not rotate around the point touching the ground since the leg would be there to stop it, thus the deflection is only caused by bending. If there is some deflection, then the front leg (with the wheel) will lift up and not receive any reaction forces since it is not in contact with the ground. It is also important to note that the simplified diagram does not include the curvature of the actual frame. The bending in the curvature can be assumed to be small in comparison to the rest of the frame since it is a small proportion of the frame. Also the stress concentrations introduced while bending the frame make it more difficult to bend. Figure 3 shows a simplified diagram of the frame that will be used for the first order analytical analysis.

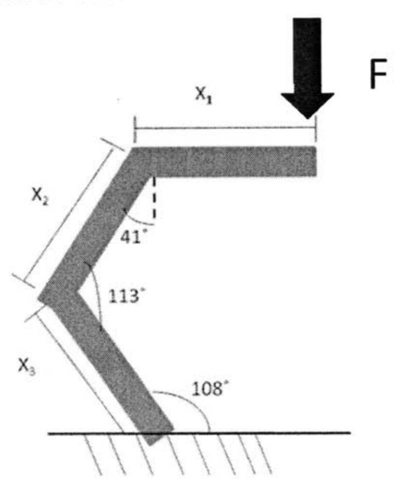

Figure 3: *Diagram of Simplified Frame*

Using the concept of superposition this complex shape can be broken down into three separate cantilevered beams in order to find the deflection. Figure 4 shows the simplified diagram broken down into components with their respective reaction momments and forces.

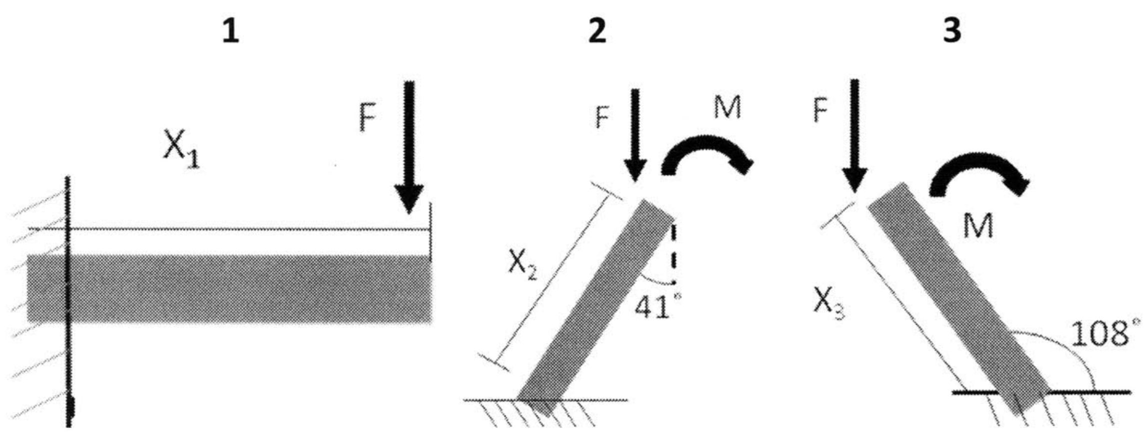

Figure 4: *Simplified Frame Diagram Broken into 3 Cantilevered Beams*

Bending Equations for Frame

The total deflection of the frame is simply the sum of the deflections for the three different cantilevered beams shown in figure 4. This is a rough estimate of the upper bound of the actual deflection (since not all deflections are in the downward direction). Equations 1,2,3 and 4 show the resulting deflections, Δ, where *F* is the force applied by the person. The elastic modulus of the material is *E*, and *I* is the moment of inertia.

$$\Delta_1 = \frac{Fx_1^3}{3EI} \tag{1}$$

$$\Delta_2 = \frac{Fx_1x_2^2}{2EI} + \frac{F\sin(49°)x_2^3}{3EI} \tag{2}$$

$$\Delta_3 = \frac{F(x_1 + x_2 \cos 41°)x_3^2}{2EI} - \frac{F \sin(17.5°)x_3^3}{3EI} \quad (3)$$

$$\Delta_{Total} = \Delta_1 + \Delta_2 + \Delta_3 \quad (4)$$

Expected Results

After inserting conservative values and a force of 682 N (150 lb.) into equation 4, spreadsheets were used to determine which tubing sizes would be optimal for the frame. Table 1 shows the deflection in meters for various tube sizes. Table 2 shows the estimated weight for the frame for each respective tube size. The acceptable deflections(less than 1 cm) and weights(less the 6 lbs) are highlighted in each table.

