AN ABSTRACT OF THE THESIS OF

Brenton D. Gibson for the degree of Master of Science in Mechanical Engineering presented on June 4, 2009.

Title: Design of a Mechanically Assisted Dependent Transfer Mechanism for Use On Board Commercial Aircraft.

Abstract approved:

_________________________________________________________

Joseph R. Zaworski

Business and recreation in the modern day world often include air travel as their cornerstone. Travelers who are disabled and wheelchair bound have to undergo a transfer process to board and deplane a commercial aircraft. This transfer process is typically done manually, with agents physically lifting the passenger who is disabled. This manual process exposes the passenger and agents to risk of injury. By developing a mechanical device to aid in the transfer process, those risks could be minimized while simultaneously providing a better experience for those involved. Other Individuals have investigated and quantified various aspects of this design challenge. The work presented in this document was conducted to first combine the previous research, and then make further developments through analysis, design, and testing. The developmental efforts were focused on four major components of the prototype: the lifting column, the passenger interface, the links of the articulating arm, and the base. In this development process, care was taken to ensure that the individual components would integrate to make a single prototype device capable of completing a passenger transfer on board a commercial aircraft.
Design of a Mechanically Assisted Dependent Transfer Mechanism for Use On Board Commercial Aircraft

by
Brenton D. Gibson

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APPROVED:

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Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

__________________________________________________________________
Brenton D. Gibson, Author
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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 INTRODUCTION</td>
<td>2</td>
</tr>
<tr>
<td>1.1 Background on Air Travel with Disabilities</td>
<td>2</td>
</tr>
<tr>
<td>1.2 Manual Transfers</td>
<td>5</td>
</tr>
<tr>
<td>1.3 NCAT Computer Survey</td>
<td>8</td>
</tr>
<tr>
<td>1.4 Overall Project Goals</td>
<td>9</td>
</tr>
<tr>
<td>1.5 Proposed Solution</td>
<td>10</td>
</tr>
<tr>
<td>1.6 Prototype Development</td>
<td>13</td>
</tr>
<tr>
<td>1.6.1 Design</td>
<td>13</td>
</tr>
<tr>
<td>1.6.2 Testing</td>
<td>14</td>
</tr>
<tr>
<td>1.6.3 Iteration</td>
<td>14</td>
</tr>
<tr>
<td>1.7 Summary</td>
<td>14</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 BACKGROUND</td>
<td>16</td>
</tr>
<tr>
<td>2.1 Existing Transfer Methods</td>
<td>16</td>
</tr>
<tr>
<td>2.1.1 Manual Transfer</td>
<td>16</td>
</tr>
<tr>
<td>2.1.1.1 Biomechanics Study</td>
<td>17</td>
</tr>
<tr>
<td>2.1.1.2 Transfers in Healthcare</td>
<td>19</td>
</tr>
<tr>
<td>2.1.2 SureHands</td>
<td>21</td>
</tr>
<tr>
<td>2.1.3 Sling Systems</td>
<td>23</td>
</tr>
<tr>
<td>2.1.3.1 Haycomp (Products: Eagle 2 &amp; Eagle 3)</td>
<td>24</td>
</tr>
<tr>
<td>2.1.3.2 Xpiration (Products: XPCBoardingChair)</td>
<td>25</td>
</tr>
</tbody>
</table>
TABLE OF CONTENTS (Continued)

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2 Alternative Transfer Methods</td>
<td>27</td>
</tr>
<tr>
<td>2.2.1 Existing Patents</td>
<td>27</td>
</tr>
<tr>
<td>2.2.1.1 Mr. Jon Mast’s Patent Search</td>
<td>27</td>
</tr>
<tr>
<td>2.2.1.2 Mr. Sushim Koshti’s Patent Search</td>
<td>33</td>
</tr>
<tr>
<td>2.2.1.3 Recent Patent Search</td>
<td>39</td>
</tr>
<tr>
<td>2.2.2 Previous NCAT Work</td>
<td>42</td>
</tr>
<tr>
<td>2.2.2.1 Mr. Ulrich Wörz’s Work</td>
<td>43</td>
</tr>
<tr>
<td>2.2.2.2 Mr. Jon Mast’s Work</td>
<td>50</td>
</tr>
<tr>
<td>2.2.2.3 Mr. Sushim Koshti’s Work</td>
<td>60</td>
</tr>
<tr>
<td>2.2.3 Current Design Direction</td>
<td>73</td>
</tr>
<tr>
<td>3 PROTOTYPE DESIGN OBJECTIVES</td>
<td>75</td>
</tr>
<tr>
<td>3.1 Project Goals</td>
<td>75</td>
</tr>
<tr>
<td>3.2 Customer Requirements</td>
<td>76</td>
</tr>
<tr>
<td>3.3 Engineering Requirements</td>
<td>77</td>
</tr>
<tr>
<td>3.4 Design Constraints</td>
<td>79</td>
</tr>
<tr>
<td>4 METHODS</td>
<td>82</td>
</tr>
<tr>
<td>4.1 Overview</td>
<td>82</td>
</tr>
<tr>
<td>4.2 Column</td>
<td>83</td>
</tr>
<tr>
<td>Section</td>
<td>Title</td>
</tr>
<tr>
<td>---------</td>
<td>-------</td>
</tr>
<tr>
<td>4.3</td>
<td>Passenger Interface</td>
</tr>
<tr>
<td>4.3.1</td>
<td>Analysis</td>
</tr>
<tr>
<td>4.3.2</td>
<td>Design (Part 1)</td>
</tr>
<tr>
<td>4.3.3</td>
<td>Finite Element Analysis</td>
</tr>
<tr>
<td>4.3.4</td>
<td>Testing</td>
</tr>
<tr>
<td>4.3.5</td>
<td>Design (Part 2)</td>
</tr>
<tr>
<td>4.4</td>
<td>Links</td>
</tr>
<tr>
<td>4.4.1</td>
<td>Analysis</td>
</tr>
<tr>
<td>4.4.2</td>
<td>Design</td>
</tr>
<tr>
<td>4.4.3</td>
<td>Finite Element Analysis</td>
</tr>
<tr>
<td>4.5</td>
<td>Base</td>
</tr>
<tr>
<td>5</td>
<td>FINAL RESULTS</td>
</tr>
<tr>
<td>5.1</td>
<td>Column</td>
</tr>
<tr>
<td>5.2</td>
<td>Passenger Interface and Links</td>
</tr>
<tr>
<td>5.3</td>
<td>Base</td>
</tr>
<tr>
<td>6</td>
<td>CONCLUSION</td>
</tr>
<tr>
<td>6.1</td>
<td>Overall Summary</td>
</tr>
<tr>
<td>6.2</td>
<td>Limitations</td>
</tr>
<tr>
<td>6.3</td>
<td>Suggestions for Future Work</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Demonstration of different physical needs by differing demographics</td>
</tr>
<tr>
<td>2</td>
<td>Typical aisle chair; unoccupied (left), and in use on a jet way (right)</td>
</tr>
<tr>
<td>3</td>
<td>Manual transfer process of a passenger with disabilities</td>
</tr>
<tr>
<td>4</td>
<td>NCAT survey results for passenger rating of transfer experience [12]</td>
</tr>
<tr>
<td>5</td>
<td>Model of prototype transfer device</td>
</tr>
<tr>
<td>6</td>
<td>Experimental layout of biomechanics study [10]</td>
</tr>
<tr>
<td>7</td>
<td>Pictures from transfers performed during biomechanics study [10]</td>
</tr>
<tr>
<td>8</td>
<td>SureHands Body Support device being tested by NCAT</td>
</tr>
<tr>
<td>9</td>
<td>Haycomp Eagle 2 [18]</td>
</tr>
<tr>
<td>10</td>
<td>XP BoardingChair being used to perform a transfer [20]</td>
</tr>
<tr>
<td>11</td>
<td>Patient Transfer Apparatus [21]</td>
</tr>
<tr>
<td>12</td>
<td>Wheelchair Mounted Invalid Lift [22]</td>
</tr>
<tr>
<td>13</td>
<td>Person Lifter/Rotator [23]</td>
</tr>
<tr>
<td>14</td>
<td>Person Lifter/Rotator power chair alternative [23]</td>
</tr>
<tr>
<td>15</td>
<td>Compact Portable Patient Lift [24]</td>
</tr>
<tr>
<td>16</td>
<td>Compact Portable Patient Lift in use [24]</td>
</tr>
<tr>
<td>17</td>
<td>Travel Insert Chair and method of transporting the physically handicapped [25]</td>
</tr>
<tr>
<td>18</td>
<td>Easy Transport Seat [26]</td>
</tr>
<tr>
<td>19</td>
<td>Wheelchair and platform device for movement of a disabled person from a wheelchair to a chair seat support in a vehicle and aircraft [27]</td>
</tr>
<tr>
<td>Figure</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>------</td>
</tr>
<tr>
<td>20</td>
<td>37</td>
</tr>
<tr>
<td>Method and means for assisting a person to, into, and out of a seat in a confined space [28]</td>
<td>37</td>
</tr>
<tr>
<td>21</td>
<td>38</td>
</tr>
<tr>
<td>Lift and transfer apparatus for a disabled person [29]</td>
<td>38</td>
</tr>
<tr>
<td>22</td>
<td>40</td>
</tr>
<tr>
<td>Patient Lifting Device [30]</td>
<td>40</td>
</tr>
<tr>
<td>23</td>
<td>41</td>
</tr>
<tr>
<td>Patient Lift and Transfer Device and Method [31]</td>
<td>41</td>
</tr>
<tr>
<td>24</td>
<td>42</td>
</tr>
<tr>
<td>Additional strap in use on the Patient Lift and Transfer Device [31]</td>
<td>42</td>
</tr>
<tr>
<td>25</td>
<td>44</td>
</tr>
<tr>
<td>Possible solution of combination of working principles [33]</td>
<td>44</td>
</tr>
<tr>
<td>26</td>
<td>45</td>
</tr>
<tr>
<td>First dependent lift prototype, unoccupied (left) and occupied (right) [33]</td>
<td>45</td>
</tr>
<tr>
<td>27</td>
<td>47</td>
</tr>
<tr>
<td>Matrix of working principles [33]</td>
<td>47</td>
</tr>
<tr>
<td>28</td>
<td>48</td>
</tr>
<tr>
<td>Conceptual Sketch of Wörz’s second prototype [33]</td>
<td>48</td>
</tr>
<tr>
<td>29</td>
<td>49</td>
</tr>
<tr>
<td>Wörz suspended in his second prototype [33]</td>
<td>49</td>
</tr>
<tr>
<td>30</td>
<td>51</td>
</tr>
<tr>
<td>Proof of concept for horizontally articulating links [12]</td>
<td>51</td>
</tr>
<tr>
<td>31</td>
<td>52</td>
</tr>
<tr>
<td>First prototype capable of lift and transfer movements [12]</td>
<td>52</td>
</tr>
<tr>
<td>32</td>
<td>53</td>
</tr>
<tr>
<td>Strap system used for generating medially-directed force [12]</td>
<td>53</td>
</tr>
<tr>
<td>33</td>
<td>55</td>
</tr>
<tr>
<td>Pneumatic setup for applying an adjustable medially-directed force [12]</td>
<td>55</td>
</tr>
<tr>
<td>34</td>
<td>56</td>
</tr>
<tr>
<td>Average discomfort as related to average applied medially-directed force [12]</td>
<td>56</td>
</tr>
<tr>
<td>35</td>
<td>58</td>
</tr>
<tr>
<td>Mast’s Proof of concept of integrating aisle chair with sliding base [12]</td>
<td>58</td>
</tr>
<tr>
<td>36</td>
<td>59</td>
</tr>
<tr>
<td>Telescoping column mounted to sliding base of aisle chair [12]</td>
<td>59</td>
</tr>
<tr>
<td>37</td>
<td>62</td>
</tr>
<tr>
<td>Virtual aircraft environment [32]</td>
<td>62</td>
</tr>
<tr>
<td>38</td>
<td>63</td>
</tr>
<tr>
<td>Tony in standing and seated positions [32]</td>
<td>63</td>
</tr>
<tr>
<td>39</td>
<td>64</td>
</tr>
<tr>
<td>Components and nomenclature of the simulated transfer device [32]</td>
<td>64</td>
</tr>
<tr>
<td>Figure</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>------</td>
</tr>
<tr>
<td>40</td>
<td>66</td>
</tr>
<tr>
<td>41</td>
<td>67</td>
</tr>
<tr>
<td>42</td>
<td>69</td>
</tr>
<tr>
<td>43</td>
<td>70</td>
</tr>
<tr>
<td>44</td>
<td>71</td>
</tr>
<tr>
<td>45</td>
<td>71</td>
</tr>
<tr>
<td>46</td>
<td>72</td>
</tr>
<tr>
<td>47</td>
<td>85</td>
</tr>
<tr>
<td>48</td>
<td>86</td>
</tr>
<tr>
<td>49</td>
<td>88</td>
</tr>
<tr>
<td>50</td>
<td>89</td>
</tr>
<tr>
<td>51</td>
<td>90</td>
</tr>
<tr>
<td>52</td>
<td>91</td>
</tr>
<tr>
<td>53</td>
<td>95</td>
</tr>
<tr>
<td>54</td>
<td>99</td>
</tr>
<tr>
<td>55</td>
<td>99</td>
</tr>
<tr>
<td>56</td>
<td>100</td>
</tr>
<tr>
<td>57</td>
<td>101</td>
</tr>
<tr>
<td>58</td>
<td>103</td>
</tr>
<tr>
<td>59</td>
<td>104</td>
</tr>
<tr>
<td>60</td>
<td>107</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>61</td>
<td>Von Mises stress from FEA of final revision of support arm</td>
</tr>
<tr>
<td>62</td>
<td>Final design of passenger interface support arm</td>
</tr>
<tr>
<td>63</td>
<td>Final design of passenger interface pivot support bracket</td>
</tr>
<tr>
<td>64</td>
<td>Interface of pivot support bracket with support arm of final design of passenger interface</td>
</tr>
<tr>
<td>65</td>
<td>Assembly of final design of passenger interface lift arm and support bracket</td>
</tr>
<tr>
<td>66</td>
<td>Assembly of final design of passenger interface</td>
</tr>
<tr>
<td>67</td>
<td>Cardboard link model testing of 10/12 link configuration (transfer device left, aircraft seat right)</td>
</tr>
<tr>
<td>68</td>
<td>Comparing 8/12 links to 12/12 links in aircraft seat</td>
</tr>
<tr>
<td>69</td>
<td>Discovered clearance issue with aircraft seats during movement down the aisle</td>
</tr>
<tr>
<td>70</td>
<td>Cardboard model testing of 8/14 link configuration (transfer device left, aircraft seat right)</td>
</tr>
<tr>
<td>71</td>
<td>CATIA sketch of link and passenger interface geometry</td>
</tr>
<tr>
<td>72</td>
<td>Model of articulating arm</td>
</tr>
<tr>
<td>73</td>
<td>Model of base link design</td>
</tr>
<tr>
<td>74</td>
<td>Model of second link design</td>
</tr>
<tr>
<td>75</td>
<td>Model of base mount design</td>
</tr>
<tr>
<td>76</td>
<td>Von Mises stress from FEA of base link in 90 degree loading</td>
</tr>
<tr>
<td>77</td>
<td>Von Mises stress from FEA of base link in 0 degree loading</td>
</tr>
<tr>
<td>78</td>
<td>Von Mises stress from FEA of second link in bending</td>
</tr>
<tr>
<td>79</td>
<td>Von Mises stress from FEA of second link in torsion</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>80</td>
<td>Von Mises stress from FEA of base mount in 0 degree loading</td>
</tr>
<tr>
<td>81</td>
<td>Von Mises stress from FEA of base mount in 90 degree loading</td>
</tr>
<tr>
<td>82</td>
<td>Von Mises stress from FEA of base mount in 135 degree loading</td>
</tr>
<tr>
<td>83</td>
<td>Load testing of Mast’s sliding base prototype</td>
</tr>
<tr>
<td>84</td>
<td>Folding onboard aisle chair by Innovint Aircraft Interiors</td>
</tr>
<tr>
<td>85</td>
<td>Wheel configurations considered for base</td>
</tr>
<tr>
<td>86</td>
<td>Caster wheel nomenclature</td>
</tr>
<tr>
<td>87</td>
<td>Illustration of effects of caster swivel radius on lateral stability</td>
</tr>
<tr>
<td>88</td>
<td>Dimensions and configuration of base wooden mock-up</td>
</tr>
<tr>
<td>89</td>
<td>Testing base wooden mock-up on board a Boeing 737</td>
</tr>
<tr>
<td>90</td>
<td>Pride Mobility Go-Chair base</td>
</tr>
<tr>
<td>91</td>
<td>Isometric view of assembly of passenger interface, links, and base mount</td>
</tr>
<tr>
<td>92</td>
<td>Assembly of passenger interface, links, and base mount</td>
</tr>
</tbody>
</table>
## LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1  Design Configurations for arms of transfer device [32]</td>
<td>68</td>
</tr>
</tbody>
</table>
### LIST OF APPENDIX FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>93</td>
<td>Static Analysis of links and passenger interface</td>
<td>169</td>
</tr>
<tr>
<td>94</td>
<td>Measurements taken at boarding area on Boeing 737</td>
<td>171</td>
</tr>
</tbody>
</table>
### LIST OF APPENDIX TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>170</td>
</tr>
<tr>
<td>3</td>
<td>170</td>
</tr>
<tr>
<td>4</td>
<td>170</td>
</tr>
</tbody>
</table>

2  Measured aisle widths from Boeing 737
3  Measured dimensions for food cart on Boeing 737
4  Measured dimensions for food cart caster wheels

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Design of a Mechanically Assisted Dependent Transfer Mechanism for Use On Board Commercial Aircraft
1 INTRODUCTION

1.1 Background on Air Travel with Disabilities

Many of us take our ability to travel by air for granted. We rely on our ability to cover hundreds or thousands of miles in a matter of hours. It is difficult to keep in mind that it has only been a little over 100 years since the Wright brothers pioneered sustained flight. In today’s day-in-age, air transportation plays a key role in day-to-day business and pleasure activities. Even though the process of flying on commercial aircraft has been simplified, there are still many things that need to happen after arriving at the airport in order for the trip to be successful. Tickets need to be picked up, luggage needs to be checked, security checks need to be cleared, gates need to be made, carry-ons need to be stowed, and seats need to be taken. These tasks may become difficult to impossible for a passenger with disabilities to carry out on their own accord.

