COMPUTER-AIDED DESIGN & APPLICATIONS, 2015
VOL. 12, NO. S1, 48–55
http://dx.doi.org/10.1080/16864360.2015.1077074

Ergonomic design and analysis for portable assisted mobilization devices

Mauricio Garcia and Javier Garcia-Mendoza

New Mexico State University

ABSTRACT
The purpose of this investigation is to propose a novel approach for the assessment of ergonomics in the design of mobility devices targeted towards the 5^{th} and 95^{th} percentiles in size dimensions of the Brazilian population. The method delivers the optimal ergonomic specifications that eliminate injury risk, provide comfort, and reduce fatigue of users operating a mobility device in a high-density metropolis. These ranges and measurements have undergone a feasibility assessment with the use of Tecnomatix Jack software and the building of a prototype. The ergonomic design characteristics have been analyzed with a Quality Function Deployment (QFD) Matrix to evaluate their impact in the overall device's design and feasibility solutions have been generated with the use of the Theory of Inventive Problem Solving (TRIZ).

KEYWORDS
Mobility device; ergonomics; injury risk; comfort; feasibility

1. Introduction

This research project deals with the ergonomic design of a Portable Assisted Mobility Device (PAMD) to meet future transportation necessities. General Motors market analysis shows that by 2030, urban areas will hold more than 60% of the world's 8 billion people [3]. This would cause public infrastructure to flounder when accommodating transportation needs of people living in densely populated cities. This has lead to design alternative forms of mobility such as the PAMD, which consists of a small and lightweight electric powered vehicle that can be carried in a train, bus or even indoors by allowing it to fold like a carry-on bag. This would save the user time, and avoid metropolitan usual issues such as pollution or traffic jam.

The PAMD of the current research project should comply with a maximum weight of 35 lb and to be able to transport the one user at 15mph. However, when designing any transportation device, the manufacturer needs to take into consideration the safest possible correlation of the user and the vehicle, which could also be referred as ergonomics. Ergonomics, also called human engineering, has the goal to improve the quality of the product in order to achieve a successful injury free interaction between users and the machine, allowing the producer to keep and expand its demand. The importance of ergonomics in this scheme is to fit the PAMD to the person and not the person to the device, allowing the user to be comfortable and with a reduced risk of injury, while keeping the vehicle to be feasible and subject to manufacturing constraints of size (as small as possible), performance (speed limits), duration (battery-wise), and capability (folding and unfolding).

2. Design constraints

Focusing on the scheme of human factors, different parts of the PAMD were designed based on Brazilian anthropometric measurements provided by General Motors (GM). A system consisting of the handles, foot support, and seat components was constructed, in which these fitted the 5th to 95th percentile of the Brazilian population of both male and female population pools. Ergonomically, the PAMD accommodates these populations so that the shortest person can reach and the biggest person fits for both male and female populations, which can also be known as design for clearances. When folded, the PAMD had to conform to specific constraints, therefore the components' size and mechanisms were a major factor in the ergonomic design feasibility analysis.

The seat was designed to maximize comfort for prolonged time duration. Comfort is inevitably lost after a certain amount of time; it is desired to prolong that duration of comfort when the subject is sitting on the PAMD. The seat had to be wide enough to comfortably sit people at the top end of the 95th percentile and small enough (length) to accommodate those at the bottom of the 5th percentile. In order for this to be viable, the seat had to be wide enough to accommodate the ischial tuberosities, otherwise known as sit bones, of the biggest person on

CONTACT Mauricio Garcia maugm@nmsu.edu

the farthest end of the 95th percentile. Seat length, the distance from the lower back to the rear of the knee (measured while seated), must be extensive enough for the largest person to sit comfortably, but not excessive where there could exist chafing or rubbing on the back of the knee of the person with the shortest seat length within these percentiles. The material should be comfortable for extended use and thin enough to be able to fold within the PAMD. The seat folding mechanism will allow the seat to fold in the PAMD for its folded characteristic transportation.

