DESIGN AND DEVELOPMENT OF AUTOMATED PARALLEL BARS

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ABSTRACT

The Physical Therapy Clinic at Nazareth specializes in the rehabilitation of stroke and other neurologically impaired patients. An essential part of their rehabilitation is relearning to walk, which is aided by a parallel bar system. Unfortunately, the current system is difficult and time consuming to adjust, which often results in patients skipping this vital step. In conjunction with Nazareth, this project created a new system to simplify the adjustment of the parallel bars, while increasing repeatability and safety.

The current pin and post system was replaced by two sets of three power screws connected in series by a drive shaft, powered by a stand-alone hand crank. This redesigned system has many strengths. These strengths include usability, safety, appearance and the ability to revert to the previous system. Both sides of the parallel bars can be easily adjusted from one central location, at the hand crank, rather than walking around to adjust the six individual posts. The system is safe with a drive shaft and hand crank tower safety covers to protect against the rotating drive shaft and nip points. From an aesthetic perspective, the system is finished with a durable, neutral grey powder coating. Lastly, should the customer be unsatisfied or the design does not function as expected over time, the system can be removed and the previous system can be reinstalled.

INTRODUCTION

The physical therapy clinic at Nazareth College frequently uses parallel bars with adjustable height to aid patients in relearning to walk. The previous system was difficult to adjust, consisting of six posts, each with a hole-and-pin system (Fig.1).

Due to the length of the bars, the current system is very difficult to properly align. The difficulty lies in accurately matching the number of holes exposed and results in nonparallel bars. Additionally, if a therapist positions a patient on the bars and discovers that the height needs a slight readjustment, the patient is required to sit back down. The difficulty of some patients to stand up a second time often results in the session being aborted. To improve the system, the clinic would like to have a set of bars with a mechanically assisted height adjustment to improve the quality of care that the patients receive per
session and to increase the number of patients who can use the parallel bars each day.

The expected customer benefits included:
- Increase use of parallel bar systems by physical therapist to improve quality of sessions for patients.
- Reduced set-up time of system, allowing more patients to use per day.
- Eliminate potential safety concerns for unlevel bars
- Decreased frustration levels of physical therapist.
- More repeatable height for individual patient.

**DESIGN PROCESS**

**Customer Requirements**

Customer needs were developed based on conversations and interviews with Professor JJ Mowder-Tinney, the lead therapist at Nazareth College. These fundamental needs were broken into seven main categories, which were further expanded.

- The system must be safe to use for both the physical therapist and the patient.
  - Support net weight of patient and bar
  - Little horizontal deflection
  - No exposed pinch points
  - Does not create a spill or trip hazard
  - Will not snag clothing
  - Stable upright supports
  - No exposed greasy components
  - Must be stationary (base plate anchored)
- The system must be accurate.
  - Maintain accuracy between the two bars
  - Ensure bar is always horizontal
  - Adjust height under patient’s load
  - Height indicator
- The system must be reliable.
  - Performance will not degrade over time
  - Withstands stress of use throughout lifespan
  - Preservation of existing system (ability to “roll back”)
- The system is easy to install.
  - Maintain similar footprint
  - Availability of power source
  - Costs of relocating parallel bars
- The system is easy to use & maintain.
  - Ease of adjustment to raise and lower
  - Reasonable time to adjust
  - Adjust bars together
  - Machine operation guide
  - Detailed maintenance Guide
- The system is within the National Science Foundation budget.