Some disabilities are outwardly obvious, while others are not. The Americans with Disabilities Act (ADA) defines a person with disabilities as one who has a physical or mental impairment that substantially limits one or more major life activities [1]. The ADA prohibits the discrimination against a person based upon their disability within employment, public services and facilities, transportation (excluding aircraft and certain rail operations), telecommunications, and state and local government [1]. While the ADA does not cover transportation by aircraft, the Air Carrier Access Act (ACAA) of 1990 goes into the specifics of accommodating passengers with disabilities within air travel. It specifically states that an airline may not refuse service to a passenger with disabilities, who is otherwise qualified to fly, based solely on their disability [2]. Additionally, the act placed several regulations in effect that serve to improve the accessibility of aircraft. For instance, it is required that at least half of
the aisle seats on an airplane with a capacity exceeding 30 passengers have moveable arm rests, unless trumped by an Federal Aviation Administration safety regulation [2]. Any aircraft with more than one aisle that also contains lavatories must provide at least one accessible lavatory, and any aircraft with a capacity of 60 or more passengers and an accessible lavatory must be equipped with an on-board wheelchair for use by passengers [2]. Additionally, any aircraft with a capacity over 60 passengers must provide an on-board wheelchair for use upon the advanced notice of a passenger who requires it to reach and use an inaccessible lavatory [2]. If the aircraft has a capacity over 100 passengers, then the Act requires that there be at least one location where a passenger’s folding wheelchair may be stowed in the passenger cabin [2].

The before-mentioned regulations help to ensure passengers with disabilities are accommodated, but there are also economic and social factors that should be considered as drivers for accessible air transportation. There are significant numbers of people with disabilities. According to a census taken in 2005 by the United States Census Bureau, of the 291 million people in the country, 54.4 million (18.7 percent) have disabilities and 35.0 million (12.0 percent) of them have severe disabilities [3]. The census results from 2000, 2002, and 2005 show a steady rise in these figures [3], [4], [5]. Narrowing the 2005 statistics down, the population group of age 15 years and older includes 3.3 million people that rely upon a wheelchair or similar device and 10.2 million that use crutches, a cane, or a walker [3]. Just because these people have disabilities does not mean they avoid air travel. One 2005 study found that 31 percent of adults with disabilities had traveled by air at least once during the previous 2 years [6]. Combining their 2005 survey results with 2005 U.S. Census data reveals the estimated number of travelers with disabilities, who fly at least bi-annually, to more recently be 15.2 million [3], [5], [6]. The findings of another report
suggest that an even higher number of 17 million travelers with disabilities fly each year [7]. Given current ticket prices, this equates to annual expenditures that are considerable. Looking to the future, it is expected that the percentage of Americans with disabilities will continue to grow. One researcher predicts the percentage of citizens with disabilities to increase to 24 percent by 2030, meaning an estimated increase of 30.9 million people who are disabled [6]. This increase is likely closely linked to an aging population. In 2007, 37.9 million people in the United States were of age 65 or older [8]. Predictions show this age group to substantially increase between 2010 and 2030, driving the total number of people over age 65 to 72 million [8], [9]. These future predictions emphasize that accommodating people with disabilities will continue to be socially and economically prudent.

Regulations have been imposed to ensure people with disabilities are accommodated for during air travel, and studies have shown economic reasons why such accommodations are favorable. Additionally, improving accommodations for people with disabilities can benefit others. For instance, a person of extreme height may be unable to fit into a standard airline seat. A person who has disabilities due to extremely short stature also has difficulty reaching a standard airline seat due to the limited space between the front of the assigned seat and the back of the seat in front of them. By providing seating options with more “leg” room, both extremes in stature are better accommodated (Fig. 1). This concept has been called universal design. That is, if a design to better accommodate a given demographic is done right, then it will better serve other demographics as well. Nonetheless, the current environment encountered by air travelers with disabilities is far from ideal. The number of disability-related complaints received by air carriers is on the rise. From 2004 to 2007, the number of complaints filed with air carriers rose by 33 percent [7]. Many opportunities for improvement exist and span such areas as navigation within
airports, boarding and deplaning the aircraft, personal wheelchair stowage in the cargo hold of the aircraft, and accessing aircraft lavatories. The area of focus for the rest of this document will be the transfer of a passenger from their personal wheelchair to their assigned aircraft seat during boarding and deplaning.

Fig. 1 Demonstration of different physical needs by differing demographics

1.2 Manual Transfers

Currently, most common process of getting a wheelchair-bound passenger to and from their aircraft seat involves a series of manual transfers and a narrow wheelchair called an aisle chair. The manual transfers pose a risk of injury to both the transferors and the passenger being transferred. To understand the risks, it is important to understand the manual transfer process.

As briefly introduced above, the foundation for getting a dependent passenger into their aircraft seat is through the use of an aisle chair. An aisle chair is a specialty
wheelchair that is narrow enough to fit down the aisle of a commercial aircraft (Fig. 2). The boarding process starts when the passenger is transferred from their personal wheelchair to the aisle chair. The aisle chair is then taken down the aisle of the aircraft until the assigned aircraft seat is reached, then the passenger is transferred from the aisle chair to their aircraft seat. During deplaning, the same process is carried out, but in reverse. Again, the use of the aisle chair is not the essence of the concern. The problem stems in the transfer of the passenger to and from the aisle chair. This means the risk-laden transfer happens four times during the course of a single flight.

![Typical aisle chair; unoccupied (left), and in use on a jet way (right)](image)

**Fig. 2** Typical aisle chair; unoccupied (left), and in use on a jet way (right)

The typical manual transfer requires two assistants. One assistant stands behind the passenger and lifts them from under the arms, while the second assistant stands in front of the passenger and lifts their legs (Fig. 3). A biomechanics study revealed that the assistants are subject to a high risk of low back injury [10].
The manual process is highly variable depending on the strength and skill of the assistants. Because of this, prior arrangements need to be made so that trained personnel of sufficient size and strength are available for boarding and deplaning. Even then, an error on the assistants’ part could easily injure the passenger or themselves. However, it is possible that not all assistants have received proper training. One article reported that a survey of 275 Los Angeles International passenger-service workers revealed that about 60 percent of the workers said they had not been formally trained in how to lift an immobile passenger [11]. The transfer process intrudes into a passenger’s personal space, compromises their dignity, and
may be performed in front of other passengers. Add these factors to the potential of inadequately trained assistants and risk of injury, and you begin to see how the process becomes highly variable and potentially very dissatisfying.

1.3 NCAT Computer Survey

Some issues of the manual transfer process have been presented, but how do these issues affect the actual experiences of air travelers with disabilities? In 2005, the National Center for Accessible Transportation (NCAT) at Oregon State University (OSU) conducted a computer poll to evaluate the experiences of people with disabilities for various aspects of air travel. The people who responded to the survey had levels of independence varying from fully independent (a rating of 1) to fully dependent (a rating of 5). They were also asked to give their experience a rating from 1 to 5, with 1 being an excellent experience and 5 being terrible. A couple of aspects of particular interest in the survey pertained to the transfer process and features of the aisle chair. There were a total of over 300 respondents for the entire survey, 213 of which responded to the transfer process section. The survey broke the transfer process into four parts: first transfer to the aisle chair, transfer from aisle chair to seat, second transfer to aisle chair, and finally the transfer back to their personal wheelchair. The results of the transfer process section of the survey are summarized in a plot of satisfaction as a function of level of independence (Fig. 4).
It can be seen that the experience of a disabled person during a transfer process is related to their level of independence. The more independence a person felt like they had, then the better their experience was. The responses gathered from the survey regarding features of the aisle chair revealed significant dissatisfaction with the straps used for restraint, the footrest, and the size and feel of the seat. These findings clearly give some targets to aim for when trying to improve the transfer process.

1.4 Overall Project Goals

Shortcomings have been identified in the most commonly used manual transfer process. There is potential for gains to be realized by airline companies, their agents,
and the passengers. It is believed that a mechanical system could be designed to favorably assist in the transfer process. The overall goals of this transfer device are to:

- Reduce the risk and occurrence of injury for the passenger and the transfer assistants.
- Preserve the dignity of the passenger as much as possible.
- Provide as much independence to the passenger as their situation allows.
- Provide a solution that is simple to implement without requiring extensive training.
- Provide a solution that requires less physical effort.

Through a successful design, the passenger and transfer assistants would be provided with a better experience. A decrease in the occurrences of injury would yield a monetary savings to airline companies in the form of lower health insurance premiums and medical expenses. Since the portion of the population requiring aid is projected to grow in the coming years, any improvements made will only become more significant in impact with time.

1.5 Proposed Solution

There could be benefits from a mechanical system being incorporated into the transfer process. However, if the design is not carefully carried out to consider all the parameters involved in the transfer process, any realized benefits could be negated by the creation of a new set of issues. For instance, some currently available mechanical transfer aids employ the use of a sling for lifting the passenger. While this works well on the fundamental level, an issue is created that undermines any provisions for maintaining the dignity and independence level of the passenger. This is due to the newly created need to manhandle the passenger in order to correctly
position the sling under them. The proposed solution for this project involves mimicking the passenger interface of the manual transfer process. That is, the device will be designed to squeeze and lift the passenger from under the arms while also providing a means to lift the passenger’s legs. The main issues with this interface, in context of the manual transfer process, are the risk of injury and the necessary physical contact. Because these elements are lessened or removed by the mechanical device, the manual transfer interface becomes an effective method for performing a transfer. Under an ideal situation, the passenger would be able to position themselves into the mechanical lifting system with only the basic use of their arms. This would provide a higher level of independence, which would lead to an improved overall experience for the transfers from the wheelchair to the device, from the device to the aircraft seat, and vice-versa.

The lifting force for the proposed system would come from an electrically driven linear actuator. This means no high amounts of physical exertion would be required by an assistant. Largely because of this, it may be possible for the entire transfer process to be performed by only a single assistant. Aside from the lift operation and interface with the passenger, there are other general factors that need to be considered in the mechanical transfer device. One is the confined environment provided by the aisleway of commercial aircraft. The transfer device needs to be easy to maneuver into position and intuitive to use. The device should also be able to accommodate passengers of different sizes and shapes. If all these objectives are accounted for, then the design has a good chance for success.

The proposed transfer device consists of eight main components (Fig. 5). Of these eight, seven were focused on during this work. These seven components were the passenger interface, second link, base link, base mount, lift column, and transfer device base. The analysis, design, and testing done during the development of these
components is the focus of this work. The transfer device base shown is not the result of design work done by the author, but the author did perform analysis on the sizing that is represented (Fig. 5). In addition, the lift column was a prototype built by an outside vendor to NCAT’s specifications. The performance of this column was tested during this work to verify it met requirements.

Fig. 5   Model of prototype transfer device
1.6 Prototype Development

Previous work done by NCAT researchers focused on developing components of the transfer device separate from each other. This was necessary due to time and manpower restrictions. During this previous work, concepts were proven and bounds were established for some parameters of the transfer device, which later evolved into design requirements. However, this does not mean the subsequent developmental efforts were done in a plug-and-play environment. In a way, bringing all the concepts together constituted a systems design task. Work was done to ensure the components of the device would function together as a whole. In addition to bringing previous research together, new ideas and a new perspective formed some new concepts for the transfer device. The work presented in this document focuses on the efforts to form and test these new concepts and then integrate them with the results gained from the further development of previous research. The general work flow observed during this effort was to design, test, and then iterate.

1.6.1 Design

As briefly mentioned before, much time and effort was necessary to refine concepts in a way that they all integrated with each other to form a final prototype that could meet design requirements. These design requirements are discussed in section 3 of this document. To develop a design, multiple tools were used. These ranged from hand calculations, to cardboard models, to computer models. The final designs were modeled and assembled in CATIA V5, from Dassault Systems (Velizy-Villacoublay, France). CATIA V5 is a three-dimensional modeling software package that has many built-in capabilities, such as Kinematic Analysis, Human Builder, and Finite Element Analysis (FEA), all of which were used during this project. This allowed tolerances and interferences to be checked to ensure requirements were met. These models also set the stage for some work done in the testing phase.
1.6.2 Testing

Testing was required to validate the new concepts that were developed during the design phase. Some of the testing was done within CATIA via FEA. Other testing was done on physical prototypes that were built, such as for the passenger interface and the transfer device base. While the lift column was not the subject of any design work, physical testing was still necessary to verify its performance met requirements.

1.6.3 Iteration

Through the generation of designs and the subsequent testing, weaknesses and shortcomings of designs were revealed. Work then became iterative, as new designs were developed and tested until the requirements were met. In most cases, there were at least three iterations performed before reaching the current result. Since the components needed to function with each other, the designs were interrelated. A design modification of one component often affected other components. Design and testing efforts were continued until all components met requirements and functioned with each other as a system.

1.7 Summary

Air travel is a large piece of the transportation puzzle we face on a regular basis. It is likely this will not lessen in the near future. However, what is expected to change is the demographic of air travelers. The results from the US Census Bureau indicate the number of people with disabilities in the United States is on the increase, a prediction that is confirmed by other researchers. It is reported that JetBlue airlines has seen an increase in the number of passengers requesting assistance that has consistently outpaced their overall passenger growth since 2004 [11]. Accommodating passengers who are disabled is not only required by established regulations, but there are also economic reasons that show it is beneficial to do so.
One major hurdle in the air travel of a passenger bound to a wheelchair is the transfer process required during boarding and deplaning. A mechanically assisted dependent transfer device could serve to significantly lessen the risk of injury and provide a better experience for all involved.
2 BACKGROUND

This section will start with the introduction of pertinent existing transfer methods for people with disabilities. Alternative methods of transfer will then be presented, which include the prior work done by NCAT researchers. Finally, the selected design direction for the transfer device will be introduced.

2.1 Existing Transfer Methods

There are many different environments in which people with disabilities need to be transferred from one seat to another. Manual transfers are very common, but there are also other methods used in order to lessen injuries. Transfers to aircraft seats are a small percentage of the total number of transfers that happen every day. However, given the tight space constraints, it is one of the most challenging transfer environments. Here, research findings for the commonly used manual transfer process will be introduced. Discussion will then shift to a commercially available device which mimics the manual transfer interface. This section will then conclude with the introduction of several devices that have already been developed to aid in aircraft transfers.

2.1.1 Manual Transfer

As introduced before, manual transfers are still a very large part of moving people with disabilities every day. Once the process is understood, the risks involved are intuitive to see, but quantifying them is more difficult. Results of a biomechanics study done on the manual transfer of a person into an aircraft seat will be presented here, followed by research findings for manual transfers within the healthcare industry.
2.1.1.1 Biomechanics Study

Researchers within NCAT identified the manual transfer process within an aircraft as a difficult transfer environment. Identifying this fact alone was not enough. Higginson et al. conducted a biomechanics study of the manual transfer process that occurs on board an aircraft in hopes of quantifying the risks involved with that transfer [10]. The study involved the recording of the body movements of 33 pairs of healthy adult transferors as they transferred two sizes of anthropometric dummies in a simulated aircraft environment. These dummies represented a 50th percentile male passenger and 50th percentile female passenger. The movements of the transferors and dummies were recorded through the use of 74 reflective markers and an eight-camera motion capture system. Two force plates were also used to record the forces acting on each foot of the rear transferor, and an additional force plate was used to measure the compressive force between the seat back and the rear transferor’s right thigh. Additionally, an accelerometer was placed at the pelvis of each dummy in order to get an indication of the risk of injury to the passenger being transferred. The layout of the experimental setup is shown (Fig. 6), while pictures taken from actual experiment trials can be seen (Fig. 7) [10].
Fig. 6  Experimental layout of biomechanics study [10]

Fig. 7  Pictures from transfers performed during biomechanics study [10]
Results from the study revealed some interesting findings. First, when the front transferor has to work around a seat in front of the passenger, the risk of lower back injury to the front transferor more than doubles. The researchers estimated that, when transferring the large dummy under the constrained conditions of a simulated aircraft interior, the front and rear transferors respectively had a 89 percent and 100 percent probability of being at high risk of low-back injury [10]. Even for the best-case scenario of transferring the small dummy under unconstrained conditions, the probabilities of high risk of low back injury to the front and rear transferors was predicted to be 64 percent and 99 percent, respectively [10]. The risk of injury to the passenger appeared to be primarily linked to the individuals doing the transfer, thus reinforcing the need for proper training.

2.1.1.2 Transfers in Healthcare

The healthcare industry requires the frequent movement and transfer of patients. These transfers are typically done to move patients between beds, wheelchairs, toilets, sofa, etc. Even when a patient is not transferred to or from a bed, movements of the patient are still required to prevent them from developing bed sores. All of these transfers and movements are typically done manually, and put nurses at high risk of musculoskeletal disorders (MSD). In fact, nursing aids, orderlies, and attendants had the highest rate of MSD during 2007 with 252 incidences per 10,000 workers [13]. In 2002, incidence rates were 8.8 per 100 in hospital environments and 13.5 per 100 in nursing home settings [14]. These statistics are generally accepted as being low estimates due to underreporting being common within the nursing profession [14]. A survey done in 2001 at a Veterans Health Administration facility found that 62 percent of the direct patient care staff had at least moderately severe skeletal discomfort [15]. Another study done in 2002 found that 47 percent of Resident Nurses experienced back pain within the last year [15]. In
most other occupations, there has been a steady decline in the amount of work-related injuries since 1992. However, nursing is not one of those, as it has seen a steady rise in the rate of musculoskeletal disorders [14].

Research has been done to help initiate a movement for nurses to use assistive devices and implement “no-lift” policies. A two year study, done by the Patient Safety Research Center of the Veteran Affairs Medical Center in Tampa, Florida, shows some beneficial results. Through improved training of the nurses, the use of leading-edge equipment, and the implementation of a no-lift policy, there was an observed 31 percent decrease in the incidences of injuries [16]. An 88 percent decrease in the number of modified duty days was also observed while job satisfaction increased. There are economic benefits too. Taking the savings in medical costs and lost or restricted days and subtracting the annualized cost of equipment yielded a yearly savings of $127,812 [16]. This is a yearly savings value for the 23 high-risk units studied at 6 different Veteran Affairs Hospitals. When you start to look at the benefit of widespread implementation and long term savings, then the results are even more attractive.

A major source of injuries to nurses is the lifting they do, but even more key is the environment in which they lift. The old school of thought was that nurses that got injured were the ones that did not lift properly or who had weak backs [15]. A nurse’s lifting environment is seldom close to ideal due to having to lift around beds and chairs and such. Added to that, a human body is not an easy item to lift. There are no handles on a body, it is not rigid, extremities can easily move about, and there is high risk of damage to a patient if they are dropped. This creates a lifting environment that does not typically allow proper lifting posture. Other industries would not find it acceptable to allow workers to lift in an equivalent environment. The National Institute for Occupational Safety and Health has a hazard evaluation checklist for
determining risk factors of developing low back pain [17]. Five out of the nine general indicators easily apply to the lifting environment typically encountered by nurses. That is, the load often exceeds 50 pounds, the object is difficult to bring close to the body, the object lacks handles, the lifting task requires stressful body postures, and the task requires lifting in confined areas [17].