The reach was defined as the horizontal distance from the back support to the handlebars with a specified 20-degree angle between the bicep area and trunk of the body and a specified angle of 120 degrees between the bicep and the forearm when the subject is positioned on the PAMD. Additional constraints include an assumed straight-back position when using the PAMD. The reach distance should enable the person with the smallest reach to be able to firmly grip the handlebars and should enable the largest person to sit comfortably without being restricted. All should be able to adhere to the ergonomic angles already discussed. These specifications enable the user to be ergonomically placed in the PAMD, without putting too much stress and strain on different areas of the arms, back, and shoulders. The PAMD will serve for prolonged use, thus the reach distance should be adequate, since the handlebars include the driving mechanism, i.e. throttle. The handlebars should also be made of sweat-resistant, wear-resistant material(s).

The feet are assumed to adopt a natural position on the PAMD. From literature, we have deemed the angle between the calf and the thigh, otherwise known as the knee angle, to be between the values of 95° and 120° [4]. The foot support should also be comfortable enough to fit the largest foot, but small enough to be appropriate for smaller foot sizes. Material is a significant consideration factor. The material should be comfortable and shaped for ergonomic use. It must also resist tear and wear, and the amount of material used has to be optimal so that not a lot of material is wasted but enough is used to support the foot while driving. The foot support must also be placed at an appropriate location for ergonomic use. The smallest person at the lower end of the 5th percentile must be able to reach the foot support from the current height of the seat and must be able to reach them horizontally by placing his or her feet in front of them without any problems. The largest person at the high end of the 95th percentile must have enough room to comfortably fit while adhering to these angle specifications for a comfortable ride. The person should not feel limited or constrained in any way.

The design of the PAMD should enable the adjustment of reach, vertical and horizontal seat-to-foot support, and vertical and horizontal seat-to-handlebar ranges in the following ways: the horizontal adjustment of the seat, the diagonal displacement of the handlebar stem, and the vertical displacement of the foot support.

3. Concept development and design

3.1. Handlebar

One of the first approaches taken to design the handlebars was for their design to be straight and short as possible due to the space constraint. This meant taking the forearm-forearm breadth of the largest person and taking that measurement as the maximum distance the handlebars would occupy horizontally. The ergonomic PAMD design was based on the Brazilian Anthropometric Measurements; the handlebar width was designed based on the forearm-forearm breadth from the female 5th percentile to the male 95th percentile; the handlebar diameter and grip was based off of the hand breath within these percentiles. It was decided that the material needed to have a relatively high coefficient of friction and be waterproof to account for sweating. The angle between the handlebars also needed to be considered. Ergonomically speaking, the wrists have to be in a straight position with any kind of gripping motion to avoid carpal tunnel damage. This angle was acquired from literature [1].

However, it was found that the initial angle of 124 degrees would still cause carpal tunnel damage due to the handlebar being turned (the throttle would be located on the handlebars). The proposed and final solution was to have an angle of 160 degrees between the handlebars, as can be observed in Fig. 1. When analyzed with the program Jack from Siemens Software, this angle was found to be in the ergonomic range to reduce the risk of carpal tunnel damage.

3.2. Foot support

The first design of the foot support was very similar to a vehicular gas pedal. This design included an arched curvature to fit the natural arch of the foot and a minimum length of 18 cm. This design was discarded due to a consensus that its manufacture would be difficult and would make the PAMD hard to fold. A second foot support design was created, which consisted of a full support with a length of 30.48 cm and width of 11.68 cm. This guaranteed enough space in the foot support for the largest foot to fit. An angle of 15 degrees to the horizontal was obtained to be ergonomic. A better alternative support was found when analyzing prototype cost and accessibility. The optimal foot support, which can