Outer Diameter (inches)

Inner Diameter (inches)

Deflection (meters)	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8
1	0.0477	0.0204	0.0118	0.0078	0.0054	0.0038	0.0030	0.0023
1.1	N/A	0.0354	0.0163	0.0092	0.0061	0.0044	0.0031	0.0024
1.2	N/A	N/A	0.0286	0.0124	0.0073	0.0049	0.0035	0.0026
1.3	N/A	N/A	N/A	0.0222	0.0099	0.0058	0.0039	0.0029
1.4	N/A	N/A	N/A	N/A	0.0180	0.0080	0.0049	0.0033
1.5	N/A	N/A	N/A	N/A	N/A	0.0147	0.0067	0.0041
1.6	N/A	N/A	N/A	N/A	N/A	N/A	0.0121	0.0056
1.7	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.0102

***Table 1:** Estimated Deflection of Frame from 1st Order Analysis in meters*

Outer Diameter (inches)

Inner Diameter (inches)

Weight(lbs)	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8
1	1.6	3.36	5.3	7.3	9.5	11.9	14.4	17.1
1.1	N/A	1.8	3.7	5.7	7.9	10.3	12.8	15.5
1.2	N/A	N/A	1.9	4	6.2	8.6	11.1	13.8
1.3	N/A	N/A	N/A	2.1	4.3	6.6	9.2	11.8
1.4	N/A	N/A	N/A	N/A	2.2	4.6	7.1	9.8
1.5	N/A	N/A	N/A	N/A	N/A	2.4	4.9	7.6
1.6	N/A	N/A	N/A	N/A	N/A	N/A	2.52	5.2
1.7	N/A	N/A	N/A	N/A	N/A	N/A	N/A	2.7

Table 2: *Estimated Weight of Frame from1st Order Analysis in lbs*

Using the tables as a guide, and after checking with tubing suppliers for what size tubing is readily available it was determined that tubing with an outer diameter of 1.5" and an inner diameter of 1.26" would best fulfill the requirements of the frame. The expected deflection of the frame made from this tubing was 0.0075 meters with an estimated weight of 5.2 lbs. Once the first order analysis was completed, it was time to verify the accuracy with a higher level model.

Solid Modeling and FEA

Purpose

The next step in the design process is to verify the first order model with a more accurate solid model using SolidWorks and Finite Element Analysis (FEA). This is a quick and easy way to check your work and verify that your model is at least fairly accurate and can also save you a significant amount of time and money testing if you made a mistake in your original model.

Results

Figure 5 shows a dimensioned drawing of the frame used in the FEA. Figure 6 shows the load distribution on the edges of the handle, split evenly between each face (75 lbs on each face for a total of 150 lbs). The model also used the properties of 2024 Al for the analysis since that was the type used in testing.

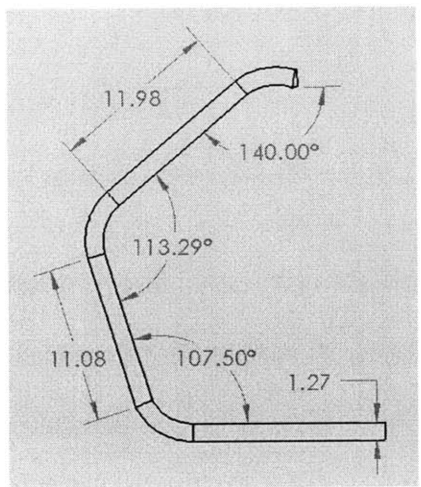

Figure 5: *Dimensioned Drawing of Frame Used in FEA(all curves have 4" radii)*

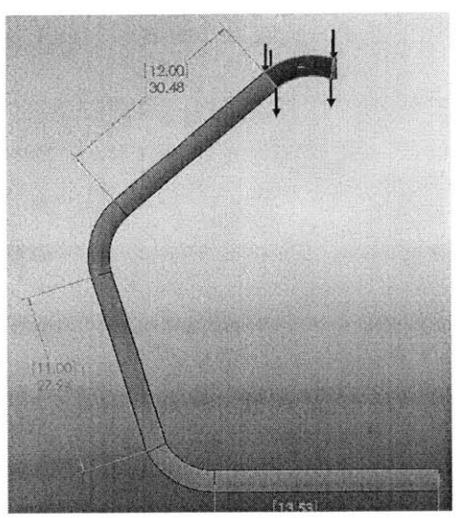

Figure 6: *FEA Load Distribution*

Figure 7 shows the displacement distribution of the model for a 150 lbs load.