Patient transfers have been identified as a key reason the nursing profession experiences high risk of injury. The lifting done by nurses is not that much different than the lifting required to transfer a passenger with disabilities to an aircraft seat. Because of this, the research results for the nursing profession map across to this project well. By providing the transferors with an assistive device, it is expected that the risk of injury will be significantly lessened.

2.1.2 SureHands

There is an assistive device currently on the market which mimics the interface used by the manual transfer process. It is fittingly produced by a company named SureHands (Pine Island, NY, USA) and is called the Body Support. The Body Support mimics the manual transfer process by using paddles to grasp the transferee under the arms and by using thigh supports under the legs (Fig. 8).
A unique feature of the Body Support is that it applies a compressive force on the torso of the person in the device. The amount of force applied is proportional to the amount of weight that is applied to the thigh supports. That means that the only adjustment needed for its proper use is to ensure the thigh supports are properly positioned under the legs of the person being transferred. Another advantage of the Body Support is the fact that it does not require the transferee to be displaced in order for a lifting sling to be positioned under them. In fact, a person with disabilities
who has moderate control over their arms and hands, such as a low level quadriplegic, could position the paddles under their arms and the thigh supports under their legs independently.

There are a couple of disadvantages with the Body Support. One of these is the fact that a person without legs could not be lifted. It may be possible to still use the Body Support, but it would require the custom design and fabrication of a support that would extend under their body. Another drawback becomes prevalent in confined spaces. The Body Support requires overhead lifting, therefore, it is unusable in some environments. One such environment is that of the interior of an aircraft, as the overhead compartments invade the necessary space.

### 2.1.3 Sling Systems

A common method for performing assisted transfers is to employ a sling and an overhead lifting device. Slings, in and of themselves, do some things well. Depending on the design of the sling, they allow the person with disabilities to be securely supported over a large surface area, thus promoting a comfortable, safe-feeling environment. However, there are several drawbacks to using slings. In order for a sling to be used, it first has to be positioned under or around the person being transferred. This means the person with disabilities may need to be manually moved just to get the sling into place. The best case scenario is that the sling can be positioned around the person without requiring any lifting, but this still invades personal space and may make many people feel uncomfortable. Since slings need to be lifted from above, the potential for overhead clearance issues exists. The lift point for the sling is sometimes positioned in front of, or near, the transferee’s face, which can lead to a poor transfer experience and an increased risk of head injury. Because of the prevalence of the use of slings for transfers in health care and elsewhere, it is
not surprising that a couple of sling-based systems have been developed to aid in the boarding and deplaning of air travelers with disabilities. The aircraft-specific products from two manufactures will be presented below.

2.1.3.1 Haycomp (Products: Eagle 2 & Eagle 3)

Haycomp is an Australian-based company housed in The University of Adelaide Research Park in Thebarton, South Australia. Haycomp produces a variety of sling-based lift and transfer devices. Their aircraft passenger hoists are called the Eagle 2 and Eagle 3.

The Eagle 2 is a passenger hoist designed to transfer passengers from their wheelchair to the starboard aisle seats in larger aircraft and vice-versa (Fig. 9). The first step of the transfer to an aircraft seat requires positioning the sling around the passenger. Once the sling is in position, the lift frame is used to suspend the passenger. The suspended passenger is then moved to their assigned starboard aisle seat on the aircraft and lowered into position. Once seated in the aircraft, the sling needs to be removed to conclude the transfer. Deplaning requires the same process, but done in reverse. Haycomp only recommends the use of the Eagle 2 on board Boeing and Airbus aircraft equivalent to, or larger than, a Boeing 717 (also known as the MD-80). It uses electric actuation to lift and to extend its legs to add stability during the transfer from the wheelchair, and it has a working load limit of 440 pounds [18]. Disadvantages of this product include the need to position and remove a sling, the fact that the passenger is suspended during the whole transfer process, and that only starboard aircraft seats can be used for a transfer.
The Eagle 3 is a smaller version of an Eagle 2. This is necessary so that it can be used in smaller commuter aircraft. Haycomp does not provide any pictures or detailed information for the Eagle 3 on their website. They do state that the Eagle 3 has all of the same operating functions as the Eagle 2 [19].

2.1.3.2 Xpiration (Products: XPBoardingChair)

Xpiration, which is a Netherlands based company, produces a product called the XP BoardingChair. This product also uses a sling in conjunction with a lift system that has been integrated onto an aisle chair. A video on their website provides a demonstration of a passenger transfer [20]. For a transfer to an aircraft to occur, the sling first has to be positioned around the passenger. Once that is complete, the XP BoardingChair is brought into position alongside the wheelchair, its stability aids are deployed, and the sling is attached to the lifting arm. The passenger is then suspended and moved laterally until they are over the seat of the XP BoardingChair. Once the passenger is lowered onto the XP BoardingChair, the stability aids are retracted and the passenger is wheeled to the location of their assigned aircraft seat. The transfer is completed when the stability aids are again deployed, the passenger is lifted, moved laterally, and then lowered into their aircraft seat. The sling may then
be removed, the stability aids retracted, and the XP BoardingChair returned to the terminal. Some drawbacks are present in this system. Like all sling-based systems, an invasion of personal space is necessary for a transfer to occur. Also, the sling attaches to the lift arm in a location that is right in front of the passenger’s face (Fig. 10). This detracts from the passenger’s level of comfort and satisfaction with the transfer process. Any mistake or carelessness of the agent could easily result in an injury from the lift arm hitting the passenger’s head.

Fig. 10  XP BoardingChair being used to perform a transfer [20]
2.2 Alternative Transfer Methods

Many creative and innovative ideas have been developed for the transfer of people with disabilities. Numerous patents have been granted for original approaches to solving the transfer problem. In addition, NCAT has done much research on ways to improve the transfer process. This section will introduce some pertinent patents, then move on to give a summary of the work that has been done by NCAT.

2.2.1 Existing Patents

With the millions of patents that have been issued, there are many that contain ideas that relate to transferring people with disabilities. A subset of these patents deal with compact, mobile devices that could be used to transfer from a wheelchair. Findings of patent searches are presented below.

2.2.1.1 Mr. Jon Mast’s Patent Search

During Mast’s time researching with NCAT, he conducted a patent search for devices that he thought contained relevant ideas for transferring a person who is disabled onto an aircraft. Several patents were discovered that fit these qualifications. Sketches of the patented devices Mast uncovered are shown (Fig. 11-Fig. 16).

The Patient Transfer Apparatus, [21], contains some concepts that apply well to assist in the transfer of a person with disabilities (Fig. 11). One good feature is that the device is stand-alone. This helps to allow it to provide aid for transfers in a variety of different environments. The lifting column is an electric linear actuator, thus requiring no strenuous operator effort. The interface with the person who is disabled can be varied, as the device allows for the use of various types of slings, depending on the environment. However, slings still require some invasion of personal space to
be effectively used. Looking at how the Patient Transfer Apparatus would perform within the aircraft environment reveals some issues. First, since the device is stand-alone, it would either require the passenger to be placed onto an aisle chair, or the passenger would remain suspended during the entire boarding or deplaning procedure. Additionally, if the apparatus could fit onto an aircraft, it would require direct access to the front of the aircraft passenger seat to complete the transfer.

![Patient Transfer Apparatus](image)

**Fig. 11** Patient Transfer Apparatus [21]

Another patent Mast investigated is the Wheelchair Mounted Invalid Lift, [22], shown in Fig. 12. A unique feature that could be valuable in the aircraft environment is that the lifting device is integrated with a wheelchair. This would allow the
passenger to be seated as they are moved to their seat on board the aircraft. The Wheelchair Mounted Invalid Lift uses an electric winch to provide the lifting force for a transfer. Another notable feature of this device is that the overhead lift and forward stability support system allow the person with disabilities to be moved forward with relation to the chair. This extends the reach of the device and allows a transfer to occur. However, in the aircraft environment, the overhead lifting rails would likely interfere with the overhead bins in the passenger cabin and prohibit a successful transfer. Additionally, it does not allow means for a lateral transfer, so if the overhead bins did not create an interference issue, the device could only perform a transfer to aircraft seats which allowed access from the front.

Fig. 12  Wheelchair Mounted Invalid Lift [22]
The next patent presented is the Person Lifter/Rotator, [23], seen in Fig. 13. The main difference in this device is that the lifting mechanism has an added degree of freedom of rotation. That is, once a person is lifted, they can then be rotated through the use of the device, thus allowing the completion of the transfer. The variant in Fig. 13 is stand-alone, but the patent also includes a power chair alternative (Fig. 14).

Fig. 13  Person Lifter/Rotator [23]
Both variants of the Person Lifter/Rotator require the person with disabilities to possess a certain amount of upper and lower body strength and coordination; it is really more of a supportive device than a transfer device. Because of this, its current form would not be useful in the fully dependent aircraft transfer environment.

The Compact Portable Patient Lift, [24], is an extremely compact unit (Fig. 15). As the figure shows, it can be easily transported on the back of a wheelchair, but it serves as a stand-alone unit when in use. Again, because of the stand-alone capability, it can be used with a wide variety of wheelchairs. Another aspect of the device that differs from those previously presented is that, while it uses a sling to lift, the interface between the sling and the device is at the passenger’s chest region (Fig. 16).
Fig. 15  Compact Portable Patient Lift [24]

Fig. 16  Compact Portable Patient Lift in use [24]
The Compact Portable Patient Lift would work well with the overhead clearance constraints within an aircraft. However, there is no way the device could position a passenger into an aircraft seat without direct access to the front of the seat and, even then, the lower legs of the device would likely interfere with the aircraft seat. The fact that a sling is employed once again means personal space boundaries would be intruded upon. Additionally, the passenger would have to either remain suspended during the movement to and from their aircraft seat, or the passenger would have to be transferred to an aisle chair as an intermediate step.

**2.2.1.2 Mr. Sushim Koshti’s Patent Search**

Similar to the patent search Mast performed, Koshti also searched for patents containing insightful concepts. Several patents were discovered which differed from those revealed by Mast’s research. A summary of the patents discovered by Koshti is given in this section (Fig. 17–Fig. 21).

The Travel Insert Chair, [25], provides a straightforward solution for providing a means of transferring a passenger with disabilities to their assigned seat (Fig. 17). This device provides no assistance for lifting or transferring the person with disabilities into it, but it does provide a means for getting the passenger secured into their assigned seat. The main idea is that the passenger would remain in the chair throughout their trip. The chair would be positioned over the top of the normal passenger seat. This would mean less transfers would be necessary, as compared to the manual transfer process. Some shortcomings do exist. Maneuvering the passenger and the chair into position appears to still be a highly manual process which would require strenuous effort. Also, since seating is already cramped in aircraft, adding the additional bulk of a seat over the top of the normal passenger
seat seems far from ideal. The seat would need to be narrow enough to fit down the aisle of the aircraft, thus necessitating the seating surface to be narrow. Spending the entire flight on this narrow seating surface would be uncomfortable for the passenger and possibly create pressure sores.

Fig. 17 Travel Insert Chair and method of transporting the physically handicapped [25]

The Easy Transport Seat, [26], (Fig. 18) contains a concept much like the idea behind the previous patent. Its principle of operation is such that a passenger seat would be made removable so that it could be brought to the passenger, after which the passenger would be transferred into it. The seat together with the passenger would then be returned to the location where the seat may be once again secured into the vehicle. A transfer to and from the seat is required, and any assistance for that transfer would need to come from another device. Due to the narrow aisles within aircraft, this method would be difficult to accommodate without a highly
modified seat. In addition, this modified seat would be uncomfortable due to its narrow width.

![Fig. 18 Easy Transport Seat [26]](image)

The wheelchair and platform device, [27], provides a method of lateral movement for the seat and passenger (Fig. 19). The device does not provide any assistance for the transfer to and from itself, but it provides a way of making the transfer to and from an aircraft seat. The wheelchair seat of the device would be affixed with two tracks that would engage a matching track on a fixed seat, such as an aircraft seat. A transfer operation would proceed as follows. The passenger with disabilities would be transferred onto the device. The wheelchair and platform device would then be moved into position next to an assigned aircraft seat, which would also require modification to provide a mating track surface for the tracks on the bottom of the wheelchair seat. Once in position, the device would move its wheelchair seat laterally until the tracks under the wheelchair seat engaged into the
tracks on the aircraft seat. The wheelchair seat would then be secured into place, the lateral transfer platforms would be retracted, and the remaining part of the wheelchair removed from the aircraft. The main drawbacks of this system are that it requires aircraft seats to be modified, and that it does not provide any assistance for the transfer of the passenger to and from itself.

![Wheelchair and platform device](image)

Fig. 19  Wheelchair and platform device for movement of a disabled person from a wheelchair to a chair seat support in a vehicle and aircraft [27]

The patent illustrated in Fig. 20, [28], provides a method of lateral transfer for a passenger with disabilities to reach seats that are difficult for them to access, such as a window seat. Its main working concept is that of using expandable cushions and transfer board aids to bridge the gaps between the occupied location and the desired seat. This would allow lateral transfer with a sliding movement rather than a lift and swing movement. With a properly designed aisle chair, the transfer to an aircraft seat could be greatly simplified. The patent does not provide any aid for getting the passenger onto the aisle chair. Another thing to note is that considerable time would
be required to set up and remove the cushions and hard transfer devices. Also, because the passenger still has to be manually moved, an invasion of their personal space occurs.

![Fig. 20](image)

**Fig. 20** Method and means for assisting a person to, into, and out of a seat in a confined space [28]

The lift and transfer device, [29], has some unique features (Fig. 21). The device in the figure is a mobile device that has motorized lift arms and a motorized platform pivot. It is claimed that the device can lift a person from either the seated or lying down positions. It accomplishes this through the use of forearm support pads and hand grips, and an optional sling. Without the sling, the person with disabilities must have enough upper body strength to keep their shoulders above the forearm pads in order for the device to function properly. If the person does possess the necessary strength, then the device would seemingly allow them to perform a transfer
independently. However, if the person did not have the necessary strength, then the device could be hazardous, if not impossible, for them to operate. The unique aspect of the device is that it lifts the user to a standing position rather than using a seated position. Because of the risks involved if the user did not possess the necessary strength, this device would not be a good option for aircraft transfers. A more ideal solution for airline transfers would be a system that could accommodate the broadest range of disabilities. It is unclear if the use of the sling would allow the transfer of a person who is fully dependent.

Fig. 21  Lift and transfer apparatus for a disabled person [29]
2.2.1.3 Recent Patent Search

Due to the fact that several years have passed since the patent searches were carried out by Mast and Koshti, it was felt that another search for recently published patents was warranted. A search was done that focused on patents issued since 2006. A couple of patents were found that are very relevant to this work.

The Patient Lifting Device, [30], was invented by Simon Christopher Dornton Walker and provides a way to suspend a patient through the use of an overhead lifting point, a pair of side pads attached to a framework, and either leg or buttocks supports (Fig. 22). The side pads interface with the patient’s rib cage right under their arms. The leg or buttocks supports are attached to the framework in such a way that weight applied to the supports generates a squeeze force at the side pads of the device, thus securing the passenger. The whole device is mounted on pivots so that there is equilibrium between the moments generated by the patient’s weight supported by the side pads and the weight supported by leg or buttocks supports. This device interfaces with the patient in a simple way that is very similar to the interface used by a manual transfer. Because of this simple interface, it could be beneficial in an aircraft environment. However, the fact that the device relies upon an overhead lifting point means that overhead space constraints within the aircraft would likely make this device inoperable on board the aircraft.
The Patient Lift and Transfer Device and Method, [31], was invented by Jerome K Aarestad and provides a mobile platform from which a lift and transfer can be completed (Fig. 23). The device’s platform is a wheeled base onto which a telescoping lift column is attached. The support for the patient is composed of three items: a back support, torso support arms, and a leg support arm. The two torso support arms each have a pad that interfaces with the patient’s side right below their arms, and a support for the patient’s forearm to rest. The weight applied to the forearm supports creates a medially-directed squeeze force at the torso pads. This force is generated through the geometry of the arms and their pivots. Through the medially-directed force generated and the resulting friction between the pads and the patient’s torso, torso support is achieved. The leg support arm is designed to
interface with the passenger under their legs, near the knee. The whole device is designed to pivot in such a way as to allow transfers to be made between a bed and a wheelchair. Additional forms of the device are presented in the patent. One form is an adaptation for use with an overhead lift. The other form is essentially identical to the presented figures with the addition of a strap that extends beneath the patient’s upper thigh area (Fig. 24). The ends of the strap each attach to one of the torso pads. This arrangement of the additional strap would allow the device to be used on patients who were not able to support much force with their forearms. The strap would supply the necessary vertical loading to the torso support arms for the generation of the necessary medially-directed force.

Fig. 23  Patient Lift and Transfer Device and Method [31]
Fig. 24 Additional strap in use on the Patient Lift and Transfer Device [31]

The Patient Lift and Transfer Device uses some ingenuity to complete a mechanically assisted transfer through the use of a patient interface very similar to that used by the manual transfer process. The device allows lifting from below head-level of the passenger, which is a benefit to transfers in confined places, such as on an aircraft. The way the leg support and torso supports interface with the passenger appear to require the device to laterally slide into place to create the interface with the passenger. This means securing the passenger from various wheelchair designs or aircraft seats could prove challenging, as the armrests could restrict necessary movements. Also, to function within the aircraft environment, the device would need to be redesigned to account for the narrow aisle widths.

2.2.2 Previous NCAT Work

During the past five years, several graduate students completed research on new methods for performing transfers of people with disabilities. Wörz studied the lifting process necessary for a transfer to occur and developed several prototype
mechanical lifting devices. He also spent much time in developing a formal design layout for an aisle chair with an integrated transfer mechanism. Later, Mast took Wörz’s results from the lifting device research and continued it further. Mast was able to determine the force requirements for a comfortable and secure lift to occur [12]. Concurrent to Mast’s work, Koshti, performed research on the space constraints of a transfer onboard an aircraft. More specifically, Koshti investigated clearances with different lateral transfer and stability-aiding mechanisms [32]. A summary of the results from the research of these three individuals is presented below.

2.2.2.1 Mr. Ulrich Wörz’s Work

While he worked with NCAT, Wörz focused a large part of his research on developing a prototype of an aisle chair incorporating a mechanical lifting and transfer device. Wörz investigated the use of two different design methodologies for this project. This meant he spent much time in developing requirements and constraints for the design, which will be presented in section 3. For the rest of this section, the emphasis will be to present the research Wörz did on developing alternative transfer methods.