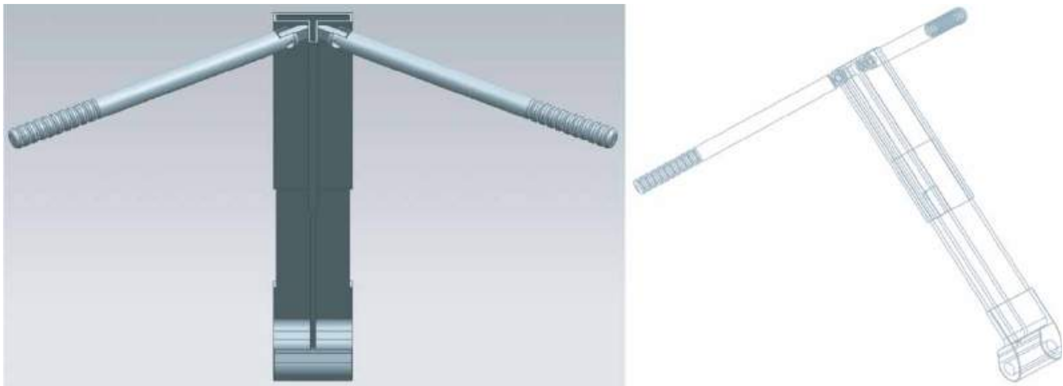

Figure 1. Handlebars NX 8.5 design (back and isometric views).

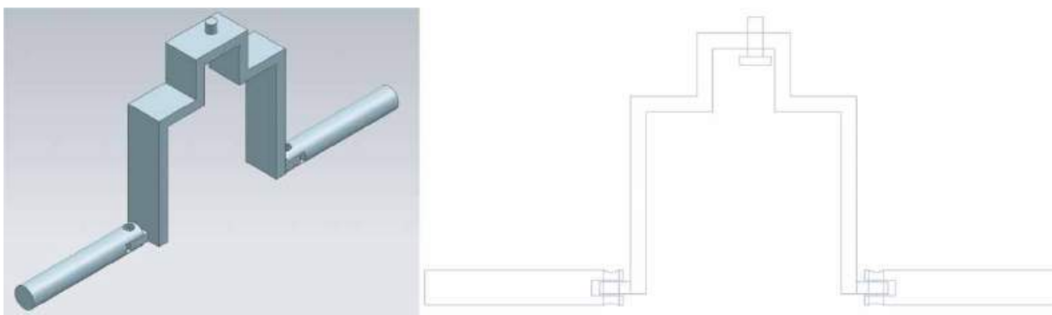

Figure 2. Feet Support NX 8.5 design (isometric and front views).

be observed in Fig. 2, consisted of a cylindrical shape with a minimum diameter of 2.54 cm and 11.43 cm long. This size foot peg is standard and readily available, consequently, labor costs and material costs are reduced. Moreover, this size foot peg is feasible within the folding mechanism of the foot support.

3.3. Seat

Ergonomic seats need to extend the duration of comfort for the user. A seat should be wide enough to accommodate the sit bones, or ischial tuberosities, of the person with the biggest hip breadth. The first design had dimensions of 51 cm long and 45 cm wide, utilizing the aforementioned anthropometric measurements. The first seat design considered a lumbar support at 95° acquired from literature, with width equivalent to that of the seat and 20 cm high. This seat was impractical due to high manufacturing costs and issues with its incorporation into the foldable design.

The problem identified consisted in fitting the thickness of the seat with the rest of the PAMD, when the device was folded Alternative designs were considered to account for these constraints and still have an ergonomic seat. One of the alternate designs consisted of a rectangular, cushioned seat, which consisted of two separate sections: memory foam and a mechanism to inflate and deflate the seat. Due to specifications, however, the previous designs were unfeasible by at least one reason. The dimensions for our final seat design included a minimum of 21.64 cm for width and a minimum of 27 cm for length [2]. These dimensions were determined from literature alongside the anthropometric measurements provided by GM, and the final seat design can be observed in Fig. 3.

3.4. Lumbar support

A lumbar support was initially added as part of the ergonomic design. This lumbar support would have an angle of 95° with the horizontal, which would ensure that the person would procure a very straight back while using the PAMD. The determined length would have been 20 cm, and it would have had a height of 20 cm. Due to manufacturing limitation, high production costs, and issues with its incorporation into the foldable design, its addition was considered impractical and unnecessary according to simulation comfort results.