**Design Specifications**

The customer requirements listed above were mapped into engineering metrics, which are listed below:

- The system is rigid under a max load of 300 lbs.
- The maximum amount of vertical deflection (as based on current) is 2.466 inches.
- The maximum horizontal deflection (as based on current) is 1.14 inches.
- A safety analysis will be performed to ensure there are no exposed moving components which can be a pinch hazard, no additional obstacles were introduced, and all greasy/dirty components are shielded.
- The intervals of height adjustment will be ½ inch.
- The maximum force required to adjust the system will be less than 17 pounds.
- The maximum torque requirements will 8.5 ft-lbs.
- The total time to adjust the system will be less than 60 seconds.
- The bars must be spaced apart three feet at the base.
- The elevation of the bars (from the floor) will be 26-42 inches for a range of motion of 16 inches.
- The system will have a lifespan of 288,000 cycles (five years of use.)
- Maintenance personnel will be provided with a detailed maintenance guide.
- The physical therapist will be provided with an operation guide.
- The total cost of the device will be under $2000.

**Background Research and Benchmarking**

The archives of the National Science Foundation were searched to locate similar projects. A project focused on the same goal was completed in 1997, titled ‘Motorized Adjustable Parallel Bars’, under the guidance of Dr. Daniel Haines at Manhattan College. [1] Dr. Haines was contacted to see if any lessons learned could be passed on and to determine the success of that project. Although this project met all the engineering specification that had been defined, it was rejected by the customer. This led to two important lessons learned: to anticipate unstipulated user needs and to keep in contact with the client every step of the way. Further discussion with the customer did indeed reveal that no electric wires could run between the two sides and that the redesigned system needed to be fully reversible (i.e. revert to old system at any time.)

Similar parallel bar systems are commercially available, but they were not physically benchmarked due to prohibitively high prices. Instead, the lead engineer at Bailey Manufacturing, the company that manufactured Nazareth’s current parallel bar system, Brian Kolenich, was contacted and provided us with
a detailed users manual as well as valuable design information regarding material selection, loading scenarios, and industry standards. Based on his prior experiences, Mr. Kolenich advised that perceived movement to the patients was one of the biggest issues in the workings of his previous systems. This meant that it was very important that the redesign was rigid to minimize rattle in the post.[2]

Last, two common trailer jacks were disassembled to learn about the internal functions, component selection, and assembly process. A rough Design for Manufacture and Assembly (DFMA) was completed.

**Concept Development**

See Table 1 below for all proposed design solutions.

<table>
<thead>
<tr>
<th>Raising Mechanisms</th>
<th>Locking Mechanisms</th>
<th>Supports</th>
<th>Power-input</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scissor jack</td>
<td>Paw</td>
<td>Angled posts</td>
<td>Human (arms/legs)</td>
</tr>
<tr>
<td>Power screw</td>
<td>Throw lock (mechanical handle lock)</td>
<td>Anchored to ground</td>
<td>Electricity (outlet, AC/DC)</td>
</tr>
<tr>
<td>Trailer jack</td>
<td>Pin</td>
<td>Cables</td>
<td>Battery</td>
</tr>
<tr>
<td>Hand crank</td>
<td>Rigid Prop</td>
<td>Platform</td>
<td>Air compressor</td>
</tr>
<tr>
<td>Foot pump (hydraulics)</td>
<td>Self-locking (square) threads</td>
<td>Truss</td>
<td>Chemical (fuel cells)</td>
</tr>
<tr>
<td>Compressor (pneumatic cylinder)</td>
<td>Bearing w/angled surface</td>
<td>Lattice</td>
<td></td>
</tr>
<tr>
<td>Forklift (bike chain/gears)</td>
<td>Magnetic self-locking motor</td>
<td>Sandwiched w/platform</td>
<td></td>
</tr>
<tr>
<td>Pulley system</td>
<td>C-clamp</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Counterweights</td>
<td>Ball &amp; spring (ratchet)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct drive motor</td>
<td>Quick release seat post</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Worm gear</td>
<td>Set screw</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rack &amp; Pinion</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rail gun</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air suspension</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stream compressor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lever</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Office chair</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 1: Brainstorming Concepts**

Each team members independently tried to combine and refine the concepts from Table 1 into complete lifting system concepts. Ideas were discussed, with duplicate and infeasible ideas eliminated, which resulted in six unique lifting concepts. The main lifting components of the systems were hydraulics, pulleys, rack and pinion, power screw, trailer jack, and a scissor jack. Using two rounds of Pugh diagrams, the trailer jack lifting concept was selected. See Figure 2 for an overview of the selected concept, with important subsystems highlighted.