Through completing a comparison of design methodologies, Wörz generated a conceptual sketch of a potential solution (Fig. 25). The main points of the sketch show that a lifting interface with the passenger would be similar to the manual transfer process, thus meeting space constraints, and allowing for the flexibility to perform lavatory transfers. Because it would require less physical contact with the agents, it would also help to preserve the passenger’s dignity and independence.
Wörz realized the most difficult aspect of fleshing out the generated concept was going to be developing the portion that interfaces with and lifts the passenger. Because of this, his first efforts were turned towards developing a device that could perform a passenger lift. With the first generated concept in mind, he studied the manual transfer process, while paying particular attention to the interface the transferors had with the passenger. The primary interface was under the passenger’s arms, with another interface under the passenger’s legs. From these initial observations, Wörz developed his first prototype (Fig. 26).
Wörz’s first prototype was designed to be supported from above only to provide a convenient interface with a hoist used for testing in the NCAT laboratory. If the design proved successful, it could later be refined to be supported in a manner that would not interfere with space constraints in the aircraft. The device interfaced with the passenger at their axillae (armpits) through the use of curved and padded arms. The passenger’s feet were supported through the use of two flat plates.

After several tests, it was determined that about 80 percent to 90 percent of the passenger’s body weight was being supported by the interface at their axillae. This was very uncomfortable for the passenger. In fact, one test subject reported bruising. In addition to being uncomfortable, it was realized that people with poor shoulder joint health could actually be at risk of shoulder joint dislocation. These results prompted a more thorough investigation of the manual transfer process. Upon
reinvestigation, it was determined that about 70 percent of a passenger’s body weight would be supported by the axillae if the support for the legs was moved from the feet to a position under the thigh to more accurately mimic the manual transfer interface. However, the most important discovery was that the rear transfer assistant, lifting under the arms of the person with disabilities, applied a “squeeze” force while simultaneously applying the lifting force.

The realization that a medially-directed force was exerted on the torso of a person during lifting led to a fresh look at commercially available lifting solutions. It was at this point that a company named SureHands was discovered. A SureHands Body Support was purchased and tested in the NCAT laboratory (Fig. 8). This commercially-available lift functioned around the concept of incorporating a medially-directed “squeeze” force when lifting a person with disabilities. While the tests revealed a comfortable and secure lifting interface, the SureHands Body Support was too large to be used natively within the aircraft environment. Because of this, Wörz developed a device that allowed a similar lifting interface as the SureHands unit, while also accommodating space restrictions and reducing overall cost. Wörz approached the new design challenge by generating a table of working principles that could potentially provide a solution to the challenge. This table was separated out into solutions that were purely mechanically activated, like the Body Support, and those that were hydraulically or pneumatically activated (Fig. 27).
<table>
<thead>
<tr>
<th>Solution principle</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Central pivot</td>
<td>two pivot</td>
<td>spine</td>
<td>guide rail with slope</td>
<td>guide rail with slope</td>
</tr>
<tr>
<td>B</td>
<td>Hydraulic/Pneumatic</td>
<td>high-centre (cylinder)</td>
<td>high-centre (cylinder)</td>
<td>separate cylinder</td>
<td>separate cylinder</td>
</tr>
</tbody>
</table>

Fig. 27 Matrix of working principles [33]
After weighing the pros and cons of each alternative, Wörz selected solution A1 as the second prototype. A statics analysis was done to try to determine the proportion of squeeze force that was generated by the SureHands Body Support device. His analysis showed the squeeze force at a lift arm to be about 86 percent of the vertical force on that arm. It was later discovered by Mast that these figures were not realistic. Nonetheless, Wörz was able to take his calculated data and develop the second lifting prototype (Fig. 28, Fig. 29).

Fig. 28 Conceptual Sketch of Wörz’s second prototype [33]
This second prototype allowed the pivot to be placed in a location where it could be supported from either above or below. A physical prototype was built to prove this concept worked (Fig. 29). It again was supported from above in order to take advantage of a hydraulic lift in the NCAT laboratory.

Fig. 29  Wörz suspended in his second prototype [33]

Testing of this second prototype revealed an experience similar to what was provided by SureHands Body Support. The lifting process was more comfortable and possessed much less risk of injury to the person being lifted than the first prototype.
The amount of horizontal squeeze force was proportional to the amount of vertical force placed on the leg supports.

There were still some drawbacks to the second prototype. As the torso width of the person varied, so would the proportion of squeeze force generated. A narrow person would not experience the same proportion of squeeze force as a wide person. Also, as the torso width varied, the angle of contact between the paddles and the torso changed significantly. This would require adjustment of the paddles for each different torso width. Another concern was the position of the pivot of the device. It appeared the pivot was not displaced very far above a seated person’s center of mass. This would mean there was a chance the device could rotate over and dump the person on the ground. This risk would be greatest for a narrow, short person, as the paddles would be higher relative to the pivot point, thus making it more difficult to keep their center of gravity a safe distance below the pivot of the device. A person with a higher center of gravity would also be more prone to tipping. The case of a person without legs would not allow any lifting to occur without a different securement apparatus in place of the leg supports.

2.2.2.2 Mr. Jon Mast’s Work

Mast worked with NCAT after Wörz had completed his work on developing the first two lifting prototypes. Mast looked at the results from the first two prototypes and took steps to push the research further. Mast worked to develop a third prototype that incorporated the findings from Wörz’s research with design elements from the SureHands Body Support. Like Wörz, Mast wanted to be able to apply a medially-directed squeeze force while lifting, and enable lifting from below the head-level of the passenger. Additionally, Mast wanted to start taking the transfer process into consideration within the design of the device. In an effort to include this
direction in the research, Mast added the goal of developing a system that would allow a considerable degree of freedom for positioning a passenger. These design goals led to a third prototype that consisted of two horizontal arms that allowed the application of combined vertical and medially-directed forces to the torso of the passenger. The lifting mechanism was attached to a fixed vertical column by two horizontally articulating links. The theory behind this arrangement was that it could provide the necessary horizontal degrees of freedom to perform a transfer. A wooden proof-of-concept was built for preliminary physical testing of spatial requirements (Fig. 30).

Fig. 30  Proof of concept for horizontally articulating links [12]
Testing of the interface of the wooden proof-of-concept with aircraft seats showed promising results. Steps were then taken to construct the third prototype out of metal so that testing of actual transfers could be done. This metal rendition initially used a hydraulic jack to provide the vertical lifting force. The articulated arm also included a three link design, as opposed to the two link design of the wooden model. The third link was added to ensure adequate movement was possible to complete a transfer to and from a wheelchair and an aircraft seat. This was the first NCAT prototype capable of performing both lift and transfer movements (Fig. 31).
The pads on the ends of the horizontal lift and squeeze arms were borrowed from the SureHands device, as were the leg supports. The leg supports were attached to a strap system that was responsible for generating the squeeze force. This strap system used the weight on the leg supports to create tension in a strap that was converted to a medially-directed force at the paddles (Fig. 32). Ideally, the medially-directed force generated was proportional to the force exerted on the leg supports by the weight of the passenger.

Fig. 32  Strap system used for generating medially-directed force [12]

Testing showed that the strap system and horizontally articulated arm worked. This same testing also raised questions regarding the magnitude of the medially-
directed force being applied to the passenger. At that point, the targeted squeeze force was the result of a static analysis of the commercially available SureHands Body Support. There was no evidence this magnitude of force was ideal. Additionally, if a single magnitude of applied medially-directed force could result in a safe and comfortable transfer for all passengers, much complexity could be eliminated. Realizing this, Mast shifted his focus to setting up an experiment to determine what amount of medially-directed force was ideal, and if a single magnitude could satisfy all passenger transfers. To do this, an experimental setup was needed that could apply the lifting force and medially-directed squeeze force independently of each other. Also, the magnitude of the medially-directed force needed to be adjustable. Attaching the leg supports directly to the lift arms (without using the previous strap system) allowed for the decoupling of the forces. The challenge then became how to generate the medially-directed force. An initial idea involved the use of a cable and pulley system, but it soon became obvious a system of this type was going to become overly complex. Because of this, a pneumatic system was selected as the method for generating and varying the magnitude of the applied medially-directed force (Fig. 33).
The main goal of the testing was to determine how a passenger’s comfort was affected by the magnitude of the applied medially-directed force, while hopefully revealing a single magnitude that provided the most comfort for all passengers. Secondary goals were to determine the minimum magnitude of medially-directed force that would prevent the passenger from slipping while being lifted, and to determine if there was a correlation between comfort and stability. The experiment was set up. The magnitude of the medially-directed force applied to the passenger was variable from 0 pounds to 150 pounds. Mast’s static analysis of SureHands
showed it applied a medially-directed force of roughly 30 to 38 percent of the body weight of the occupant. Given these results, an applied squeeze force of 150 pounds would equate to a SureHands occupant weighing 395 pounds. This 150 pound medially-directed force was deemed adequate, while still falling safely below the 393 pound threshold for rib fracture in elderly people [12]. Using a discomfort and stability scale, results were recorded for all participants at various applied medially-directed force magnitudes. The results showed a distinct relationship between the discomfort of a passenger and the magnitude of the applied medially-directed force (Fig. 34).

Fig. 34  Average discomfort as related to average applied medially-directed force [12]
The results matched Mast’s hypothesis that comfort would improve as the applied medially-directed force was increased from the minimum value until the most comfortable force value was reached, then the comfort level would decrease as the medially-directed force was increased past the most comfortable value. The results from the test showed that participants were most comfortable when the applied medially-directed force was 46 percent of their body weight. It was also determined that the average minimum medially-directed force necessary to prevent slipping was 30 percent of their body weight [12].

Concurrent to developing and carrying out the medially-directed force testing, Mast also worked to take steps towards developing a prototype that would fit the spatial constraints of testing on board an aircraft. This meant the next prototype would have to be narrow enough to fit down the aisle of an aircraft. The approach taken was to integrate Mast’s prototype with an aisle chair (AisleMaster Foldable Transfer Chair 8020, Columbia Medical, Santa Fe Springs, CA). To help visualize all that was involved, Mast created another proof-of-concept by combining an existing aisle chair with the prior wooden proof-of-concept. These two elements were joined by a sliding base (Fig. 35). The sliding base was added with the hope it would allow the use of only two links instead of the three that were used in Mast’s first metal prototype.
Encouraging results were gained from coupling the wooden prototype to the aisle chair via a sliding base. However, a hole was revealed when looking at the next step necessary for the development of these concepts into a prototype capable of testing on board an aircraft. Mast’s metal prototype relied upon a vertical column, a sleeve that slid over that column, and a hydraulic jack. While this arrangement worked well for laboratory testing, it would be too cumbersome for aircraft testing. With this, Mast began researching commercially available components that could provide the same functionality. An electrically actuated telescoping column manufactured by X2 Technology in Växjö Sweden seemed to fit the bill. The column chosen was a D-M13
driven by a variable speed control powered by a 24 volt electrical system. This column was made to custom specifications so that it would provide the necessary control while still being able to support the moment and vertical loading required to perform a transfer. Mast then created a load-bearing sliding base for the previously-used aisle chair. This base was designed to interface with the X2 Technology telescoping column. The column, sliding base, and aisle chair combined together to make the beginnings of the next prototype suitable for aircraft testing (Fig. 36).

Fig. 36  Telescoping column mounted to sliding base of aisle chair [12]
This is where Mast concluded his research with NCAT. He successfully took Wörz’s work and made further progress towards creating a functioning device capable of performing a transfer on an aircraft. Mast’s research also put valuable information into play regarding the ideal magnitude of the medially-directed force for passengers of varying weight. This all provided a firm foundation for further work.

2.2.2.3 Mr. Sushim Koshti’s Work

Koshti performed research for NCAT concurrently with Mast. The focus of Koshti’s work was the investigation of the spatial constraints imposed by the interior of the aircraft. NCAT could only simulate the interior of the aircraft through the use of two rows of aircraft seats in a lab environment. This meant that much information was missing as compared to the actual aircraft environment, such as the limitations imposed by the overhead bins. Another missing element in the lab environment was that of an aircraft aisle. At least two additional sets of seats would have been required to begin to duplicate the environment of an aircraft aisle. These additional sets of seats would have been difficult to fit into NCAT’s lab space. Because of these limitations, and because of the impracticality of creating dozens of different physical prototypes for testing, Koshti used a software package called CATIA for his analysis. As mentioned before, CATIA is software that allows 3D modeling of parts while also providing the ability to perform many different types of analysis through different modules. Koshti used one of these modules within CATIA to perform kinematic analyses of the models he created. In this way, he could create different designs and test them within a modeled aircraft environment to gain an understanding of which designs best fit within the spatial constraints. In addition to testing designs, CATIA also has a module called Human Builder that allowed the incorporation of mannequins into the analysis. The Human Builder module coupled with the kinematic
analyses allowed Koshti to simulate transfers with mannequins of various body dimensions within the modeled aircraft environment.

The first step taken by Koshti was to create a model of the aircraft seats and of a representative interior of an aircraft body. The dimensions for the seats were obtained through measuring the aircraft seats in the NCAT lab. The dimensions for the interior of an aircraft were obtained directly from a drawing of a 737 on Boeing’s website. The aircraft seats and the aircraft body were then assembled to create a virtual aircraft environment (Fig. 37). The seats were arranged at a pitch of 32 inches while an aisle width of 21 inches was maintained. This virtual aircraft environment allowed realistic clearances with the seats and overhead bins to be monitored during simulated transfers.
The mannequin used for the simulated transfers was based upon a 90\textsuperscript{th} percentile American male. This mannequin, named Tony, was created in CATIA Human Builder. Human Builder also allowed the posture that Tony would assume for the transfer to be manipulated. The standard seated position was the chosen posture for the simulated transfers (Fig. 38).
Fig. 38  Tony in standing and seated positions [32]

With Tony and the aircraft environment modeled, the next step taken by Mr. Koshti involved the development of a 3D model of the transfer device. The primary model was based upon a two link articulating arm, similar to the wooden proof-of-concept created by Mast (Fig. 39). A secondary model was created by Koshti that used a single arm between the cross-arm and the vertical column, and that also included a sliding base. This secondary model was created to test the feasibility of keeping the articulating arm as simple as possible.
The 3D model of the transfer device is where the kinematic analysis gets its foundation. Through the use of CATIA’s DMU Kinematics module, joints were created at the interfaces of the various components of the 3D model. The types of joints created within the model were driven by the geometry of the model and the necessary degrees of freedom which allowed it to move as a physical prototype would. Then, by commanding a movement to a joint or a component of the model, the rest of the model would move within the constraints of the created joints. This is how Koshti controlled the simulation of the transfer. Geometry was created that provided a path for a point within the 3D model to follow, thus creating a path-of-transfer. The path-of-transfer consisted of three sections. First, a vertical segment
would direct the model to move itself and Tony up and out of the chair, as would be required during the lifting phase of the transfer. This vertical movement was made large enough so that Tony would clear the armrest of the aircraft seat during the lateral portion of the transfer process. Second, a horizontal line was created perpendicular to the aircraft aisle. This horizontal line would direct the portion of the transfer which took Tony from the middle of the aisle to a position above the aircraft seat. The final portion of the path-of-transfer was another vertical segment that lowered Tony into the aircraft seat (Fig. 40).
Fig. 40  Transfer sequence along the path-of-transfer [32]

With the ground work complete for performing a simulated transfer, Koshti was now able to turn his focus towards testing various configurations of the transfer device. Three components of the transfer device were targeted for this experiment.
These items were the paddles, arms, and supports for the base. The design requirements were to:

- Satisfactorily complete the transfer from the initial to final position
- Not generate any interference between critical components during a transfer
- Not obstruct movement of the transfer device along the aisle of the aircraft when it is being maneuvered into place
- Provide a large range of operation
- Allow a transfer towards either side of the transfer device
- Minimize the length of the paddles
- Use arm lengths capable of the required range of motion

The study of the components was done in a piecewise fashion. The first component focused on was the paddles. The base was positioned in such a way as to allow the transfer of Tony to occur with the use of an articulating arm consisting of two equal length 12 inch long arms. Three designs were tested, two of which provided acceptable results. The two successful designs are shown (Fig. 41).

Fig. 41 Configurations of paddle design 2 and paddle design 3 (left to right) [32]
The articulating arm was the second component to undergo experimentation. A total of six different arm design configurations were tested using paddle design 3 while varying the position of the base of the transfer device along the aisle of the aircraft. The position of the base was varied in order to determine the extreme positions at which a successful transfer could still occur. The difference between these extreme positions was calculated as the range of operation. Table 1 lists the arm length parameters used for each arm design configuration and the resulting range of operation. Fig. 42 shows an example of arm design configuration 1.

Table 1: Design Configurations for arms of transfer device [32]

<table>
<thead>
<tr>
<th>Arm Design</th>
<th>Link 1</th>
<th>Link 2</th>
<th>Range of Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12”</td>
<td>12”</td>
<td>8.2”</td>
</tr>
<tr>
<td>2</td>
<td>10”</td>
<td>12”</td>
<td>6.6”</td>
</tr>
<tr>
<td>3</td>
<td>8”</td>
<td>12”</td>
<td>4.9”</td>
</tr>
<tr>
<td>4</td>
<td>6”</td>
<td>12”</td>
<td>1.0”</td>
</tr>
<tr>
<td>5</td>
<td>20”</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>18”</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Arm designs 5 and 6 did not yield a range of operation. This is due to the fact that having only a single link necessitated the base of the transfer device to possess a sliding joint. Because of this sliding joint, the range of operation calculation lost all meaning as the column and link both had to move at the same time. Due to the increased complexity of operation stemming from the synchronized movement, the single arm models were not considered as design options of greater value than the two-link arm models. Koshti evaluated his results for the arm designs and concluded the best was design 2. Design 2 still provided an ample range of operation while allowing slightly smaller packaging.

Koshti went on to evaluate four different designs for the base support of the transfer device. The function of the base support is to prevent the transfer device from tipping when the passenger is extended to either side of the transfer device. Testing of the base supports was done independently of the arms or paddles, so the positioning of the base along the length of the aircraft aisle was arbitrary relative to a
transfer position. That is, the base was positioned at various locations along the aisle and the range of operation was calculated from those positions that allowed the deployment of the supports without generating interference. Each design had a different mode of operation for extension. There was a 4-bar mechanism, a vertical wing mechanism, a horizontal wing mechanism, and a telescoping mechanism (Fig. 43-Fig. 46).

![Diagram showing 4-Bar base support in collapsed and extended states](image)

Fig. 43 4-Bar base support in collapsed and extended states [32]
Fig. 44  Vertical wing base support [32]

Fig. 45  Horizontal wing base support [32]
Testing of the base supports revealed some good information. The 4-bar design had a range of operation of 2 inches, while the vertical wing mechanism had a range of operation twice that at 4 inches. The horizontal wing mechanism performed slightly better still with a range of operation of 5.7 inches. The telescoping mechanism had the best range of motion at 6 inches. From the results, Koshti concluded that telescoping mechanism was the best method of actuation for a base support to use. However, the result for the horizontal wing mechanism was close enough that it should not be ignored for future investigations.