4. Feasibility assessment

4.1. Technical feasibility

The PAMD contains physical constraints such as a maximum weight of 35 lbs., folding capability and unfolded

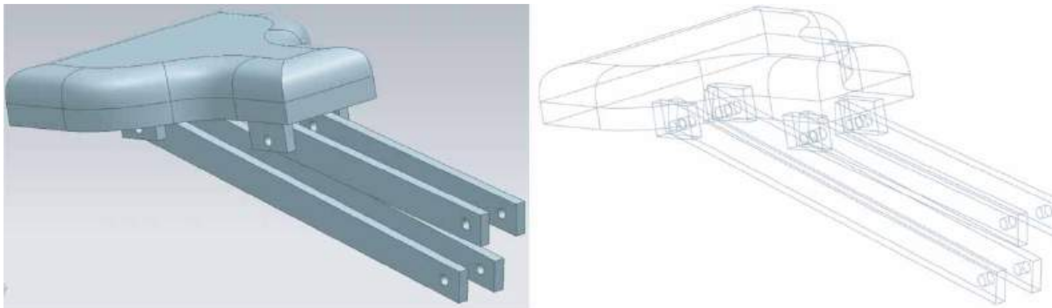

Figure 3. Seat NX 8.5 design (isometric views).

size limitations. The weight technical feasibility per part is the following:

- Lumbar support will not be incorporated for manufacturing feasibility.
- Seat weight ranges from 67 g/0.03 lb to 350 g/0.16 lb without metal parts.
- Round foot pegs account for a weight of 12 ounces.
- Handlebars weight will vary according to desired material for durability; an educated guess of 1 lb for the handles will be made.

The weight summary provides a result of 1.91 lb, which constitutes 5.45% of the overall possible weight. Thus leaving 94.55% for the rest of the components and, thus, being feasible. Regarding the foldable feasibility per part is the following:

- Foot pegs will be mounted in a rotational support that will allow them to become part of the frame.
- The handles will be mounted in a rotational support that will make them form part of the stem. Then the stem will have a telescopic-length-changing collapsing mechanism. Hence, the handles do not impede the folding property.

The different problems that have arisen have been solved with the help of a system of generated solutions called TRIZ methodology problem solving.

4.2. Evaluation criteria

The first method to evaluate the ergonomic criteria consisted of a Quality Function Deployment (QFD) matrix. With this method, the customer needs are rated by relevance and are related by their impact to the technical specifications to assess their priorities. After this, a correlation within the customer needs is done, as well as within all technical specifications. These correlations are compared while designing the features and are ranked by priorities. Non-important specifications will not affect features from higher importance if negatively correlated, since the relation will be demonstrated within the QFD matrix.

Some of the strongest parameters given by the QFD, as indicated by the costumer were: comfortable sitting, adjustability, accessibility, lightweight, folding easiness, speed control, easy to drive, injury free, and safe for riding.

5. Ranges and measurements

The optimal ergonomics measurements for the system's individual components distances (see Table 1) and adjustability ranges (see Table 2) for the overall system are the following:

Table 1. Optimal ergonomic angles and measurements.

	Handlebars	Carrying Handle	Foot Support (Cylindrical)	Lumbar Support (Not included)
Angle	124° to 160° (in between)	N/A	N/A	95°
Diameter	0.875″	0.875″	1″	N/A
Width	23.62″	N/A	N/A	N/A
Length	3.54″	3.54″	4.5″	7.87″

Table 2. Vertical to horizontal ranges given by angle.

Angle	Vertical Range	Horizontal Range	Ratio V/H*
95	5.49	4.76	1.1536
100	5.43	5.19	1.0468
105	5.32	5.60	0.9499
110	5.18	6.01	0.8612
115	5.00	6.41	0.7792
120	4.77	6.79	0.7028
125	4.52	7.15	0.6311
130	4.22	7.49	0.5634
135	3.90	7.81	0.4989

A seat horizontal/vertical range angle of 95° was chosen to be optimal, giving a vertical-to-horizontal ratio of 1.1536. The larger the number, the easier it is to adjust vertically compared to horizontally.

After having determined the appropriate distances and adjustability ranges a 1σ distances and adjustability ranges set was created to minimize cost in the prototype built. (see Fig. 4 and Table 3 for referencing).