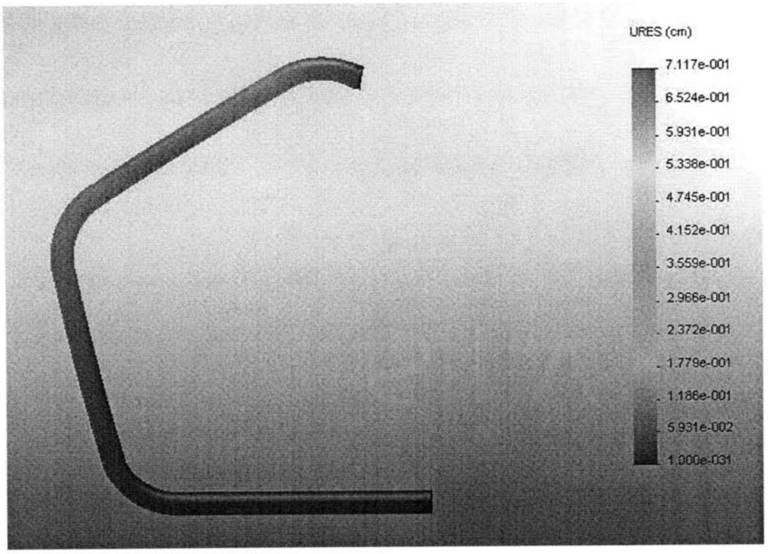

Figure 7: *Displacement Distribution under 150 lbs*

The Results of the FEA analysis compared to the first order analysis are shown in table 3. All the results are for 1.5" outer diameter tubing with 1.26" inner diameter tubing since this is the size tubing we are investigating.

Load(lbs)	Deflection (cm) of 1st order Analysis	Deflection (cm) of FEA	% Error
50	0.25	0.24	4.2 %
75	0.37	0.36	2.8%
100	0.50	0.47	6.4%
125	0.62	0.59	5.1%
150	0.75	0.72	4.2%

Table 3: *Comparison of FEA Analysis with First Order Analysis*

The results of the FEA confirm the first order analytical model. All of the deflections are within 7%. It is important to note that these loading conditions assume only a vertical load. Horizontal loads will slightly increase the deflection.

Testing

Purpose

The testing is designed to confirm both the first order analytical model and the solid model with FEA. If the models do not agree with the test results, then they are worthless. This is the last step before building another prototype. If the testing agrees, then we know we can use the models in order to determine future changes in the design. This is the most costly and time consuming step in the process but still saves a significant amount of time and money on your final prototype if there was an error in both of the first models.

Testing Setup

The first step in the test setup was to bend the tubing to the appropriate dimensions of the frame in the Pappalardo Laboratory. The tubing was bent using a hydraulic tube bending machine. A picture of the bent 2024-T3 bare drawn aluminum tube is shown in figure 8.

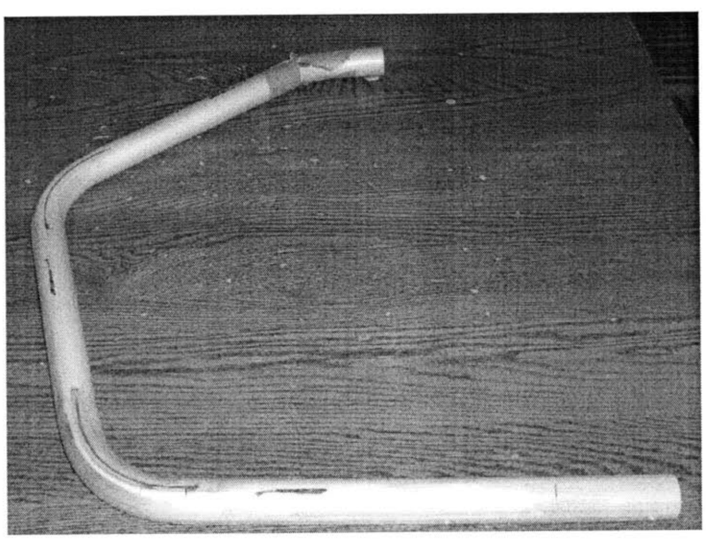

Figure 8: *Picture of Aluminum Tubing After Bending*

The 2024-T3 aluminum was chosen for its qualities in bending. It has a much higher elongation at break (18%) than other aluminum alloys which makes it easier to bend on the bending machine in lab. Other aluminum alloys may have needed to be bent differently (using heating, or possibly filling with sand before bending).