In summary, Koshti’s testing led him to conclude the best configuration for the transfer device consisted of the bent paddle design with 14 inch long arms, a two-link articulating arm with link 1 being 10 inches long and link 2 being 12 inches long, and a base support consisting of a telescoping mechanism. The range of motion for the two-link arm was reported at 6.6 inches while the range of motion of the telescoping base support was listed at 6 inches. These ranges are similar to each other, which seems to indicate they would indeed be a good match without one hindering the operational potential of the other.
2.2.3 Current Design Direction

The work done by Wörz, Mast, and Koshti provided a foundation upon which recent design efforts were based. From their work, it is known that a medially-directed squeeze force is necessary during a transfer and the preferred magnitude of this force has been determined. The interfaces of several different designs have been evaluated within a simulated aircraft environment, thus providing valuable feedback as to which designs offer the best opportunities for a successful transfer.

The overall focus of the recent design efforts was to develop a prototype that melded all the prior research into a single functioning prototype. Within this focus, there were a couple of areas of specific emphasis. One area of emphasis was to develop and refine the mechanism responsible for delivering the vertical and medially-directed forces on the passenger. It was desired that these forces be generated in the correct proportion to each other in a simple way, without the need for adjustment for each passenger. Another area of emphasis was the development of a two-link articulating arm. Prior research showed unequal length arms to be beneficial, so this was the direction sought for further development efforts.

There was also a need for additional testing to be performed on the lift column and the base. While the manufacturer specifications for the lift column purchased from X2 Technology met the expected requirements, the behavior of the lift column at the limits of its specifications was not understood. That is, when the maximum moment loading of the column was reached, would the column cease to function in a smooth and controlled manner? How much power would the column consume during full load operation? What deflections could be expected from the column during maximum loading scenarios? All of these questions were important and needed to be answered. Because of this, testing the column was made a priority. A prototype, including a sliding base that was integrated with an existing aisle chair,
had been previously-constructed. However, no research had been done on determining what size of base would be able to negotiate the corners within an aircraft. Because of this unknown, this work also included physical testing on board an aircraft. The remainder of this document will present the work done to develop the prototype to the next phase.
3 PROTOTYPE DESIGN OBJECTIVES

The objective of this work was to bring the development of the transfer device prototype to a point where it could undergo physical testing within a simulated aircraft environment. This involved melding previous researchers’ work together with new observations to form a set of requirements that would be a foundation from which to build. The requirements used for this work are described in this section.

3.1 Project Goals

Background has been given on the previous work done by researchers at NCAT. Through this research, and familiarization with the areas in need of improvement, NCAT was able to generate overall goals for this project. Although previously presented in section 1.4, a review of the goals is given here. The overall goals of this project were to create a transfer device that would:

- Reduce the risk and occurrence of injury for the passenger and the transfer assistants
- Preserve the dignity of the passenger as much as possible
- Provide as much independence to the passenger as their situation allows
- Provide a solution that is simple to implement without requiring extensive training
- Provide a solution that requires less physical effort

Through creating a design that achieved these goals, it was believed the transfer experience could be greatly improved for both the passenger and the personnel assisting in the transfer. These overall goals were kept in mind as work was done to meet the objective of this work; to develop a prototype capable of performing a transfer on board an aircraft.
3.2 Customer Requirements

During Mr. Ulrich Wörz’s time spent researching at NCAT, he studied the requirements involved in designing an aisle chair with an integrated transfer device. This work by Wörz was the beginnings of the project upon which this thesis is based. He composed a report, titled “Designing an Aisle Chair,” which compared two design methodologies, Quality Function Deployment and the Systemic Approach [33]. In his research, he identified three main groups of customers for the aisle chair. These groups were passengers that used wheelchairs, the agents assisting in the use of the aisle chair, and the airline companies. Each group had their specific demands. The passengers desired comfort and safety, the agents looked for better ergonomics and less demanded effort required, and the airlines were concerned about costs and maintenance [33]. This grouping and delineation of demands has not changed. In fact, many of the customer requirements have remained constant and were mapped straight across from Wörz’s work. The customer requirements listed in his report were surveyed, and gave much insight for the design of the transfer device. The requirements that were found to be of significance for the current stage of the prototype included:

- Provide the ability to move the aisle chair close to the wheelchair and aircraft seat
- Provide easy adjustments to the passenger’s physical requirements
- Provide stability for the device and passenger in all positions
- Allow easy movement of the passenger
- Provide comfort to the passenger
- Allow easy movement of the device with the passenger onboard
- Minimize risk of injury for the passenger and agents
- Be able to maneuver from the jet bridge to the aisle of the aircraft
- Be able to fit within the aisle of the aircraft
3.3 Engineering Requirements

Engineering requirements were also generated by Wörz and detailed in his report. Much like the customer requirements, many were still extremely applicable to the recent development efforts of the transfer device. A survey of the engineering requirements was done and those of importance for the recent stage of development of the transfer device were recorded. They included:

- Minimize the distance required between the aisle chair and wheelchair, or aircraft seat
- Minimize the time required to adjust for the passenger’s physical requirements
- Minimize the amount of required force from the passenger
- Minimize the amount of required force from the agent
- Minimize the loading under the arms of the passenger (minimize slipping of paddles)
- Provide lateral stability for the chair during transit
- Minimize the turning radius
- Minimize the force required to overcome obstacles
- Minimize the length of the aisle chair
- Minimize the width of the aisle chair
- Maximize the ability for the aisle chair to track in a straight line
• Minimize the total size
• Minimize the number of agents required

The engineering requirements listed above were derived for use in the House of Quality. While not many of the requirements actually changed, many of the target values had shifted. This means the generic forms of the engineering requirements were most useful for the recent stages of design of the transfer device. However, some of the specific engineering requirements generated by Wörz had not shifted much. Three of these engineering requirements were required while two were imposed. With their original values, they included:

• Width of aisle chair = 15.2 inches (Required)
• Length of aisle chair = 32 inches (Required)
• Turning radius = 0 inches (Required)
• Time to adjust for passenger = 6 sec or less (Imposed)
• Number of agents required = 1 (Imposed)

The only requirement listed above that had shifted in a direction that did not match the generally desired direction was the length requirement. It was still desired for the length of the transfer device to be as short as possible, but the length of 32 inches seemed too constrictive. When Wörz developed the value of 32 inches, the mode of lifting the passenger was unknown. From simple observation of Mast’s sliding base prototype, it was expected that the minimum length of the transfer device would have to exceed 36 inches, but testing would reveal the true minimum value.
3.4 Design Constraints

Many of the engineering requirements gained from the previous work of researchers had values that had shifted. This made it important to understand the constraints imposed on the transfer device. A list was developed of the constraints that needed to be met by the transfer device in order for it to operate within an aircraft. These constraints were:

- Aisle width of the aircraft
- Room available to maneuver the transfer device from the jet bridge to the aisle of the aircraft
- Distance from the center of the aisle to the center of the aircraft seat
- Room available between the rows of aircraft seats
- Height of the overhead bins in the aircraft
- Maximum passenger weight of 300 pounds

The constraints had to be accounted for in order for the objective of this work to be fulfilled. They were brought together with the requirements listed above and the prior research to form design requirements for four components of the transfer device. These components were the lift column, the passenger interface, the links, and the base. The design constraints for each component are given below.

Column:

- Be able to lift a 300 pound person
- Not exhibit any sticky movement when loaded to its maximum applied moment rating
- Provide the ability for smooth and controlled movement at all times
• Not have deflections exceeding 0.5 inch at the maximum moment rating

*Passenger Interface:*

• Simple operation
• Apply a medially-directed squeeze force to the passenger of a magnitude of 46 percent of the passenger’s body weight
• Fit torso widths from 10 inches to 15 inches wide
• Have lift arms of compact length to allow fitment between rows of seats during transfers to aircraft seats
• Keep lift arms long enough so there is no interference between the passenger and support arm
• Support a 300 pound passenger with a factor of safety of 2

*Links:*

• Provide approximately 21 inches of lateral displacement to allow a transfer to an aircraft seat without generating any interference
• Support a 300 pound passenger with a factor of safety of 2
• Allow movement of the transfer device down the aisle of the aircraft without interference with the aircraft seats
• Provide free lateral movement of the suspended passenger without requiring strenuous force
• Provide a rigid support between the lift column and the passenger interface
• Not require additional lateral space to complete a transfer as compared to the space required during transport of a passenger

*Base:*

• Allow room for passengers to be seated without hitting the lift column with their knees
• Allow room for the passenger’s feet
• Provide necessary lateral stability for transport of the passenger to the aircraft seat
• Provide necessary maneuverability to navigate within the aircraft
• Provide good directional control of the device for easy positioning close to aircraft seats
• Have a width no greater than 15 inches
• Support a 300 pound passenger with a factor of safety of 2
• Allow the interface between the jet bridge and the aircraft to be safely and easily traversed

Within Wörz’s report, he presented a very detailed list of requirements and stepped through his creation of an extensive House of Quality. Due to the thoroughness of Wörz’s work, and because not many customer requirements or engineering requirements had changed, it was deemed redundant to create a whole new House of Quality for the transfer device. Referencing back to Wörz’s House of Quality, his generated requirements, and the work of Mast and Koshti, ample information was obtained to generate a list of design requirements for the components of the transfer device that would be subject to further developmental efforts.
4 METHODS

4.1 Overview

The work done to further the development of the prototype along the direction introduced in section 2 is presented here. The goals and constraints outlined in section 3 were taken into account as research was carried out. Work was done in a methodical way, so as to minimize rework and mistakes. A couple of observations were made throughout the development process. Steps taken to further a design were based upon information that had been validated. Sometimes this meant testing was necessary. Once information was gathered, then work was focused on development. Often, furthering the development of a component meant new questions were generated or new observations were made. Because of this, a trend developed. This trend was that of iteration. Every component of the prototype was developed using an iterative process. For instance, the final version of the passenger interface was the result of four revisions, while the final base link underwent six revisions. For the passenger interface, a physical prototype was needed in order to do testing to prove that the concept worked, after which some modifications were made for the final prototype. The revisions of the base link were based purely upon creating a 3D design in CATIA, running Finite Element Analysis (FEA), then analyzing what worked about the design and what did not work.

The paragraphs that follow describe the research and development work that was done on the four main components of the prototype. These components are the lifting column, the passenger interface, the links for the articulated arm, and the base of the device.
4.2 Column

The lift column previously chosen and purchased for the prototype had specifications which met the projected requirements that would be placed upon it. However, it was not known how the column performed at its limitations. This was important information. During a transfer, the passenger would have the best experience if all movements remained slow and controlled. Jerky movements would undermine the perception of safety and raise doubt about the quality of the device. Because of this concern, it was desired for the column to provide smooth movements at its rated loading. It was also desired for it to not have an excessive speed discrepancy between fully loaded extension and retraction, as would occur if rated loading was near the maximum capacity of the drive motor. Another item of question was the amount of deflection the column would exhibit when fully loaded. This was important to know, as an excessive bouncing motion at the end of the cantilevered arm would not provide a satisfactory transfer experience for the passenger. Given that the column is of a telescoping design, the amount of deflection exhibited by it could increase as the column is extended. Knowing how the deflection changed with extension could prove to be valuable information.

Given the consideration and concerns listed above, physical load testing was done on the column. The manufacturer’s specifications for the column listed its maximum vertical loading at 674 pounds and the maximum moment it could support at 1106 foot-pounds. The primary concern was the effect the applied moment could have on the column, as this was expected to be the primary type of loading that could cause the column to lose its ability to move in a smooth manner. It was decided to test the column at 50, 75, and 100 percent of its rated moment of 1106 foot-pounds (553, 829, and 1106 foot-pounds, respectively), with simultaneous vertical loading. To do this, a constant weight was used and the offset of that weight was
varied with respect to the vertical axis of the column. As a convenience, the weight used was a person of 253 pounds. This meant the person would have to be placed at 26.2, 39.3, and 52.5 inches to achieve the respective 50, 75, and 100 percent moment ratings. The vertical loading on the column would then be 253 pounds for each moment loading scenario.

Knowing how the column was going to be loaded was only one part of developing a test. The next task was to determine what measurements needed to be taken and how they were going to be made. Measurements of interest included times to extend and retract the column, angular and linear deflections of the column at various extension lengths, peak current draw during extension and retraction, and whether or not the column exhibited a sticking behavior. Simple observation, a stop watch, and an ammeter were required for determining most of the desired measurements. The measurements of angular and linear deflections at various extension lengths required the design of a test fixture (Fig. 47). The column base was mounted to two pieces of 4 inch by 4 inch dimensional lumber in such a way as to provide stability for the column to be positioned vertically. An additional piece of the 4 inch by 4 inch dimensional lumber was used at the top of the column in a cantilevered beam configuration so that the desired moment could be created. When considering the desired deflection measurements at the top of the column, the important point of reference was the base of the column. Because of this, the fixture used to obtain the deflection measurements had a portion that rigidly clamped directly to the base of the column and then extended beyond the top of the column along an axis parallel to the column’s axis. Care was taken so that this portion of the measurement fixture did not touch the dimensional lumber. A second part of the measurement fixture bolted securely to the top of the column and had a plate that extended about 8 inches downward towards the base of the column along a plane
parallel to the axis of the column. This upper portion of the measurement fixture also provided a way to secure the upper piece of dimensional lumber to the column. The vertical plate on the upper portion of the fixture provided a surface on which dial indicators could be mounted. The dial indicators were positioned in such a way so that they indicated off of the vertical tube of the lower portion of the fixture. This arrangement allowed the deflection of the top of the column to be measured relative to the column base (Fig. 47, Fig. 48). Two dial indicators were used so their relationship relative to each other could be used to calculate the angular displacement of the top of the column with respect to the column base.

Fig. 47  Column load testing fixture
With the fixture set up, the column was run through its length of travel and marks were made along the vertical portion of the lower measurement fixture to divide the column’s travel up into ten sections. During measurement runs, the readings of the dial indicators would be recorded at each one of these marks, thus totaling 11 measurements along the travel of the column. Before the loaded measurement runs were made, three unloaded runs were recorded so that a zero-load baseline could be determined for each dial indicator. With the baselines established, measurements
were taken for the moment loading scenarios. For each loading scenario, the column was additionally run though its full travel in a continuous manner so that values could be recorded for the time required to extend and retract, and for the maximum current draw during extension and retraction. During the runs for each scenario, observations were made that no signs of sticking behavior were exhibited. The results for the three loading scenarios are provided (Fig. 49-Fig. 52).

The results from the linear deflection measurements are shown (Fig. 49). The top dial indicator was positioned at a vertical location such that its point of measurement was as near as possible to the horizontal plane created by the top of the column. With it being set up in this fashion, the deflection reading of the top dial indicator was taken as the lateral deflection value of the column. The deflection was observed to increase as the extended height of the column was increased. The relationship between the linear deflection and the height of the column closely follows a second degree polynomial. This was expected, as the relationship for the deflection at the end of a cantilever beam with an applied moment at its end is also a second order relationship, $\delta_{MAX} = \frac{ML^2}{2EI}$ [34].
The angular deflection of the column was calculated from the linear deflection measurements of the two dial indicators. By knowing the offset between the two dial indicators, and having the zero-load baseline measurements, it was possible to calculate the angular deflection of the top of the column relative to the base of the column. The results of these calculations are presented (Fig. 50). Above a column height of 22 inches, it appears that a linear relationship exists for the angular deflection with respect to the column height. The general equation for the angular deflection of a cantilevered beam with an applied moment at its end predicts this relationship, $\theta = \frac{ML}{EI}$ [34]. At column heights below 22 inches, the data seems to exhibit some other trend, which is not fully understood. It is likely an artifact from the telescoping operation of the column.
The times recorded for the actuation of the column during extension and retraction did change as the loading was increased. The recorded times were put in a chart (Fig. 51). The difference in the times to extend and retract grew larger as the moment loading was increased, but the difference never became large enough to cause a concern. Recorded extension times appear to reveal a linearly increasing relationship with respect to the applied moment, while retraction times seem to show a slightly less prominent increasing relationship. The speed discrepancy between fully loaded extension and retraction was deemed acceptable, so no further work was done to verify the exact nature of these trends.
The maximum current drawn during extension and retraction of the column was deemed important information to know for the future sizing of the electrical system of the prototype. Measurements were taken with a multi-meter during full cycles of the column at the various moment loading scenarios (Fig. 52). While the manufacturer’s data sheet claims a standard lift column within the series of the unit being tested will not draw more than 10 amps, it was found that the column made to the custom specifications of NCAT drew a max current of over 17 amps during extension under an applied moment of 1106 foot-pounds. The current draw increased as the loading increased. It should be noted that the maximum current draws observed occurred as the column approached its maximum extension.
Because of this, using these values as design parameters would provide conservative calculations for the sizing of the electrical system. Because of the design of the drive system, there was no current draw to hold the column in place when under load. Another note made was that the current draw for extension and collapse would converge at some loading scenario higher than 1106 foot-pounds. This converging trend reveals that at high loading, the friction generated within the column requires more force from the drive motor than the force needed to purely lift the weight. Speculation indicates that if the current draw ever became equal for extension and collapse of the column, then the column would be in a seized state and not be able to move at all. This is because, in theory, the only way for current draw to be equal is for the load on the motor to be equal, thus necessitating the stall condition.

![Graph](Fig. 52 Maximum current measurements from column testing)
The testing of the column answered the questions generated and provided verification that the column was capable of providing a lifting environment suitable for a good transfer experience. During all loading scenarios, the column remained smooth and quiet in operation. There were no jerky movements observed, and fine control of the column was easily achieved. The maximum horizontal linear displacement recorded was 0.105 inches, while the maximum angular displacement was calculated at 0.372 degrees. Both of these were at full extension of the column with an applied moment of 1106 foot-pounds and a 253 pound vertical load. These deflections were impressively small and well within acceptable ranges for the prototype. With an assumed length for the transfer arm of 36 inches, the maximum deflections of the column would result in movements at the end of the arm of 0.23 inches vertically and about 0.11 inches horizontally. In summary, the column from X2 Technology was revealed to be an excellent fit for the requirements generated by the transfer device.

4.3 Passenger Interface

The passenger interface consists of the part of the transfer device that is responsible for applying the medially-directed force on the passenger as it simultaneously delivers the lifting forces of the column to the passenger. Wörz and Mast both did work on developing prototypes of this component of the transfer device, as was presented in section 2 of this document. None of the prior results fully met what was desired in the design of the passenger interface, namely, applying the desired amount of medially-directed force to the passenger in a simple and secure way. Because of this, recent efforts on the passenger interface focused on
developing the device so that it could apply medially-directed force to a passenger without requiring large amounts of adjustment for each passenger.