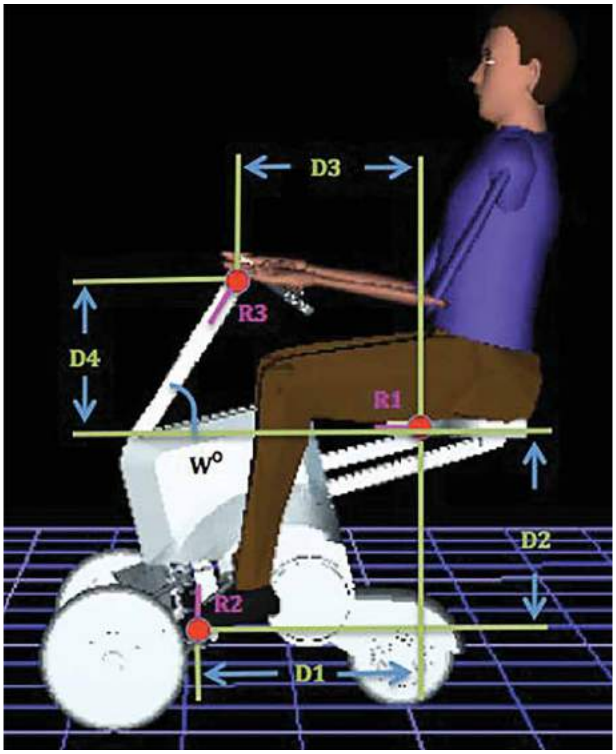

Figure 4. PAMD distance labeling.

Table 3. Optimal 1σ distances and ranges using a V/H 95° angle.

95°	Seat/Foot Peg		Seat/Handle	
Distance	Horizontal (D1) 26.33″	Vertical (D2) 18.83″	Horizontal (D3) 15.31″	Vertical (D4) 8.31″
Range	Seat (R1)	Foot Peg (R2)	Handle Horizontal	Handle Movement Down
	4.76″	5.49″	2.22″	1.38″
			Stem Angle (w)	Adjustability in Stem Angle (R3)
			31.88″	2.61″

After determining the optimal measurements and angles, the CAD model was successfully imported into Jack software for testing (see Fig. 5).

6. Simulation and testing

The human engineering software simulation was performed through a Siemens Human Simulation System named Tecnomatix Jack 7.1, which allows the creation of an ergonomic assessment for the user of the Portable Assisted Mobility Device (PAMD). Jack also allows the user to analyze and improve the safety, efficiency, and comfort of the individual in the system analyzed, as well as to include important parameters such as injury risk, user comfort, reachability, and fatigue limits.

The human avatar used for the analysis was created based on General Motors 2009 Global Anthropometric Data for Latin America (Argentina, Brazil, Chile), which included 28 different measurements from the 95th percentile of the Brazilian population. The subject named 'brazilian3' was created having a height of 1.762 m and a weight of 79.1 kg. The critical dimensions used from this data include the following:

- Acromion Height (143.8 cm): Measures the distance from the floor to the high point on the tip of the scapula where the bones of the shoulder complex meet.
- Bideltoid Breadth (49.0 cm): Measures between the most outward points of the skin off the deltoid muscles on the upper arms on a subject with their arms relaxed and their arms straight down at their sides.
- Buttock to Knee Length (62.0 cm): Measures horizontally from the most rearward point of the buttock to the most forward point on the knee of a subject seated on a horizontal surface with their thighs parallel and their lower leg aligned vertically.
- Elbow to Fingertip (47.0 cm): Measures horizontally from the rear of the curvature of the elbow to the middle finger tip on a subject with their hand and wrist straight and their lower arm in a horizontal orientation.
- Shoulder Elbow (37.7 cm): Measures vertically from the acromion landmark to the bottom of the

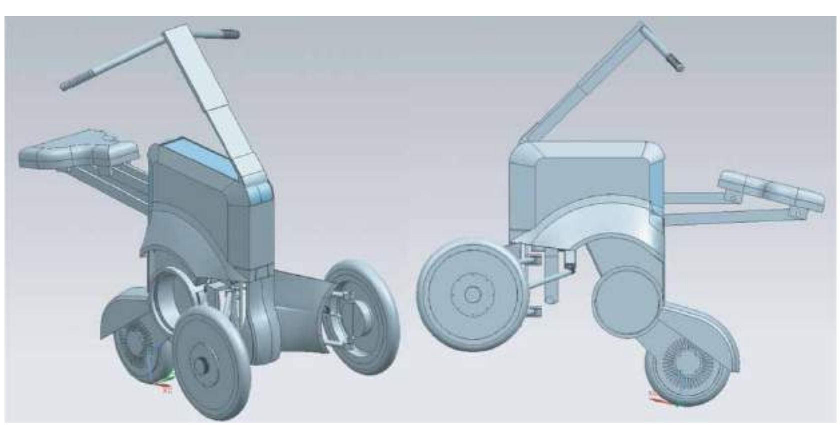

Figure 5. CAD Final Model (isometric and lateral views).