The bottom of the frame was then rigidly attached at the bottom to a piece of plywood so that the frame did not rotate or tip. Weights were hung from the handle of the frame. A Vernier motion sensor was used to measure the deflection of the frame under varying loads of up to 150 lbs. Tape was used on the handles to better reflect the ultrasonic sound waves from the motion detector since it was not consistently reflecting off the aluminum surface. Figure 9 depicts the experimental setup.

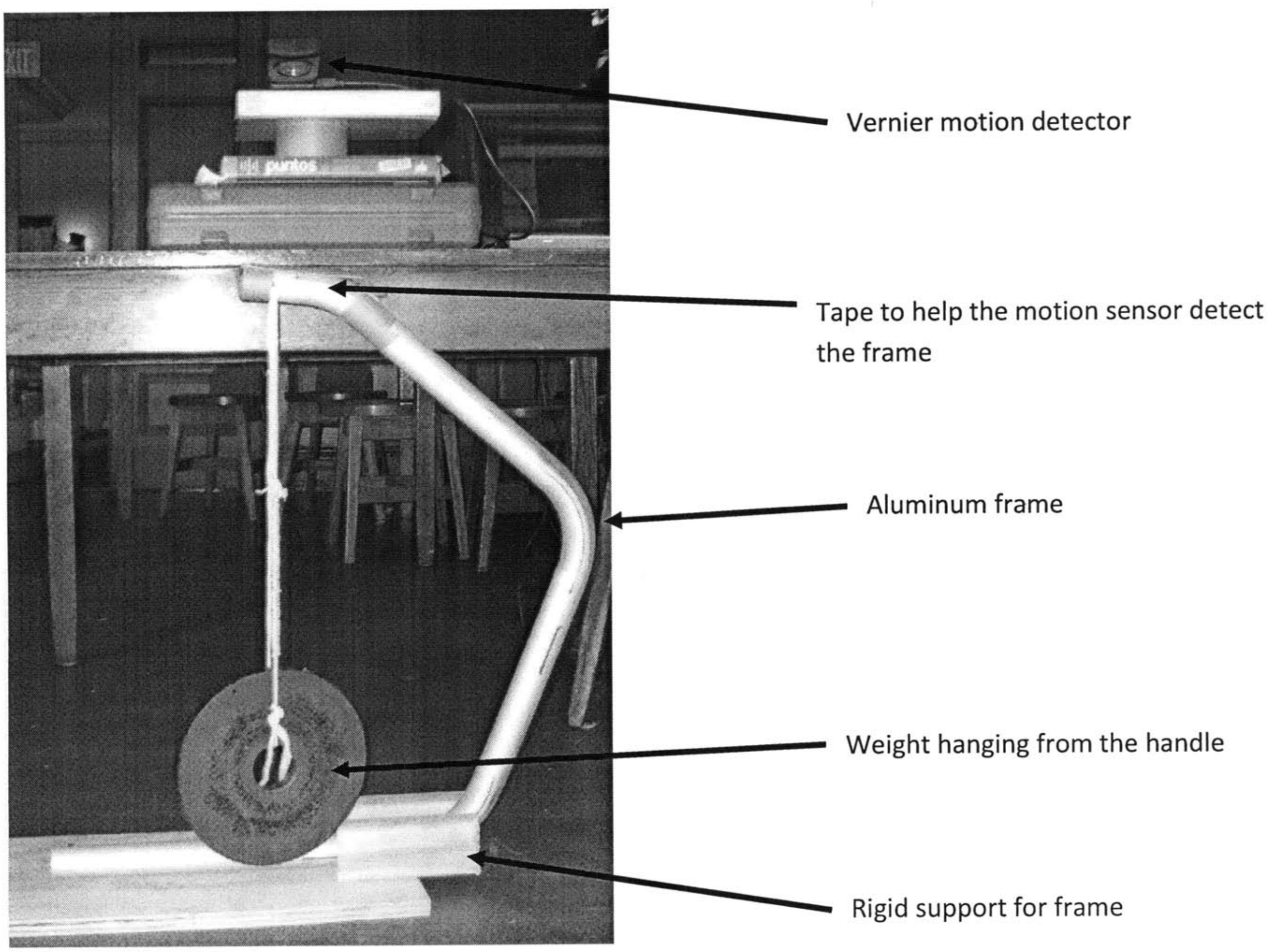

Figure 9: *Experimental Setup*

Test Results

The results of the test proved to be higher than expected at first glance, but this was due to the fact that the frame was not bent to the exact dimensions described before and the weights were hung slightly further back causing a larger bending moment on the frame. The results in table 4 reflect those changes in dimensions in the FEA analysis.