4.3.1 Analysis

From Mast’s work, it was known that a passenger was most comfortable when being lifted with a paddle and leg support system when the paddles applied a medially-directed squeeze force to the torso of passenger. The ideal magnitude of this force was found to be 46 percent of their body weight. Mast’s testing apparatus used a pneumatic cylinder to generate the necessary force. A pneumatic system was a nice fit because it provided an adjustable force, as well as the ability to adjust how quickly the force was applied. It also allowed the force to be applied in a way that allowed cushioning. That is, if for some reason the passenger had to move slightly while in the device, such as for a deep breath, the pneumatic cylinder would allow that slight movement to occur. The drawback to using pneumatics on the mobile transfer device prototype was that it would require a pressurized air tank, an air compressor, or both. This added complexity and increased the chance of failure. A spring system was also considered for applying the medially-directed force. The difficulty with the spring was that the stretched length needed to be precisely controlled and adjusted to suit the needs of different passengers. A drawback of both the pneumatic and spring systems was that the body weight of the passenger needed to be known ahead of time in order for adjustments to be made to the device so that it generated the desired medially-directed force. The pneumatic system or a combination of an electronic linear actuator and a spring system could be set up to automatically adjust for a passenger’s weight. However, this would require miscellaneous sensors and a control system. The complexity and increased failure modes did not make this an attractive option.
Time was spent thinking about a way to mechanically generate a medially-directed force when a vertical force is applied. Thoughts were guided towards other devices that had some sort of similar characteristics. Through piecing together aspects of several different analogous devices, an initial concept was developed. This initial concept involved the use of a cam to guide the movement of the arms inward as they pivoted downward on spherical pivots. By developing the correct cam angle and pivot geometry, generating the appropriate amount of force was a feasible task. Upon calculation of the required arm lengths, it was realized that the room required for the design did not exist on the prototype transfer device. The passenger interface would be too large to complete a transfer to an aircraft seat. This meant heading back to the drawing board. The only important aspect of the cam design was that the arms were forced to move inward as they moved down. This same movement could be dictated through using angled cylindrical pivots. With this realization, calculations were done to determine the necessary angle of the pivots needed to generate the desired medially-directed force. Each arm of the transfer device supports half of the passenger’s body weight. The results for calculations with a 300 pound passenger are summarized (Fig. 53).
The next step of the analysis was to determine if enough lateral movement was available to accommodate flesh and rib deflections while still being able to supply the necessary medially-directed force on the torso of the passenger. Calculations were done for the geometry in Fig. 53. It was determined that for every inch each paddle was deflected downward, about 1.1 inches of lateral movement was generated. In other words, for an inch of vertical movement, the passenger would receive 2.2 inches of chest compression. Intuition said rib deflections would not be this great during a transfer, but research was done to verify this. A brief search revealed a section in a book about flail chest injuries. This type of injury is a life-threatening condition in which multiple ribs have been broken, possibly in multiple places. The book reported that research done on cadavers showed rib fractures occurring for
deflections of 3 inches and no rib fractures occurring with deflections under 2.3 inches [35]. While it appeared the loading configuration of the chest was significantly different than that generated by the passenger interface, the forces generated by the passenger interface would be well below what would generate a rib fracture in a normal person. The medially-directed force of 150 pounds being developed by the largest passenger was less than half of what Mast’s research uncovered as the critical rib fracture force of 393 pounds. This relationship implied that the passenger interface would likely be able to apply the necessary medially-directed force without requiring a large amount of vertical displacement of the paddles. This was enough information to continue on with development, but physical testing of the concept was necessary to prove the device would be capable of lifting a passenger in a satisfactory way.

The calculations (Fig. 53) were based upon all of the passenger’s weight being supported at a location at the center of the paddles. This was not entirely correct, as the leg supports would also be supporting some of the passenger’s weight, and these could not be hung from the center of the lift paddles. The leg straps were to be suspended from the tubes supporting the lift paddles. The position of the leg supports on the tubes was able to be varied, so the amount of force carried by the leg supports was also variable (as the location of the support on the leg changed in a corresponding way). The vertical force from the leg support also generated a medially-directed squeeze force, but this force was generated at a location away from the center of the paddles. Only a portion of the medially-directed force generated by the leg supports was delivered at the center of the paddles. This proportion was related by the distance from the point at which the force was generated (location of the leg support) to the pivot axis, and the distance from the center of the paddles to the pivot axis. If the force was generated at the pivot axis, no
amount of the force would be realized at the center of the paddles, while a force generated at the location of the center of the paddles would be completely transmitted to the paddles. Additionally, by varying the location of the leg supports, the magnitude of the vertical force carried by the leg supports would change, thus changing the magnitude of the medially-directed force generated. Because of the availability of a multitude of adjustments, and because of the complex interrelationships that existed between passengers of various sizes and leg supports at different positions, it was decided the best way to prove out the concept was to build and test it.

4.3.2 Design (Part 1)

With the concept generated and initial analysis showing promising results, attention was turned towards developing a physical prototype to prove out the concept. Simultaneous to this work, analysis was performed on the link lengths of the articulating arm and the sizing of the passenger interface. This was done to determine sizing parameters that would allow a transfer to an aircraft seat to occur without generating any interference. From the results of that analysis, the length of the lift arms of the passenger interface was set at 15.125 inches. Using this length and a design force of 600 pounds (a 300 pound passenger with a factor of safety of 2), calculations were done to determine the loading on the tubes supporting the lift paddles and on the bearings at the cylindrical pivot. Because of the nature of the concept of this device, it was necessary to minimize the friction at the cylindrical pivots. Because of this, bushings were not suitable. Looking at rolling element bearings revealed that cylindrical roller bearings or needle bearings were required to meet the loading requirements generated by the design force and the necessarily small packaging of the pivot. A vendor was identified that supplied bearings that met the size and loading requirements (NA4901 & NKXZ12, Misumi Group Inc., Tokyo).
The pivot joint design was completed with the use of a shoulder bolt as the pivot shaft. Bending was anticipated to be the largest mode of loading for the tubes supporting the lift paddles. Because of this, a bending analysis was done to size the tubes so they easily met the generated stresses. The outer diameter of the tubes supporting the lift paddles was the driving constraint on the minimum length of the cylindrical pivot, as the pivot bearing housing was going to be welded to the arm tube.

The next step was to develop the brackets that would supply a method for the arms to be attached to their support. Several considerations were accounted for during the design of the brackets. The prototype was designed to allow for adjustability of the various parameters that could need to be varied. One parameter that could require adjustment was the angle each of the lift arm pivots made with a vertical plane. The calculated angle for these pivots was 42 degrees from vertical. Accommodations were made to allow adjustment of about 15 degrees on either side of this value. Additionally, it was uncertain if the width between the pivots needed to be set at different values for different torso widths. It was convenient that the prototype Mast had developed for his medially-directed force testing could be disassembled to provide a simple tube interface for the new brackets. The brackets were then designed in such a way as to allow them to be mounted on the tube weldment of Mast’s prototype while providing a simple method for width adjustment. The design width between the pivots was set at 15 inches. The lift arms, brackets, and cross arm from Mast’s prototype were all modeled in CATIA (Fig. 54-Fig. 57).
Fig. 54  Assembly of passenger interface lift arm and support bracket

Fig. 55  Close-up of passenger interface pivot geometry
Fig. 56  Passenger interface pivot support bracket
Fig. 57  Assembly of first design of passenger interface
4.3.3 Finite Element Analysis

This first prototype of the passenger interface was designed to be significantly overbuilt, so little FEA was performed. The forces on the pivot mount bracket were rather large, with about 2,400 pounds being applied to each ear of the bracket that supported the shoulder bolt pivot. Preliminary (hand) calculations showed that 3/16 inch steel plate would be adequate for the design, but combined loading of the bracket did exist. Thus, FEA was used to validate the material selection. Loads of 2,400 pounds were applied to the ears supporting the pivots while restraints were added at the locations the bolts were to restrain the bracket. The results showed 3/16 inch steel plate to be feasible (Fig. 58).
4.3.4 Testing

The first prototype of the passenger interface designed to consider the results from Mast’s research was built (Fig. 59). The brackets were initially set at the calculated design angle of 42 degrees from vertical, and the leg supports were suspended from the lift arms. The paddles were clamped into the lift arms, and their rotation about the centerline of the lift arm tubes was chosen in such a way as to match the torso contour of most passengers.
Initial tests yielded favorable results. It was possible to complete a secure and comfortable lift with the new design. The SureHands Body Support was set up to allow an immediate comparison between the lifting devices. Initial comparisons indicated that a slightly greater amount of slipping occurred for the prototype as
compared to SureHands. Because of this, the angle of the pivots was increased from 42 degrees to a value of about 45 degrees. This small change was all that was required to seemingly equalize the amount of slipping felt in both the SureHands device and the prototype.

It was noticed that a person of wider torso width preferred the distance between the pivots to be increased by 2.5 inches to a value of 17.5 inches. This was primarily due to the angle the paddles made with the torso. The narrower distance between the pivots created a slightly awkward angle between the paddles and the torso, thus creating some slight pressure points. People of narrower torsos would not notice the pressure points, as the angle of the paddles changed enough to eliminate them. The deduction from this observation was that the lift arm tubes (extending from the pivots to the paddles) needed to be modified to include a bend in them. In this way, the original design spacing between the pivots could be maintained without generating pressure points for passengers of wider torso widths.

Another note made about the design was that the location of the leg supports along the passenger interface lift arms had a considerable effect on the amount of slipping experienced. Putting the leg supports right next to the pivots caused large amounts of slipping to occur, as was expected. Moving the leg supports back to about mid position on the lift arm tubes resulted in generally secure lifting. Moving the leg supports as far towards the paddles as possible resulted in no slipping being noticed at any time. This indicated that the leg support straps should be constrained so that they could only be positioned at a location somewhere between mid position on the lift arm tubes and the paddles.
With the adjustments made during testing, the passenger interface device was capable of performing comfortable and secure lifts that were comparable to those provided by the SureHands Body Support. Taking the information gathered from the testing, the design process was revisited to create a second version of the passenger interface.

4.3.5 Design (Part 2)

Overall, the first design of the passenger interface was a success. It was confirmed that the geometry was capable of a successful passenger lift. The testing done with the first passenger interface prototype revealed some areas that needed refinement. These findings were used for the second design iteration of the passenger interface. For this second iteration, attention was also turned towards creating a design that would integrate with the new designs for the links of the articulating arm.

While testing was being done on the first design of the passenger interface, work was also being done on developing a design for the links of the articulating arm. Once the links of the articulating arm were developed, work needed to be done to develop a new support arm for the passenger interface. This support arm needed to mesh with the design of the second link so that the necessary movements could be made without generating any interference. The first design iteration of the new support arm included a 1 inch diameter pivot shaft arranged in a cantilevered configuration. The design loads were applied at the locations the pivot mount brackets would interface with the support arm, and corresponded to supporting a 300 pound passenger with a factor of safety of 2. This meant that for each side of the support arm, a load of 1,817 pounds was applied horizontally to the top tube at an appropriate location, while a simultaneous vertical load of 300 pounds was applied
downward at the same location. Each side of the lower tube then received a loading of 1,817 pounds horizontally, at an appropriate location, in a direction opposite the corresponding load applied to the top tube. The necessary restraints were then applied to the spindle of the support arm. FEA testing of this design showed the shaft of the first design to not be adequate to support the forces generated by the passenger interface device (Fig. 60). Work was done to revise the support arm to include a hollow pivot shaft of 1.5 inch diameter. This resulted in a design capable of supporting the design loads (Fig. 61). The design of the second link was then revised to accommodate the larger bearings necessary for the increased shaft size.

Fig. 60  Von Mises stress from FEA of early revision of support arm
For the final revision of the support arm, the FEA analysis reported the maximum von Mises stress at just over 44,600 pounds per square inch. This value was slightly greater than what the material could support at yield, but careful inspection showed these maximum values occurred at the very end of a rigid seam welding connection property. The trade off of using this connection property is explained later in section 4.4.3. Since the rest of the support arm appeared to have stress levels of acceptable magnitude, the design was accepted as final.

The final design of the passenger interface support arm (Fig. 62) maintained the ability for the width between the lift arm pivots to be easily adjusted, as future testing could reveal a narrower width being necessary for thin passengers. This adjustability was provided through designing the support arm to provide a surface on which the support brackets could be slid.
As previously discussed, the passenger interface seemed to provide a better lifting experience when the angle of the pivots of the lift arms was set a couple of degrees farther from vertical than initially calculated. Having determined an angle that provided the desired results, it was now desired to make a set of support brackets that would hold the pivots of the lift arms at a fixed 45 degrees. Care was also taken to ensure the brackets would not interfere with the second link during transfer movements. The final design of the pivot support brackets met these desires while also supplying an interface that allowed easy sliding along the support arm (Fig. 63, Fig. 64).
As previously discussed, the first design of the passenger interface created some slight pressure points at the interface of the paddles with a wide passenger’s torso.
After a couple of iterations of the model of the arm in CATIA, a design was chosen that had a 7 degree bend in the arm near the interface of the lift arm with the paddle (Fig. 62). Analysis showed this amount of bend to help alleviate the pressure points for wide torsos while still accommodating thin passengers well. With this lift arm designed, assemblies could now be made between the lift arm, paddle, pivot mount, and support arm (Fig. 65, Fig. 66).

Fig. 65  Assembly of final design of passenger interface lift arm and support bracket
Fig. 66  Assembly of final design of passenger interface
4.4 Links

Research done by Koshti showed that an articulating arm consisting of two unequal length links performed well. The best option Koshti investigated was a length combination of a 10 inch link for the link extending from the column (base link) and a 12 inch link (second link) between the first link and the support arm of the passenger interface. Suggestions for further research made by Koshti were to investigate links of different lengths around the 10/12 (length of base link in inches/length of second link in inches) link configuration. This is where research was focused when developing a link configuration to connect the lifting column to the passenger interface.

4.4.1 Analysis

While Koshti used CATIA for his analysis of link lengths, it was felt that any further investigation for the link lengths needed to be done physically. Additionally, it was time to start bringing all the components of the transfer device together into one unit. As a first step in this process, some cardboard was used in conjunction with Mast’s sliding base prototype and the lift column. The cardboard was fashioned into rectangular pieces, which functioned as the links and the passenger interface. Holes were punched into the pieces of cardboard to create pivot points. An array of holes was made so that the links could be arranged at different lengths. Fishing line was cut into small lengths and tied through the holes in the cardboard to “pin” the links together. This cardboard mock-up was taped onto the top of the lift column. The lift column was fastened to Mast’s sliding base prototype. Through this arrangement, it was possible to get an idea of the physical layout of the transfer device.
The length of the sliding base was adjusted to a dimension that just allowed room for the legs of a passenger of 99\textsuperscript{th} percentile in height. With the base set at a given length, the aircraft seats were positioned as they would be within an aircraft. The cardboard link system was then used to test several different configurations of link lengths. Throughout the testing of the different links, the passenger interface remained constant. The length of the lift arms of the passenger interface were set at 16 inches and the distance between the pivots of the lift arms was 15 inches. The first link configuration tested was with a base link of 10 inches with a second link of 12 inches. The movement of this 10/12 link configuration was observed as a transfer was physically simulated with the cardboard link model between the transfer device and the aircraft seat. Pictures were taken at the beginning and ending positions of this simulated transfer with a passenger (Fig. 67).

![Cardboard link model testing of 10/12 link configuration (transfer device left, aircraft seat right)](image_url)

The support arm of the passenger interface had to overlap with the second link during a transfer. This can be seen from the right portion of Fig. 67. This fact was going to play a large role in determining the geometry that was feasible between the
passenger interface and the second link. Looking at the arrangement of the links when positioned at the aircraft seat, the cardboard link mock-up was adjusted to create 8/12 and 12/12 link configurations. The 8/12 link arrangement was just barely able to reach the aircraft seat in the fully extended position while the 12/12 link arrangement reached the aircraft seat with length to spare (Fig. 68).

![Fig. 68 Comparing 8/12 links to 12/12 links in aircraft seat](image)

The results from the 8/12 link configuration showed that the amount of reach that it could provide cut margins too short. The 12/12 configuration reached the aircraft seat fine, as did the 10/12 configuration. This is when another observation was made. When the cardboard links were positioned for a passenger seated in the transfer device, the links hung out a considerable distance towards the side of the aircraft opposite the direction of the transfer (Fig. 69). While it appeared that no interference would be generated during a transfer, this lateral hang out of the links would create a problem during the movement of the transfer device down the aisle of the aircraft.
If the links of the transfer device struck a seat of the aircraft during movement down the aisle of the aircraft, that impact would be transmitted back to the passenger. This would not promote a pleasant transfer experience or uphold a high level of safety. A shorter length for the base link would help to alleviate this potential clearance issue. Because of this, an 8/14 link arrangement was assembled with the cardboard mock-up (Fig. 70).
The 8/14 link arrangement provided an improvement for the aisle clearance issue during movement down the aisle. It also allowed adequate length for a transfer to the aircraft seat. The extra length of the second link allowed plenty of clearance with the passenger interface support arm and its pivots. The main concern with the 8/14 arrangement was the angle the base link made with respect to the column when the passenger was seated in the transfer device. The loading at the pivot of the base link was the highest of any of the pivots, and it was important to keep the device rigid under loaded conditions. This meant it was expected that a cantilevered spindle design for the base link pivot would not be acceptable. The pivot for the base link would need to be supported at both ends. This meant the base link would be limited in the amount it could pivot forward, away from the passenger. The amount the base link had to pivot forward was considerably more for the 8/14 configuration than it was for the 10/12 configuration. This meant the balance between link lengths would be somewhere between these configurations.