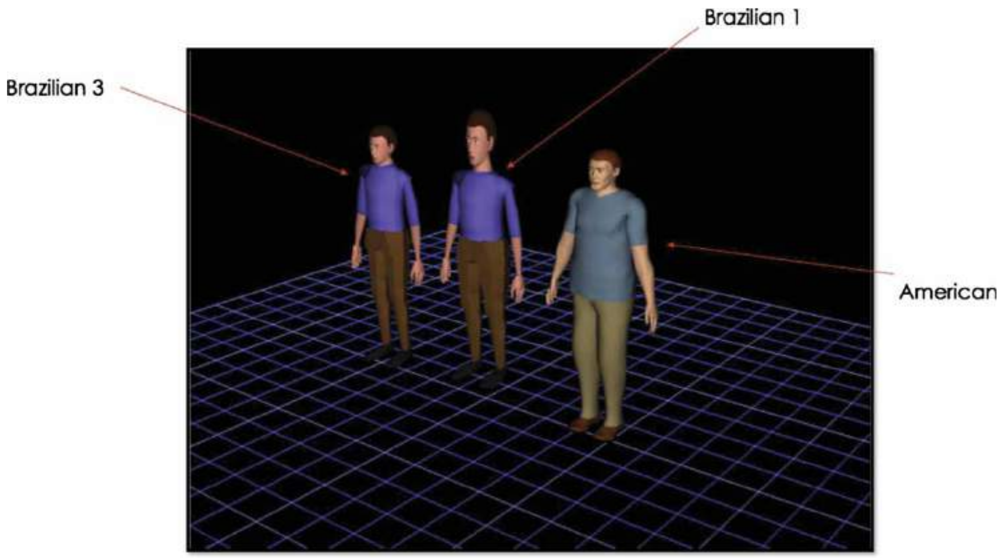

Figure 6. Human avatars.

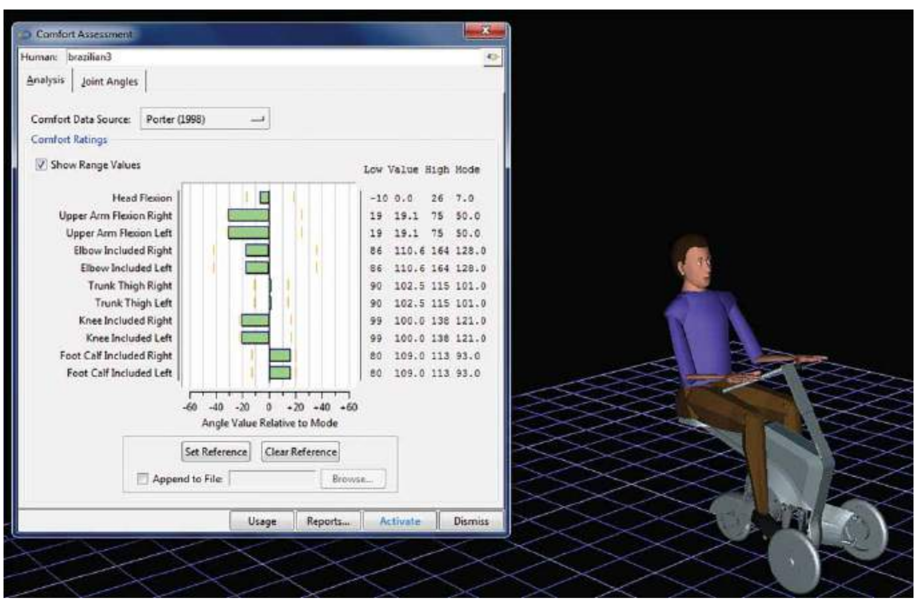

Figure 7. 'Brazilian 3' comfort assessment and joint angles.