**DESIGN IMPLEMENTATION**

**Ergonomic Implementation**

Thorough market searches were performed to try to locate a commercially available jack that would meet the customer’s needs; however, no suitable matches were found. The current jacks available on the market would not be appropriate for this application because they could not support the necessary minimum height or the required range of motion.

<table>
<thead>
<tr>
<th></th>
<th>Force, (6 inch handle)</th>
<th>Equivalent Torque</th>
<th>User Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>17 lbs.</td>
<td>8.5 ft-lbs.</td>
<td>Need to use two hands to use</td>
</tr>
<tr>
<td>2</td>
<td>13 lbs.</td>
<td>6.5 ft-lbs.</td>
<td>Starts to get a little uncomfortable after a few revolutions</td>
</tr>
<tr>
<td>3</td>
<td>11 lbs.</td>
<td>5.5 ft-lbs.</td>
<td>Could do, but difficult at bottom of revolutions</td>
</tr>
<tr>
<td>4</td>
<td>8.5 lbs.</td>
<td>4.25 ft-lbs.</td>
<td>Could comfortably do this all day</td>
</tr>
</tbody>
</table>

**Table 2: Results of Ergonomic Study**

The goal of this ergonomic study was to set a value for the engineering specification of the maximum torque requirement. The maximum torque was found to be 8.5 ft-lbs, with an ideal torque requirement of 4.25 ft-lbs.
The height of the hand crank was another important ergonomic consideration. Using the Link Length Proportion Mannequin, the ideal height for the hand crank would be at the hip to elbow level.

**Figure 3: Link Length Proportion Mannequin**

Hip height = \(0.530H\)    Elbow height = \(0.630H\)

Using the height of the 50 percentile female (64.09 inches) as obtained from the ANSUR database, the ideal height for the hand crank was found to be between 33.97 and 40.38 inches.

**Torque Calculations**

To validate the lifting system concept, the amount of input force required to generate the torque to raise and torque to lower three jacks at the same time was calculated. The first step in these calculations was to calculate the weight of the previous setup. Components of the previous setup were used on the new system. Statics was used to calculate the reaction force at each post.

**Figure 4: Free Body Diagram of System**

The torque to raise and lower the three jacks at the same time was then calculated using the reaction forces and theory for acme thread power screws. [3]

<table>
<thead>
<tr>
<th>Jack</th>
<th>Threads (type)</th>
<th>Acme</th>
<th>(d_m) (in)</th>
<th>(f) (friction coef.)</th>
<th>(l) (in) Lead</th>
<th>(\alpha) (degrees)</th>
<th>(L) (in) Length</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Acme</td>
<td>9/16</td>
<td>0.20</td>
<td>1/8</td>
<td>29.00</td>
<td>18</td>
<td></td>
</tr>
</tbody>
</table>

**Table 4: ACME properties**

<table>
<thead>
<tr>
<th>Torque to raise ((T_R))</th>
<th>(T) (in-lbf)</th>
<th>3.287</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(T) (ft-lbf)</td>
<td>0.274</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Torque to lower ((T_L))</th>
<th>(T) (in-lbf)</th>
<th>1.481</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(T) (ft-lbf)</td>
<td>0.123</td>
</tr>
</tbody>
</table>

**Table 5: Calculated torque**

The following chart was then derived using the torque to raise. This was used to determine the proper gear ratio between handle crank and drive shaft, and proper crank length for ease of use.