Having identified a couple of areas of potential interference issues, it was time to do a more thorough investigation of link lengths. After deriving the necessary
formulas and inputting them into Excel (Microsoft Corporation, USA), it was clear that a graphical tool would greatly help the study. The investigation needed to use a method that allowed quick and simple adjustments of the geometry to be made while conveying the results equally as well. It was decided to turn to CATIA for help in this investigation. A simpler process than full 3D Kinematic Analysis was desired. If the analysis stayed 2D, then everything could be done with a simple sketch within CATIA. Constraints could be made for items in a sketch so that the only degrees of freedom left were the ones desired for carrying out the analysis. In this way, links and pivot points within the sketch could be dragged around while the reference dimensions created would update their values on the fly. An example is provided of the sketch made within CATIA (Fig. 71). Through using the sketcher within CATIA as a 2D simulation tool, multiple variations of link length configurations could be quickly analyzed. It was from the combination of the information gained through these simulations and the cardboard mock-ups that the final link length geometry was selected.
Choosing link lengths involved making a set of compromises. The primary constraint was the combined overall length of the links. It was observed that a combined overall length of about 24 inches provided the necessary movement. Deciding how to split this combined length between the links was the challenging part. A shorter base link allowed less lateral hang out, thus minimizing the chance for...
the links to hit an aircraft seat during the transit of the transfer device. However, this short base link required a longer second link. This meant that the base link would have to pivot farther forward during the use of the transfer device. This would limit the options available for supporting the pivot of the base link so that it was not cantilevered. The lengths chosen of 9.125 inches and 13.2 inches, for the base link and second link respectively, were able to provide a good balance between compromises. Adequate clearance was given for travel and use in the aisle, while still providing room for the design of a rigid mount for connecting the base link to the column.

The chosen combination of link lengths allowed the passenger to be moved 21 inches laterally, while generating an overhang of about 9 inches when the device was transported down the aircraft aisle. The 9 inch lateral overhang would allow for clearance with the aircraft seats of the measured Boeing 737 of about 1.25 inches, assuming the transfer device was centered in the aircraft aisle. This clearance value would permit the use of a pivot with an outer diameter of about 2 inches between the base link and the second link. The clearance between this pivot and the aircraft seat would only slightly decrease (by about 0.1 inches) during the lateral movements of a transfer. It was important to note the change in the clearance between this pivot and the seat backs during a transfer. If this clearance was considerably reduced during a transfer, then a case could exist where the transfer device was brought to the specified position and secured for a transfer, but a transfer could not be completed due to the decreased clearance created during lateral movement of the passenger. This would result in the passenger having to be lowered back onto the transfer device so that it could be re-positioned to eliminate the interference issue. The repetitive and uncertain nature of this occurrence would undermine a pleasant transfer experience for the passenger. With the link geometry chosen, a transfer
could be performed so long as the transfer device was initially positioned without any clearance issues with the seat backs. This promoted the ease-of-use of the device, as the operator would not have to learn the intricate behavior of the device through training or trial and error.

Knowing the overall lengths desired for the links, it was now time to determine the loading being applied to each link and the pivots between the links. Loading was assumed to be 600 pounds, which accounted for a 300 pound passenger with a factor of safety of two. A time could exist when all the links and the passenger interface would be fully extended, even though this would not occur during typical operation. Nonetheless, the calculations were based upon the worst case scenario. The moments and vertical loading generated at each pivot were calculated. The moments generated were the important values because they were the primary factor in determining the loads applied to the pivot bearings. The results of the calculations can be found in Appendix A.

4.4.2 Design

With the geometry of the links chosen and the loading at the pivots known, it was time to begin the design work on the links (Fig. 72). The design work was primarily done in sequence. The logical place to start the design was at the base link. This link saw the greatest amount of loading. Also, its final geometry would influence the geometry of the mount between the base link and column and the geometry of the second link. After six design iterations, a design for the base link was reached and work shifted to the design of the second link and the base mount. The base mount did not undergo many revisions, as both mating components were already determined. However, the second link had to interface with the base link and the support arm of the passenger interface, so it required a total of five revisions before
the design met requirements. The design of the passenger interface support arm required several revisions as well, some of which drove the need to revise the design of the second link. While the design of the support arm was done after the second link, the work was previously presented in section 4.3.5.

Fig. 72 Model of articulating arm

*Base link:*

The base link supported the largest moment of any of the links. At its main pivot, the design moment was about 1873 foot-pounds. This design moment exceeded the specifications of the lift column, but it should be noted that the design loading included a factor of safety of two. The maximum specified operational loading of the base link would generate a moment of 936 foot-pounds, which was well within the column specifications.
From the analysis that had been done up to this point, it was known that the second link was going to have to be able to fold in tight next to the base link. This meant the base link was going to have to be designed to consist of a main tube for the support at the first pivot (the pivot at the column) with two arms supporting the second pivot (the pivot between the base link and the second link). With this configuration, the worse case loading scenario for the main tube of the base link was that of torsion (when the second link and passenger interface would be extended off to the side of the base link). This dictated a large diameter for the main tube of the base link. It was important for the vertical deflection at the paddles of the passenger interface device to be kept minimal. Because of the location of the base link, small deflections in it would be amplified to produce considerably larger deflections at the paddles. This is why it was important for the base link to be rigid. It was not known if a longer or shorter main pivot tube would minimize this deflection. It was known that a longer tube would have a larger angle of twist about its length for a given loading. However, a longer main pivot tube of the base link would allow the base link arms to have a greater spacing between them, thus lowering the force applied to their ends. This in turn lowered the torsional loading on the main pivot tube. A symbolic analysis of this relationship was performed, and it was found that the length of the pivot tube cancelled out of the equation. Taking this result, and looking at the relationship between the deflections at the paddles for a given deflection of the base link, it was found that a longer tube would provide better control over the deflection at the paddles. Also, a longer main pivot tube allowed room for the second link to collapse next to the base link. It also allowed for lower loading on the bearings. However, the drawback to a longer main pivot tube was that it made the design of the base mount more challenging. This was important to consider because a cantilevered spindle for the main pivot of the base link would have relatively large deformation under load. This created a set of balances between the designs for the base link, the second link,
and the base mount, and was the main driver for many of the design iterations of each component.

The first iterations of the base link focused around a sheet metal design for the arms of the base link. It was soon found that the thickness of material required was such that rectangular steel tubing became a good option. One design was even centered on using machined arms in hopes of creating a stiffer link. In the end, the design chosen for the base link used 2 inch by 3 inch rectangular steel tubing for the arms which would be cut and welded to a 3 inch diameter round steel tube that was sized just long enough to allow the second link to fold in tight (Fig. 73). This design was chosen because of its low manufacturing costs and because FEA showed it provided small amounts of deflection when under load. The FEA done will be presented in Section 4.4.3.
While the base link was undergoing its design iterations, thought was being put towards choosing what type of bearings would be selected for use in the link. It was essential that the articulating arm be free moving under load. Given the high loading of the link, a bushing configuration would have been a well-suited choice. However, there was concern that bushings would not allow the desired ease of movement. Calculations done for a bushing being considered showed that the torque required to
turn the bushing under the loading seen in the base link would be around 90 foot-pounds. This value was too high for manual movements of the links of the articulating arm. Because of this, attention was directed towards rolling element bearings. However, the loading was higher than the recommended limits of ball bearings of the right size. The final bearing selection was tapered roller bearings (LM29749/LM29710, The Timken Company, Canton, OH USA). These bearings could support the radial and thrust loads, while still allowing a large diameter shaft to be used. In addition, the tapered roller bearing could be adjusted to take out all free play at the pivot, while they also allowed for slight misalignment of the bearing bores in the ends of the base link’s main pivot tube. These bearings required seals, so the base link design was finalized for the selected bearing and corresponding seals.

Second link:

It was known that a large part of the loading seen by the second link during use would be torsion along its length. Also, it was known that the second link would have to fold up tight next to the base link. Calculations were performed to determine what shape of tube would be better suited for this environment. Calculations were made for round tube and square tube, each of a wall thickness of 0.1 inches and both having a maximum outside diameter or width of 3 inches. It was found that the square tube was stiffer. Square tubing was selected for use on the second link because of these facts, and because manufacturing would be simplified with square tubing.

Design work on the second link started at the interface with the base link. It was known that the pivot between the base link and the second link needed to be as small a diameter as possible to avoid creating interference with the aircraft seats. Several iterations were done in evaluating different pivot designs with different types of bearings. In the end, tapered roller bearings were again selected (L44643/L44610,
The Timken Company, Canton, OH USA). This allowed a shaft of large enough diameter to be used at the pivot while keeping the outer diameter of the housing at 2.25 inches, which was just under the 2.5 inch limit. Once again, the tapered roller bearings also allowed for slight misalignment of the bores in the bearing housing while still providing a means for creating a pivot without any free play.

Analysis showed that a 3 inch square tube would allow the link to nest tight enough to the base link to provide the desired movement. The design was then completed using steel tubing of this size. A couple of design iterations of the second link stemmed from the adjustment of the size of the bearings at the pivot for the passenger interface. The final bearing housing used for the passenger interface was constructed of a 3 inch diameter tube, which mated nicely with the square tube of the second link (Fig. 74).
Base mount:

The base mount was developed after the base link and second link were well defined. It was known that a large diameter pivot shaft within the base mount would be important for the rigidity of the articulating arm and passenger interface assembly. As an initial test, the design loading conditions were placed upon a 1.5 inch diameter hollow steel spindle which was supported at one end, much like a hub spindle of an automobile. The spindle showed severe deflection and yielding. Work was then done to develop a support for the top of the spindle. The base mount was bolted directly to the top of the column, so it made good sense to tie the support
system directly into the two rear bolts. As the spindle support was developed, care was taken to allow for the necessary movement of the base link. The final design of the base mount included four separate pieces which bolted together. This was done to allow for the use of an aluminum spindle, which would result in considerably easier manufacturing. Additionally, the 4 piece design allowed for the easy assembly of the base link with the base mount (Fig. 75).

Fig. 75 Model of base mount design
The assembled model of the base link, second link, base mount, and passenger interface were analyzed for the desired range of motion. Initial findings revealed some interference between the components throughout movement. Design modifications were done until the movements could satisfy the requirements of performing a transfer.

4.4.3 Finite Element Analysis

The FEA work done within CATIA on the links and the base mount is summarized here. Each component was modeled as an assembly of parts. Because of this, it was important to create the correct connections between these parts within the FEA analysis. The main types of connections made were rigid seam welding properties, fastened connection properties, bolt tightening connection properties, and contact connection properties. Actual bearings were not included in the FEA model, so virtual parts were used to mimic the interface of the bearing with the component. The virtual parts allowed for the forces to be transmitted to the part much the same way the bearings would transmit them. The components were then suitably restrained while the calculated loads were applied. Attention was paid to the maximum von Mises stress and maximum displacement of the final designs. Once the stresses and displacements fell within acceptable levels, attention was turned to mesh sizing. It was desired to achieve a mesh size for which small changes in size did not correspond to a considerable change in the results. In reality, the primary limiting factor for FEA model refinement was time and computing power. The analysis for the base mount was one of these instances. With over 307,000 mesh elements and numerous contact constraints coupled with bolt tightening connection properties, running an analysis became very time consuming. The focus of the work was to develop a prototype, not create a perfect FEA model, so once confidence was gained in the ability of a design to meet requirements, the focus was turned to other aspects of the design process.
It was noted that the rigid seam welding connection property seemed to generate regions of high stress concentrations in manners that would not always seem appropriate. It was concluded that the rigid approximation, while simple to set-up within the analysis, did not provide the most real-life results. When the rigid seam was placed in areas where the material was deforming elastically, small localized regions of high stress would appear at its boundaries. This was a trade off made by the simplicity of this type of connection. An investigation was made into using other types of seam weld connection properties, but none were successfully implemented. Because of this, designer intuition was needed to determine how much concern should be placed on high stress values generated near the rigid seam welding connections.

**Base Link:**

The base link was the first component to be designed. Several different iterations were run through FEA and compared to each other. The results for the deflections of the base link were then used in hand calculations to determine what the corresponding deflections would be at the paddles of the passenger interface. Even within the designs that provided acceptable von Mises stresses, the calculated deflections at the paddles varied from just over 0.41 inches to just under 0.23 inches. In this manner, much of the design of the base link was driven by controlling deflections rather than controlling stresses. FEA allowed various design configurations to be effectively compared. In this way, the design iterations and analysis cases for the base link were refined until an acceptable result was reached.

The final design iteration was subjected to two different loading scenarios. One scenario had the applied loads at the ends of the arm acting at 90 degree angles to the arms (Fig. 76). This was analogous to the second link making a 90 degree angle with the base link. The second loading scenario had loads applied along the axis of
the arms of the link, as if the second link was in line with the base link (Fig. 77). For both cases, the main pivot of the base link was restrained while loads were applied at the pivot where the second link would interface. The magnitude of the bearing loads applied were 2,697 pounds (based upon bearing spacing and the moment supported at that pivot), while a vertical load of 600 pounds was applied downward on the lower arm of the base link at the second link pivot area.

![Von Mises stress from FEA of base link in 90 degree loading](image)

Fig. 76  Von Mises stress from FEA of base link in 90 degree loading
It was apparent that the 90 degree loading scenario was the critical one to consider. This loading put the arms of the base link in bending and the main tube of the link in torsion. The maximum von Mises stress reported for this loading was just under 79,000 pounds per square inch. This value was well above the yield value, but it occurred in a region right at the boundary of the rigid seam welding connection property. From prior experience with analysis involving this type of connection property, these highly localized high stress regions did not generate large amounts of concern. The rest of the analysis looked well within the yield limits of the material, so this design was accepted as final.

Fig. 77  Von Mises stress from FEA of base link in 0 degree loading
Second Link:

The design of the second link was not as complex as the base link. FEA was primarily used as a tool for selecting the material thickness needed in the main tube. This tube saw loading scenarios of torsion and bending during the use of the transfer device, the proportions of which were related to the angle the passenger interface made with the second link. Analysis was done for both loading scenarios for the final design iteration of the second link (Fig. 78, Fig. 79). For both loading scenarios, the bearing loads used at the passenger interface pivot were 3,974 pounds (based upon bearing spacing and the moment supported at that pivot). A 600 pound vertical force was applied downward on an appropriate surface at the same pivot.

![Von Mises stress from FEA of second link in bending](image)

Fig. 78  Von Mises stress from FEA of second link in bending
Both loading scenarios of the second link provided acceptable results. The maximum von Mises stresses reported were well over the yield value of the material. These maximum stresses once again occurred in highly localized regions that were believed to be generated by boundaries of the rigid seam welding connection properties. The rest of the stress values appeared acceptable, so the design was accepted as final.

*Base Mount:*

The analysis of the base mount design took more work than those of the links. The base mount was composed of four separate sections. The connection properties between these sections had to be correctly set up before the FEA analysis would
generate any realistic results. Once the connection properties were set up, the final design iteration of the base mount was analyzed for three different loading scenarios. These scenarios corresponded to the loading created from all the links being extended straight (in line with each other) then positioned at three different orientations with respect to the main pivot of the base mount. The first loading scenario positioned the links rearward towards the seat of the transfer device at 0 degrees (straight away from the spindle support), the second straight off the side of the transfer device at 90 degrees, and the third angled forward at 135 degrees (up against the spindle support) (Fig. 80-Fig. 82). The bearing loads applied for each scenario had a magnitude of 3,745 pounds (based upon bearing spacing and the moment supported at that pivot). A vertical force of 600 pounds was applied on a suitable surface of the spindle of the base mount.
Fig. 80  Von Mises stress from FEA of base mount in 0 degree loading
Fig. 81  Von Mises stress from FEA of base mount in 90 degree loading
A high maximum value for the von Mises stress appeared in the 0 degree loading case. This is a result of the manner in which the base plate of the mount was constrained. The base plate was constrained by fixing the tapered surfaces where the flat socket head cap screws would secure it to the column. For the 0 degree loading, there was a bending moment generated at the base plate, which these small surfaces had to restrain. In reality, the top of the column would be there to support the base plate. Because of this, and because the regions of high stress were extremely
localized at the bolt head surfaces, these high von Mises values were not considered a concern. The loading scenarios for the 90 degree and 135 degree case contained good results, so the model of the base mount under analysis was accepted as final.

### 4.5 Base

Mast developed a sliding base prototype which integrated with an existing design of an aisle chair. The sliding base potentially served two purposes. First, if it was desired to test the functionality of a single link for the arm responsible for the lateral transfer of a passenger, then the sliding base could provide the additional movement necessary to complete the transfer. Secondly, the ability to adjust the length of the base provided a means for determining a base length which provided a good transfer experience with the two-link articulating arm design of the transfer device. However, the potential for considerable moment loading developed at the column created concern over the robustness of the sliding base. Physical testing of the sliding base was necessary to determine its viability as a platform for future development work of the transfer device.

The sliding base was designed to so the lift column could be mounted to it. Because of this, the best way to test the sliding base was to mount the column to it and load the column in a manner similar to what would occur during a transfer. The testing of the sliding base was carried out after the testing of the column, so some of the column test fixture was able to be used to generate the loading at the column (Fig. 83).
Once again, the loading was generated by placing a 253 pound person on the 4 inch by 4 inch dimensional lumber. It was estimated that 36 inches was the maximum distance the passenger could be extended from the column by the proposed transfer device. In an effort to duplicate this, the dimensional lumber was positioned in such a way that the 253 pound person could position themselves about 36 inches from the column.

Testing revealed a significant amount of deflection from the sliding base. This was due to a couple of reasons. First, the interface between the carriage and the track that it slid upon was not tight. Secondly, the supports for the carriage were positioned in such a way that the tracks and carriages were required to carry a combined vertical load and moment load. The moment loading was generated by the relationship between the supports for the carriages and the positions of the wheels.
The moment load coupled with the loose interface between the components of the slide produced a significant amount of play in the base. The measured amount of vertical play that a passenger would experience was approximately 1.5 inches and the rear wheels of the device were no longer in contact with the ground. There was a springy feel to the base when in this loaded condition. In fact, only moderate movement of the test person, which created dynamic loading, generated small amounts of localized yielding in the tracks. The yielding was primarily due to the moment being carried by the carriages and tracks. These results were not acceptable for a final prototype, but provisions could be made to use this setup for limited laboratory testing. For instance, blocks could be placed directly under the mounts for the carriages, thus eliminating the moment loading of the carriages and tracks and reducing the amount of deflection experienced by the passenger. The elimination of the moment loading would also prevent the localized yielding of the tracks.

A key function of the base is to provide the necessary mobility for the transfer device to maneuver into position within the confined space of the aircraft. While the size of the base is a key component of this functionality, the configuration of the wheels completes the rest of this equation. The wheel configuration of three sets of fixed wheels on the sliding base prototype only allowed straight-line motion, unless the base was lifted or the wheels were skidded across the ground. The final base of the prototype needs to allow easy maneuvering without requiring the use of strenuous forces. With this need in mind, research was done to determine what wheel configurations would allow the best maneuverability of the device.