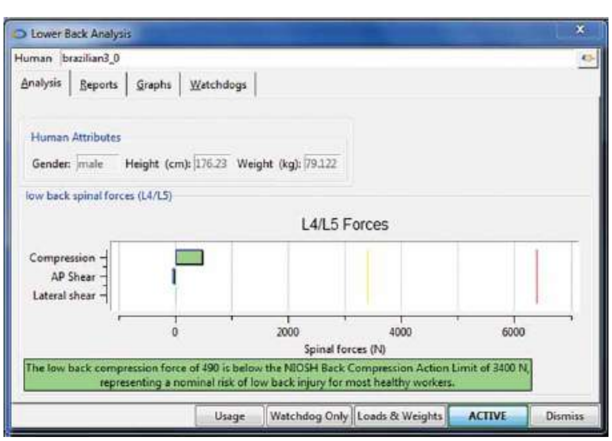

Figure 8. Lower back analysis.

curvature on an elbow when the subject has the shoulders relaxed, the upper arms straight down at the sides, and the lower arms horizontal in orientation.

- Sitting Acromial (58.3 cm): Measures vertically from a horizontal seat surface to the high point on the tip of the scapula where the bones of the shoulder complex meet.
- Sit Knee Height (56.0 cm): Measures vertically from the floor to the highest point on the patella when a subject sits with their feet firmly planted and their lower legs held in a vertical orientation.

The other 19 measurements were calculated using the Army Anthropometric Survey (ANSUR), which comprises statistical data, including 240 measurements from more than 75,000 individuals. This anthropometric database was used due to the fact that if all GM Global Anthropometric Data dimensions were to be used, an unevenly human would be created, and would not accurately represent the Brazilian population. This is due to the fact that each dimension is an average of the population, and is not an actual real-life proportional human. So, by using the Brazilian data for the required measurements, and letting Technomatix Jack to calculate the rest of the measurements using ANSUR, it was possible to 'create' a physically possible human that would accurately represent the 95th percentile of the Brazilian populace.

In the previous image (Figure 6), 'Brazilian 1' represents an uneven human created using all GM Brazilian Anthropometric Data, 'Brazilian 3' represents an accurate human combining GM Brazilian Anthropometric Data and ANSUR measurements, while 'American' represents the 95th percentile of the United States population, which would be the control variable.

After the subject creation, the PAMD NX Model, was exported as a *.wrl* extension and imported into Jack for a user-device interaction analysis. The PAMD was sized to its actual dimensions, and the user was successfully placed on the device, taking into consideration the different joint and position angles obtained from the ergonomic analysis (see Figure 7).

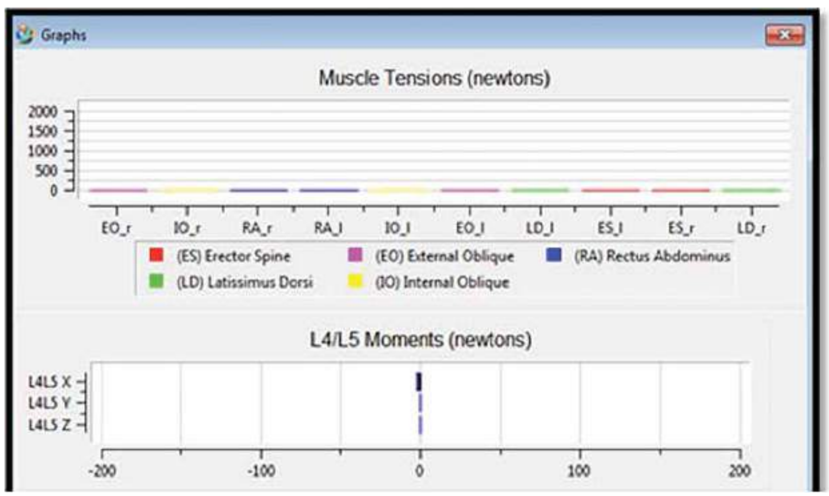

Figure 9. Vertebrae assessment.