<table>
<thead>
<tr>
<th>Gearing</th>
<th>Crane 5 - 15 in</th>
<th>Force input to raise at various lever arm length (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(d)</td>
<td>(D)</td>
<td>(N)</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1.00</td>
</tr>
<tr>
<td>1</td>
<td>1.5</td>
<td>0.97</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>0.90</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>0.33</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>0.25</td>
</tr>
<tr>
<td>1</td>
<td>5</td>
<td>0.20</td>
</tr>
<tr>
<td>1</td>
<td>6</td>
<td>0.17</td>
</tr>
<tr>
<td>1</td>
<td>7</td>
<td>0.14</td>
</tr>
<tr>
<td>1</td>
<td>8</td>
<td>0.13</td>
</tr>
<tr>
<td>1</td>
<td>9</td>
<td>0.11</td>
</tr>
<tr>
<td>1</td>
<td>10</td>
<td>0.10</td>
</tr>
</tbody>
</table>

**Table 6: Gear Ratios**

Based on the calculations above and the ergonomic study, a lever arm of 6 inches and a gear ratio of 1:4 were selected. This requires 2.19 lbf input to raise the three jacks at constant speed. The acme threaded rod has a lead of \(0.0625\) inches, the 1:4 gear ratio allows for a height adjustment of \(1/2\) inch for each complete hand crank rotation. This configuration would require a 0.0338 HP motor if the customer eventually decided to automate this system.
**Bolt Calculations**

To mount the lifting subsystem to the concrete floor, bolt strength calculations were performed to ensure the current 10-32 bolts utilized on the previous system will provide enough strength to withstand a 200 lbf, at 42 inches from the floor perpendicular to the lifting subsystem.

From the calculations, it was determined that the maximum tensile force the bolts would be subjected to was 752 lbf. The maximum shear force the bolts would be subjected to was 75 lbf. These results indicated that the existing 10-32 bolts may be sufficient, depending on the grade of the steel. The floor bolts that were used to secure the previous system are also being used to secure the new system. Further analysis will be done to confirm that they are safe for continued use.

**Safety Implementation**

One safety consideration was to shield all moving components, which will prevent the patient and physical therapist from becoming entangled. This led to the necessity of designing a drive shaft cover and a removable hand crank tower cover. The drive shaft cover will protect against the rotating drive shaft that runs along the floor, and must also be able to withstand use as a step.

**Lifting Subsystem Implementation**

Using the basic design of a trailer jack, a lifting system was developed in which the trailer jack is inverted, so that only about 1/3 of the weight of the jack is acting against the lifting force. There are a total of six lifting systems, three per side which are spaced every six feet apart. The lifting system consists of three main components: the inner shaft, the outer shaft, and the miter gear assembly.

**Drive Shaft Subsystem Implementation**

One of the most important customer needs was to ensure the system is accurate and always level. The system was designed to have a drive shaft which runs parallel to the floor, connecting three trailer jacks. Each side (three jacks) are controlled by one drive shaft, resulting in all trailer jacks turning at the same rate, ensuring the system is level.

As part of the design, Universal joints were used to accommodate for any unevenness of the floor and any resulting transverse deflection and angular adjustment. The use of Universal joints also combats unevenness in the shaft itself, due to the inability to find perfectly straight, seven foot long sections of circular stock. Even the slightest bend can lead to larger deflections downstream of the bend. Adding Universal joints improves the robustness of the design in the event of an imperfect piece section of the drive shaft, particularly since the longer the section, the higher probability of unevenness.

The drive shaft was recognized as a critical component, meaning that without it the system is totally unfunctional. Protecting a critical component, such as the drive shaft, is an important design aspect of every mechanical system. Using the ANSYS software, the drive shaft cover was analyzed to be able to withstand a five hundred pound force, which exceeds the OSHA standard 1928.57(a)(8). OSHA standard 1928.57(a)(8) states that the guard should be “capable of withstanding the force a 250 pound individual leaning or falling against the guard would exert upon the guard.”

[4] Safety is an important...
need of the project; it is vital to protect the physical therapist and patients should they fall on the drive shaft cover.