Weight (lbs)	Deflection (cm) of test	Deflection (cm) of FEA	% Error
25	0.26	0.23	13.0 %
45	0.43	0.41	4.9 %
70	0.63	0.63	0.0 %
95	0.88	0.86	2.3 %
125	1.18	1.13	4.4 %
150	1.36	1.35	0.7 %

Table 4: *Comparison of Test Results versus FEA Theoretical Results*

Also important to note, is the linearity of the deflection as weight increases up to 150 lbs. This means that the tubing is only undergoing elastic deformation and not plastic deformation. A plot of the experimental results is shown in figure 10.

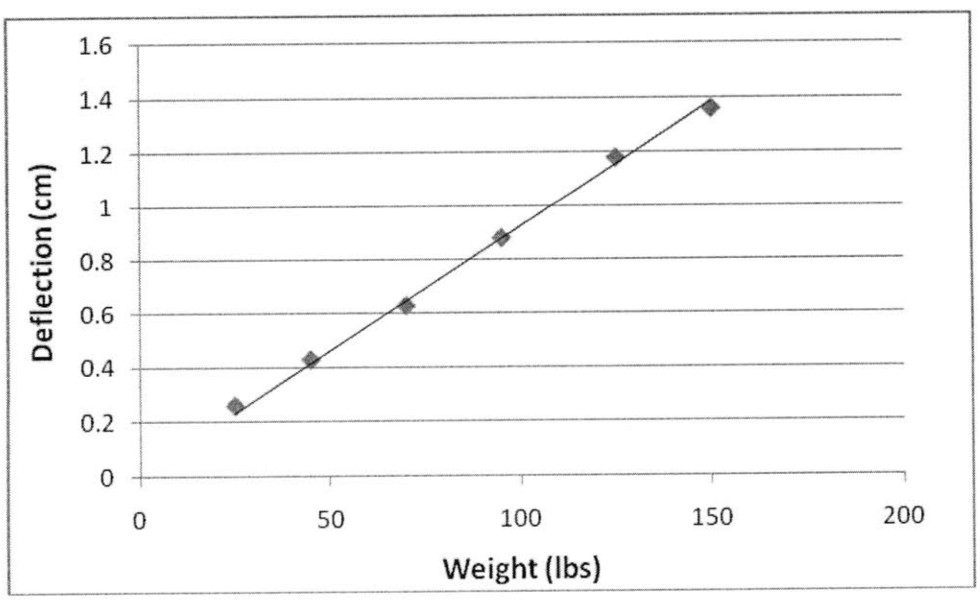

Figure 10: *Plot of Deflection (cm) versus Weight (lbs)*

Conclusions and Recommendations

Discussion of Results

The results of the testing show that, for the most part, the FEA accurately determined the expected deflection of the tube to within 5% excluding the outlier (deflection for 25 lb. load). The first order analysis gave a good starting point from which to move forward onto the FEA of the frame without wasting considerable time on the FEA first. The deflection from the first order analysis ended up being within 7% of the deflection from the FEA. The agreement between the first order analytical model, the solid model/FEA, and the testing show that the models are accurate enough to use for the selection of the tubing to be used in the frame.

Tubing Selection

Since the results of the test confirm the theoretical models, the tubing selection process has already been done using the first order analytical model. Since we also do not have a factory where we can draw aluminum tubing to our precise needs we are limited by what is currently available through vendors. Thus, for the specified frame dimensions in figure 5, it would be best to use 1.5" tubing with 0.12" thick walls. This will yield an expected mass of approximately 10 lbs for the entire walker (5 lbs for the frame) and a deflection of 0.75 cm under the maximum load of 300 lbs equally distributed on each side of the frame. The rest of the walker's mass is made up of primarily the joint and some other accessories. The frame would have a Factor of Safety (FoS) of 1.8 (from the FEA), meaning it could handle a load of 540 lbs before deforming plastically. This size tubing adequately meets the requirements for - maximum load before failure, deflection, and weight of the frame.

Recommendations and Further Work

Although the round tubing is satisfactory for the current requirements, if the weight or the deflection would need to be decreased, alternative designs would be necessary. Possible solutions that could be further explored include; changing the geometry of the frame to something more likely to handle the load by decreasing the moment, using either elliptical or different shaped tubing to take advantage of the higher moment of inertia in the direction of bending, or possibly using gussets to eliminate the bending around the curved portions of the frame.