As a beginning point for the investigation of wheel configurations, currently available aisle chairs were researched. The aisle chairs produced by Columbia Medical (Santa Fe Springs, CA) use three fixed sets of wheels (Fig. 2, Fig. 3). These aisle chairs were designed so that a maximum of only two sets of wheels could be in
contact with flat ground at any single point in time. This means that, through tipping the chair, there was a region where only one set of wheels made contact with the ground, thus allowing for easy turning of the aisle chair. This configuration is simple and effective, but can require moderate force from the operator to complete a turn. Given the prototype transfer device would be longer and heavier than Columbia’s aisle chairs, the amount of force required to perform a similar tip-to-turn movement could be increased. Also, there is a certain amount of uncertainty experienced by the passenger as the aisle chair tips beneath them. These aspects led future design considerations away from three sets of fixed wheels. Another commonly used onboard aisle chair, made by Innovint Aircraft Interiors (Hamburg, Germany), uses four caster wheels (Fig. 84). The four casters allow the chair to be easily positioned without any tipping movements. However, with a caster wheel at each corner, it can become challenging to get the chair to move in a straight line. The designers at Innovint thought of this when they added a swivel locking mechanism to one of the front casters. When the swivel lock is engaged, the caster behaves like a fixed wheel and it helps to guide the chair along a straight line. The wheel configuration of the Innovint aisle chair provided some good ideas for the base of the prototype transfer device.
The wheel configurations of other devices were also observed, and four were selected for further evaluation (Fig. 85). Items such as shopping and utility carts are commonplace in the world around us. From observations during use of these carts, some insight was gained. A configuration with a set of fixed wheels on one end of the cart and casters at the other can have two different behaviors during use. The two different behaviors depend on which end the cart is pushed from. Pushing from the end with the fixed wheels, such as a shopping cart, provides intuitive control of the cart. However, pushing the cart from the end with the caster wheels requires constant attention to keep the cart traveling in a true direction. Another drawback of
pushing from the end with the caster wheels is that if the cart gets too close to an obstacle, the only real way to maneuver away from it is to back up. This makes positioning the cart close to something a task that takes either careful attention or some patience. Carts with caster wheels at each corner were hard to keep moving in a straight direction, but were very maneuverable in a tight environment. Further research uncovered another wheel configuration. This configuration had a set of casters at the front and rear of the cart with a set of fixed wheels at the center. This configuration showed potential and seemed to provide a balance between control and maneuverability.

Insight was gained from careful evaluation of the different wheel configurations. For the confined spaces in which the prototype was required to move, having a four
caster wheel arrangement would be beneficial. However, navigating the straight narrow aisles of aircraft would be easier if there were fixed wheels on the base. Some options to achieve both were considered, such as lockable or steerable casters, but the increased complexity was a concern. There was also some concern over the lateral tipping stability of the base if it was only supported by four casters. To clarify this, an explanation of caster wheels needs to be given. The concern was primarily based upon the fact that casters do not turn about the center of their contact patch with the ground. There is an offset between the center of their contact patch and the vertical axis about which they are allowed to swivel (Fig. 86). This gives the caster wheel what is known as trail, and is responsible for helping to keep the caster from developing flutter. The drawback to trail is that it creates a larger swivel radius. Swivel radius is a measure of how much room a caster needs to pivot about its vertical axis. A caster with a larger swivel radius requires more room to pivot. Because of this, swivel radius is something that has to be paid attention to when designing the base for negotiating tight places. Positioning the caster wheels too wide or narrow may mean they will not have enough room to pivot 180 degrees when the direction of the base is reversed. This creates a trade-off between picking a large diameter caster wheel that allows easy movement of the transfer device, and picking a small enough diameter caster to meet packaging requirements.
This brings the discussion back to the concern over lateral stability of a narrow base supported by only four casters. The lateral stability of the base is dictated by its track width. The designed track width between the castors only provides an idea of the stability of the base if all the casters are pointing front-to-back. As soon as the base is pushed sideways, the casters shift their orientation. The lateral stability is now dictated by the interaction between the designed track width and the caster offset (Fig. 87).
The effective half-track width was an important variable to consider. The prototype transfer device has to traverse between the aircraft and the jet bridge. This interface is often not smooth, so a change in the stability of the device as it traverses this could prove disastrous. This realization was the main reason behind the choice to avoid using a four caster wheel configuration. The preferred configuration used a set of caster wheels front and rear with a set of fixed wheels near the center of the base. The fixed wheels near the center of the base would be in a position near the center of gravity and, thus, provide a consistency to the lateral stability of the device.

Having identified a wheel configuration that seemed favorable, the next step was to try it out. A wooden mock-up of the base of the prototype transfer device was developed from the best estimates of the final overall dimensions. The basis of the dimensional estimates stemmed from analysis of the sliding base prototype, the
cardboard links, and the passenger interface. This mock-up was constructed and outfitted with caster wheels at each corner and two fixed wheels just rear of its midpoint. The location of the fixed wheels would affect how the wooden mock-up would be able to maneuver. Because of this, it was necessary to get an approximate idea of where the fixed wheels would need to be located on the final prototype. Analysis showed that the fixed wheels needed to be offset rearward to give the passenger clearance for their feet while allowing room for an adequate wheel diameter. It was desired that the fixed wheels be of a diameter larger than 6 inches but smaller than 14 inches. The minimum size was put in place due to the desire for the device to roll easily and to lessen the effort required to traverse the interface between the jet bridge and the aircraft. The upper size limit was put in place due to the need for clearance room for the passenger’s feet. From observation, it was estimated that a wheel near 8 to 10 inches in diameter would provide a good balance between the constraints. The locations of the fixed wheels of the wooden mock-up were then based upon a wheel diameter of 8 to 10 inches. With the overall length dimension of the lower portion of the wooden mock-up being 38 inches, the axle centerline of the fixed wheels would be about 16 inches forward from the rearmost face. The overall width of the wooden mock-up was chosen at 14.25 inches. A full-width handle was constructed at the rear of the lower portion of the mock-up and extended upward to an overall height of about 37 inches and rearward of the lower portion of the base by about 5 inches, to give the mock-up an overall horizontal length of about 43 inches. The wooden base mock-up was constructed with these dimensions and tested on board a Boeing 737 (Fig. 88, Fig. 89). During the onboard testing, measurements of the aisle width were taken at several different heights (Appendix B). Minimum aisle widths in coach class were measured at 17 inches between the arm rests. Aisle width at floor-level was 19.5 inches with a distance of 20.5 inches being measured between the seat backs.
Fig. 88  Dimensions and configuration of base wooden mock-up

Fig. 89  Testing base wooden mock-up on board a Boeing 737
The wooden mock-up proved to be maneuverable enough to navigate the interior of the aircraft. The point of tightest clearance was in making the 90 degree turn when transitioning from the passenger entry at the galley of the aircraft to the aisle of the aircraft. Clearances at this point were around a couple of inches, so any device of a greater width or length would quickly run out of room to maneuver.

Another device was brought along for testing on the Boeing 737. The base from a Pride Mobility (Exeter, Pennsylvania USA) Go-Chair was of an overall width of 18.5 inches (Fig. 90). This was narrow enough that it was questioned if it fit down the aisleway without any modifications. Testing was done, and it was found to maneuver adequately down the aisle of the aircraft, which was about 19.5 inches wide at the level of the Go-Chair. Since the Go-Chair uses two 5 inch diameter casters at its front corners, particular attention was paid to how these casters interacted with the tight space constraints. There was not enough room for either caster to make an outboard swing between the seats; however, the casters could swing inboard when the direction of the Go-Chair was reversed. Also, the foot level aisle width of 19.5 inches only occurred between opposing rows of seats. The locations where passengers would walk between rows of seats were not constrained by this aisle width measurement. When the direction of the Go-Chair was reversed between rows of seats, the casters would either swing inboard, or begin to swing outboard until they hit the lower portion of the seats, at which point they slid along the seat until the opening between rows of seats was reached where they could then complete their rotation. However, given the design of the support arm of the casters, the position of the casters during reverse travel caused the overall width of the Go-Chair to increase by about 2 inches so that it would no longer fit down the aisle of the aircraft.
While first observation of the Go-Chair on board the aircraft seemed to indicate the track width of the casters may not be that important, some aspects should be noted about that environment. First, the weight on the casters of the Go-Chair was minimal, thus allowing the casters to easily slide along the seats until they could complete their swing when they reversed directions. Once additional weight was added to the device, sliding would not occur so easily. Secondly, since the width of the Go-Chair was so close to the width of the aisle, the angle the sliding casters made from the direction of travel was small. That is to say that not much force was being directed into the seats, but most of it was still being directed along the aisle. If the width of the Go-Chair was less, but still wide enough that interference between the casters and seats would exist, the casters would have rotated away from the direction of travel by a larger angle. This condition would be more likely to cause binding due to the increased amount of force being directed out towards the aircraft seats. These two factors combine to show the importance of choosing an appropriate caster track width for the prototype transfer device.
An analysis was done in Excel for a range of caster wheel sizes to aid in the selection process of the caster size and track width. While this analysis was started before the on board testing of the wooden mock-up and the Go-Chair was performed, the information gained from the testing provided valuable insight. Additions were made to the analysis to include the measurements taken from the aircraft and the specifications for a caster wheel that was liked for its unusual combination of quality and aesthetics. The desirable caster wheel was from a Pride Mobility Quantum Q610 powered wheelchair. Analysis showed the caster from the Q610 wheelchair would function well on the prototype transfer device at a design track width of about 10.5 inches. This track width would keep the overall width across the casters at 14 inches and would allow both casters to simultaneously swing outboard in the constricted portion of a Boeing 737 or equivalent aircraft. The lateral stability provided by these casters when they are positioned for lateral movement would be equivalent to a fix wheel track width of 6.5 inches. This equivalent track width is quite narrow, so the stability from the middle set of fixed wheels would be a very important aspect of the design. There is a possibility that only a single caster centered at the front and rear of the transfer device (rather than a pair of casters at each end) would be sufficient when combined with the set of fixed wheels near the center of the transfer device. However, analysis to determine the stability trade-offs of this wheel configuration was not done.

An observation of a hospital bed provided additional insight into maintaining stability and mobility of the transfer device. The hospital bed had the wheel configuration that was most desired for the transfer device. That is, there were a pair of casters at the front and rear of the bed, with a fixed set of wheels in the middle of the bed. The unique aspect of the bed was that the fixed set of wheels in the middle of the bed could be retracted so that they did not contact the floor. This capability
allowed the bed to be positioned with the use of the caster wheels in tight situations, while the fixed set of wheels in the middle provided directional stability when making trips down the halls of the hospital. This is exactly how the bed was used. This functionality could prove very beneficial for the prototype transfer device. However, testing would need to be done to determine the minimum limits on the effective track width of the caster wheels. It is likely that the 6.5 inch effective track width of the currently selected casters would prove too unstable, and casters with a smaller offset or casters of a smaller size would be required.
5  FINAL RESULTS

5.1  Column

A lift column was selected for use on the transfer device. It was a prototype configuration of a model DM13-400 built by X2 Technology. Testing was necessary to verify its operation met requirements. A fixture was designed and testing was done to measure the deflections of the column, its maximum current draw, time to extend and retract, and whether or not it could provide smooth operation under maximum loading. The maximum deflections measured at the column would only result in vertical movement of the passenger of about 0.23 inches. The maximum observed current draw was just over 17 amps and the times for actuation were around 12 seconds and 7 second for extension and retraction, respectively. Throughout the entire testing procedure, the column delivered consistently smooth operation with no signs of sticking. These results verified the column was well suited for use on the transfer device.

5.2  Passenger Interface and Links

The passenger interface, the links, and the base mount all had to interface with each other. Care was taken to perform the work in a methodical manner. The end result was an assembly of components that interfaced with each other to form a system capable of supporting a passenger during a transfer (Fig. 91, Fig. 92).
Fig. 91  Isometric view of assembly of passenger interface, links, and base mount
The passenger interface was developed around pivots that were set at an angle away from vertical so that a vertical force applied to the paddles on the lift arms would result in a proportional inward medially-directed force being generated. The angle of the pivots was set at 45 degrees from vertical, thus applying a medially-directed force on the passenger near the ideal value found by prior research. The distance from the pivot to the center of its corresponding paddle was set at 15.125 inches. The horizontal distance between the angled pivots for each side was designed
at 15 inches. To accommodate the broadest range of passengers, the lift arms of the passenger interface incorporated an inward bend of 7 degrees (Fig. 92). This bend allowed the paddles to interface with the passenger’s torso in a way that appeared to generate fewer pressure points.

The base link was designed with a length of 9.125 inches. This length was based upon analysis of generating the desired movements while not creating interference with the aircraft seats. The length of the second link was set at 13.2 inches. The length combination of the base link and second link allowed for lateral movement of the passenger to be approximately 21 inches within the context of a transfer on board an aircraft. The size of the tubes used for the base link and second link were based upon rigidly supporting a 300 pound passenger with a factor of safety of 2.

The base mount was the connection of the links to the lift column. Since small deflections of the main pivot of the links would be amplified at the location of the passenger, special consideration was made for creating a rigid design. The final configuration of the base mount incorporated a support for the top of the main pivot spindle to prevent the spindle from being cantilevered. The components of the base mount were shaped to eliminate any sharp corners in an effort to minimize the risk of injury from incidental bumps that could occur during use of the transfer device.

5.3 Base

The base was the component that linked the transfer device together into a single unit. Analysis done with the sliding base prototype, lift column, and cardboard mock-up for the links and passenger interface revealed the general overall dimensions required. Additional analysis of the sizing of caster wheels for use on the base was completed. While it was intuitive that large diameter caster wheels required more space to pivot, it was only upon further investigation that the realization was made
that caster wheel size also affected the stability of the transfer device during lateral movement. This stability issue, coupled with the difficulty of directing a cart with casters along a straight path, was the driving factor behind the choice of the wheel configuration. With the overall dimensions and wheel configuration determined (Fig. 88), a wooden base mock-up was constructed. This mock-up underwent testing on board a Boeing 737, and successfully navigated within the aircraft.
6 CONCLUSION

6.1 Overall Summary

Business and recreation in the modern day world often include air travel as their cornerstone. There are many areas which could be improved upon for air travelers with disabilities. One such area is the process of boarding and deplaning of passengers who are wheelchair bound. The typical method currently used involves an undignified manual transfer that exposes both the passenger and transferors to risk of injury.

Work by NCAT has been done to improve the transfer process through the use of a mechanically assisted transfer device. Careful study of the transfer process has allowed researchers to identify key aspects required for a successful transfer to occur. Additionally, a primary goal of the transfer device is for it to provide assistance while maintaining the dignity of the passenger. The resulting transfer device is of a design that interfaces with the passenger at their legs and upper torso, while reducing the need for the invasion of a passenger’s personal space. This device then assists in the transfer from the personal wheelchair to the aircraft seat and vice-versa.

Much information was presented in the previous sections on the development of the various components of the transfer device. The results from previous researchers were combined and new concepts and designs were created. From this, efforts were made to produce a unified prototype of a transfer device which was capable of providing a secure and comfortable transfer experience. The prototype was designed so it could be tested in the laboratory and on the aircraft. The work done to develop the prototype covered areas from analysis, to physical testing, to computer solid modeling, to FEA. Attention was paid to how each component would function with
the others to result in a single operational device. While strides were made in the right direction, the final build of the recent designs was not completed at the time of writing. Future work will be done on performing physical testing of the prototype within the environment for which it was designed.

Much of the development work done on the prototype can be applied to other fields which involve the transfers of people with disabilities. One such field is that of health care, where transfers commonly occur in confined spaces. Injuries to personnel performing the transfers could be greatly reduced through the use of an assistive device, while simultaneously providing an improved experience to the patient.

6.2 Limitations

While much testing and development was presented in this work, the results should not be taken as final. A complex environment is created by the interactions between the components of the device, the aircraft environment, and the users of the device. Care was taken to account for these, but that in no way replaces physical testing done within the actual environment. The limitations of this work primarily lay in the need for the transfer device to be constructed and tested within its intended environment by the intended users.

The passenger interface showed good results during its first testing. Changes were made and the updated design needs to undergo similar testing. Additionally, the testing done with the first passenger interface was not performed with the end users’ demographics. This fact alone could affect results and therefore necessitates future testing.

The analysis of the base, the wheel sizing, and the selection of the wheel configuration were highly subjective. While a mock-up was used for physical testing,
it did not have casters of the chosen size and in no way was it representative of the stability of the final transfer device. Additionally, no testing was done for the development of a stability system to be used during lateral transfers.

The FEA done was all based off of static loading. While fatigue life was thought of during the design phase, no work was done to complete any detailed fatigue calculations. Items of particular interest are the aluminum pivot spindles of the base link and the second link. With the stress values given from FEA, comparisons were made to various charts for the fatigue life of wrought aluminum alloys. From these comparisons, it was estimated that a fatigue life for the aluminum spindles were at a level which was acceptable for the purposes of the prototype. However, for the development of a final production design, work would need to be done to complete detailed fatigue calculations to establish inspection intervals of critical components that are not readily seen, such as the aluminum pivot spindles. Regular inspection of the regions of high stress in the other components would also be important to establish.

6.3 Suggestions for Future Work

The prototype needs to be manufactured and tested in its intended operating environment. To do this, research needs to be done to design and integrate a stability system with the base of the transfer device. Without a stability system, a passenger is not able to be suspended to the side of the device. To further take the device from a prototype to a finished design, thought needs to be put into a braking system for the main wheels of the base. Another idea mentioned that would be of value to investigate further would be to determine the practicality of making the fixed set of wheels of the base retractable in order to gain maneuverability. This would entail quantifying stability requirements for the transfer device while using caster wheels. It would also complicate the design of the braking system.
Investigation was not done on improving how the passenger is secured to the seat of the transfer device. Capturing the paddles at the sides of the passenger while they are seated in the device may provide a convenient method of passenger securement during transport. Additionally, when the lift arms of the passenger interface are not occupied, they currently droop. This is not an aesthetically pleasing demeanor for the arms, and could provide negative initial impressions of the device to the users. A system to maintain or return the lift arms to a given height when not in use could also prove beneficial for helping a passenger to interface with the paddles. Additionally, the same mechanism may be able to be used to generate a gentle squeeze force to supplement the force generated by the angled pivot geometry. If this is true, then there is potential that people missing all, or parts, of their legs could still be accommodated.
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BIBLIOGRAPHY (Continued)


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BIBLIOGRAPHY (Continued)


APPENDICES
Appendix A: Static Analysis of Links and Passenger Interface

Fig. 93 Static Analysis of links and passenger interface
Appendix B: Measurements from B-737

Table 2: Measured aisle widths from Boeing 737

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<th>Seatback (in)</th>
<th>Arms (in)</th>
<th>Floor (in)</th>
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<tr>
<td>First Class</td>
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<td>19.0</td>
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<td>Coach Class</td>
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<td>19.5</td>
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Table 3: Measured dimensions for food cart on Boeing 737

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<th>Length (in)</th>
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<th>Height (in)</th>
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<td>Food Cart</td>
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Table 4: Measured dimensions for food cart caster wheels

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<td>Food Cart Casters</td>
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Fig. 94  Measurements taken at boarding area on Boeing 737