For ease of assembly, the system was designed to have a short section of the drive shaft inserted through the lifting system. This allowed for easier adjustment and alignment of the miter gears. Pillow blocks and bearings were selected to support the drive shaft to avoid having seven feet of unsupported drive shaft. To accomplish this, twelve inch sections for each lifting system were connected to a larger section with the U joints as described above.

Limiting the horizontal movement was crucial to the design, since misalignment of the miter gears results in failure of the system. Even the slightest bit of movement in any of the six shorter sections would result in greater wear in the teeth of the gears or even an opposite shift of the gears away from the point of contact. By using rod clamps, the shorter twelve inch sections of the drive shaft were secured from moving horizontally.

**Hand Crank Tower Implementation**

Based on the results of the ergonomic study, the ideal torque was found to be 4.25 ft-lbs. This resulted in a design with at least a 4:1 gear ratio. The smaller sprocket has 15 teeth, while the large sprocket has 60 teeth. The acme rod has eight threads per inch, which results in the system raising or lowering $\frac{1}{2}$ inch per revolution of the hand crank. A belt was selected to be used, rather than a chain, because a belt was assumed to be quieter and required less maintenance. The belt selected was 3/8 inch wide, with 385 teeth belt, resulting in the belt being 77 inches long. A belt tensioner was used to maintain adjustability and account for belt elongation over time.

A removable hand crank with a square head was utilized so that the crank could be removed. This prevents the system from accidently being engaged in the middle of a session. The hand crank was tethered to the hand crank tower to prevent it from being misplaced.

**DESIGN VALIDATION**

**Prototype**

A functional prototype of the lifting system was developed to test that all customer requirements were met and that the system performed as expected. This was completed to catch any issues before commencing on the machining of the remaining five lifting supports. As seen in the Bearings Choice Test and Miter Gears Test below, this allowed the team to make design changes early in the build phase.

**Full Extension Systems Deflect Test**

This test was designed to measure how much deflection the redesign was going to have, and to verify that it did not exceed the current system.

One lifting post was securely fastened to a board with a plumb-bob mounted from a vice. The location of the plumb-bob was marked on the piece of paper taped in place.

The post was extended to a height of 44” and a light push was applied both inwards and outwards. The location of the plumb-bob was measured and repeated at two inch measurement. The procedure was repeated at 60 lbs force. The difference between the two measurements was found using calipers.
Based on the results above, it was decided to limit the maximum functional height to 42”, a reduction already approved by customer. One design trade off of this decision is it allows the redesigned system to maintain the overlap between the inner and outer posts. As well, it was decided to buy and experiment with plastic shims, as well as powder coat the inner post to decrease the gap and reduce the natural wobble.

**Bearing Choice Test**

This test was designed to discover the advantages and disadvantages of two different bearing choices: a Heim Joint and a traditional pillow block. Horizontal, vertical and rotational loads were applied to a shaft the bearings were mounted on and movement of the bearing was measured. It was conclude the Heim Joint was too flexible and not suited for the necessary application.

**Miter Gears Test (Skipping or Breaking)**

This test was designed to ensure the miter gears were correctly installed and was completed upon the completion of the prototype. The test consisted of applying at least five sets of quick crank direction changes, as well as, applying a twisting force to the drive shaft.

Initial observations included that the system made a loud, grinding noise, was difficult to turn and occasionally jammed up. When the gear were inspected they appeared to mesh well, but significant movement of gears was noted.

The resolution of this test was to redesign the drive shaft and miter gears alignment. The drive shaft was redesigned to include a snap ring to prevent any gear travel as well as two split collars to restrict the motion of the shaft.

**ACME Nut Alignment Test**

This test was designed to ensure the ACME nut was properly welded on the end of the inner post. Through inspection it was concluded that the nuts were not welded square, resulting in the rod contacting the shaft wall. The resolution of this test was to turn down the corners of the acme nut from the as-built to a standard sized hole. The benefit of this was the threaded rod was closer to the true center of the shafts, than the variable tolerances of the nut. A half-part chamfer was added to keep the part square to the shaft as it was welded.