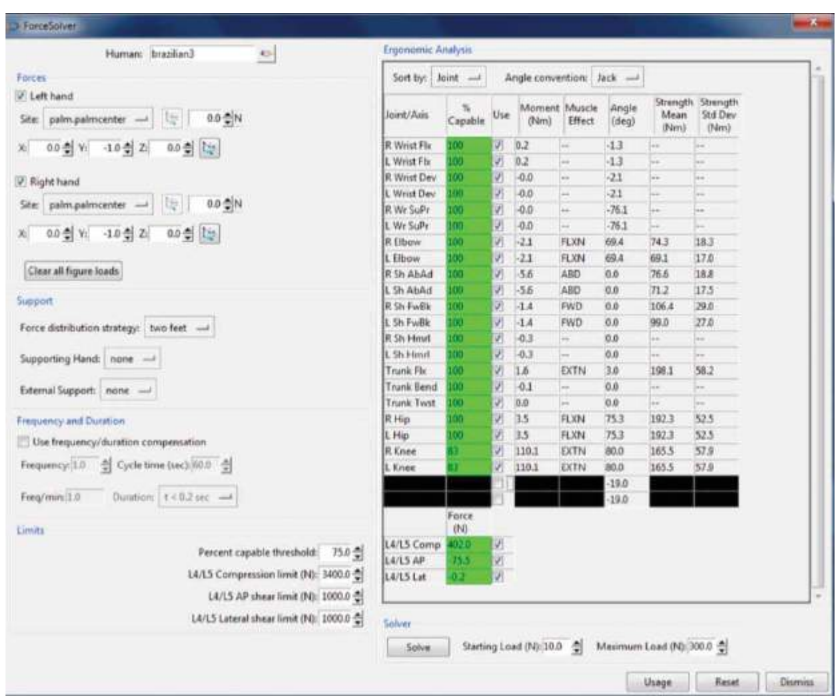

Figure 10. Body part functionality assessment.

After the subject was correctly placed in the apparatus, the comfort assessment, showed that all the different body parts were within the specific ranges of comfort. Hence, another analysis was carried out (see Fig. 8) to show the impact of the device on lower back, including the L4 and L5 vertebrae, which are also known as the lumbar vertebrae.

The analysis showed that the device would put a 402N compression load on the L4 and L5 vertebrae, which is much lower than the National Institute Occupational Safety and Health's (NIOSH) accepted limit of 3400N. To further analyze the load on the user, a vertebrae assessment, shown in Fig. 9, was done illustrating the muscle tensioning on the user when the device is in use, as well as the moment forces on lower vertebrae.

Finally, an analysis was performed related to the capacity of each body part to perform functions, illustrating that all body parts can effectively perform their functions, as can be observed in Fig. 10.

7. Conclusion

It can be stated that the proposed Portable Assisted Mobility Device does fit the 90% of the Brazilian population (in-between of the 5^{th} and 95^{th} percentiles) by exhibiting a comfort assessment that falls between the limits of user comfort, hence proving a reduced risk of injury and fatigue. The proposed PAMD also displays positive results when subjected to NIOSH Lower Back and Body Part Functionality Analyses. The apparatus was designed to successfully meet the manufacturing constraints of size, performance, duration, and capability; and has been successfully manufactured. This prototype has been tested for its easiness and safeness to ride, resulting in exceptional results.

Acknowledgements

This work has been possible thanks to the support of New Mexico State University (NMSU) Department of Industrial Engineering, PACE (Partners for the Advancement of Collaborative Engineering Education), and AMP (Alliance for Minority Participation).

ORCID

Mauricio Garcia http://orcid.org/0000-0002-6968-3415
Javier Garcia-Mendoza http://orcid.org/0000-0001-7086-278X

References

[1] Corlett, E.N.; Clark, T.S.: The Ergonomics of Workspaces and Machines: A Design Manual, Second Edition, 1995.
[2] Pheasant, S.: Bodyspace: Anthropometry, Ergonomics, and the Design of Work, Second Edition, 1996.
[3] PACE (2012). 2012–2014 PACE Portable Assisted Mobility Device (PAMD) Global Collaborative Project Brief. Retrieved from: http://www.pacepartners.org/files_pub/PAMD_Project_Brief.pdf
[4] Tompkins, J. A.: Facilities Planning, Fourth Edition, 2010.