**Design Changes**

During the manufacturing process, it was decided to go with a larger diameter support for each of the lifting systems. By implementing a larger support, the lifting system structure was improved from 3/8 inch rod welded to the base plate and the outer post piece to a ½ inch rod welded in the same manner at approximately the same position.

In addition to the larger diameter support, larger welds where also added in a manner very different from the previous. The weld diameter increased slightly from the previous system, which used about a 1/8 inch weld where as the new system used about a 1/4 inch weld. By increasing the weld size, the structure would be able to with stand a greater axial force (horizontal) as well as take a far greater time to fatigue due to repeated loading.

A second change to the weld method was also implemented. Since a square hole was employed to assure ease of access in the case of part failure, a second weld was added on the bottom of the lifting system base plate. Adding this square hole not only helps the accessibility, but also proved to increase the strength of the structure as well. Lastly, the thrust plate was redesigned due to a previous error in calculations.

**CONCLUSIONS**

A redesigned parallel bar system was developed that meets the customer’s basic requirements, while providing some additional functionality over the existing system. All high levels needs were satisfied, resulting in a system which is safe for the patient and the physical therapist, while being easy to adjust and accurate. All design specifications were met, although the torque to raise needs quantification. The system has passed initial usability testing. As demonstrated, the results of the initial testing from the prototype, helped to guide the design process for the remaining components. The project was completed for a cost of $1533.14, which is well under the $2000 limit. The project was behind schedule due to the long lead time at the powder coaters, and unrealized errors in a successful prototype which necessitated much de-bugging upon completion of the rest of the project. The customer is pleased with design and implementation of the project and looks forward to using the system when installation is complete.
RECOMMENDATIONS FOR FUTURE WORK

From a redesign perspective, there are currently misalignment issues with the sprockets in the hand crank tower. The contact of the belt and the flange may lead to premature belt wear. If given the opportunity, the team would have further pursued the idea of using a chain and cogs. There is also a large amount of deflection due to the clearance between the inner and outer posts. The material for these critical components was purchased from a discount steel supplier, whereas a better option would have been to spend more to purchase higher quality materials.

From a future enhancement perspective, the system was designed to be easily converted to an electric motor. It would be necessary to add a motor mount and to wire electricity under the floor between the bars, but the mechanics of the system are completely compatible. This design modification would be particularly useful if the Nazareth Physical Therapy clinic experienced a drastic increase in the number of patients, or if a pediatrics program were developed. With the development of a pediatrics program the total range of height adjustment per day will increase, resulting in more cranks. Unfortunately, due to the architectural design of the Nazareth PT clinic, facility changes would be necessary to implement any type of electric motors, while keeping the system in its current setup.

If electricity was supplied, the height gauge could be upgraded. This could be done with a simple position sensor, which is typically found in motors with frequency sensing capabilities. Also, a simple controller might prove effective for the user to input a height number to a digital display resulting in an analog output in the motors change in position. Employing this sort of design decreases the time that the physical therapist needs to make the appropriate changes, bypasses any manual input to the crank, and allows the user to easily document what might be the proper height for the patient.

Electrical building code, as well as costly equipment, will be required to implement this idea. This idea should be approached from a cost optimization point of view. It should also be noted that a previous NSF project under Dr. Daniel Haines at Manhattan College attempted and failed to utilize a similar design. This was due to trip hazards posed by the power cords in the walking path of both the physical therapist as well as patient. To avoid this, a suitable layout would need to be planned out ahead of time to meet both building codes and the ergonomic and safety requirements.

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Corporate Contact: Nazareth Physical Therapy Clinic (JJ Mowder – Tinney and Lindsey Pendleton)

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Other Contributors: Rob Kraynik, Steve Kosciol, Dave Hathaway, Frank Lucisano, Andrew Cappella

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REFERENCES


