Design of Two Beach Wheelchairs

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The theme of this master's degree thesis is the reduced mobility on the beaches and the obstacles the incapacitated individuals face. In order to improve the quality of life for those people and make the beaches more accessible, an improved solution is requested. After MMM's project More Moving Moments, whose purpose consists on developing a beach wheelchair for children and provide it freely on the beaches, a new project followed from the former IST student Luís Brazão's master thesis. The main goal of this new project was to design and analyse a new concept with dimensions and a capacity specific for adults. However, given the simplicity of these previous models, a new project, developed on this thesis, was requested, in which improvements should be made to the existent models. This new project follows two approaches: design of a new public beach wheelchair and design of a new personal beach wheelchair. Firstly, a brief market study is developed, in order to identify the main characteristics of a beach wheelchair and which of those are the most important to the user. To avoid misleading and incorrect information, an online inquiry was created. This questionnaire allowed the understanding of the biggest problems found on the existing models and the identification of the main and most crucial improvements to be implemented. Following this study, comes the focus of this thesis, that consists on the design of the new solutions, clearly identifying the main mechanisms and the materials to be used. Finally, a structure analysis is conducted on the two final concepts.

Keywords: beach wheelchair; accessible beaches; reduced mobility; mechanical design; mechanisms; structural analysis

1. Introduction

1.1. Motivation and framing of the theme

Motor disability is a limitation of the physical-motor functioning of a human or animal and may be congenital or acquired. The origins of these problems occur in the brain or locomotor system, resulting in malfunction or paralysis of the lower and / or upper limbs [1].

According to a study conducted at ISCTE in 2007, it is estimated that about 8% to 10% of the Portuguese population has some form of disability [2]. There are approximately 134 million people with reduced mobility in Europe [2]. These numbers allow to classify reduced mobility as a relatively common problem in society.

In the most serious cases, it is sometimes necessary to use wheelchairs. In addition to these equipment, other strategies have been developed that facilitate the daily city life of people with reduced mobility. Another context that has also been analysed is accessibility on beaches. In 2004 the project "Praia acessível –

Praia para todos!" was created, which aims to promote accessibility on the beaches. In 2018, through this project, 214 beaches in Portugal, mainland and islands were considered accessible [3]. This accessibility is characterized by the installation of access ramps and walkways, the creation of zones for these individuals and the installation of beach wheelchairs. These chairs are an important feature as they allow the user to better adapt to the beach. However, it is important to understand that beach wheelchairs are still relatively basic and have few features.

1.2. Problem statement

Following More Moving Moments (MMM) association [4] first project and the previously mentioned master thesis [5], a new project is required.

The main objective of this master thesis is to create an improved wheelchair. This new wheelchair should be adjustable in size, in order to be used by any individual, regardless of their body structure. Another important aspect consists on the possibility to use the wheelchair in urban spaces and in the beach. However, such level of complexity is considered as not compatible with MMM's project. Therefore, two new chairs were developed: a public free beach wheelchair and a personal purchasable one.

1.3. Document structure

This document has four main chapters (excluding introduction and conclusions). The first of this four consist on a general study regarding wheelchairs. After, an online inquiry and respective analysis are presented. The chapter that follows consist on the main part of the thesis: the design of the wheelchair. Finally, after the design, some analysis and calculations are necessary, in order to ensure the safety and good conditions of the develop product.

2. Components and dimensions of a wheelchair

2.1. Main components

In order to develop a new beach wheelchair, there is a need to understand the main components of a wheelchair. A wheelchair can be divided in three main components: structure, rear wheels and caster wheels. The structure can either be rigid or articulated. In the second case, the structure can be closed to facilitate the transportation. There are two types of articulated structures: horizontal closing and vertical closing. The rear or driving wheels are usually the ones with bigger diameter and located in the back. The caster or steering wheels are usually the front wheels and have a smaller diameter [6].

2.2. Dimensions of a wheelchair

The dimensions of a wheelchair should be adequate and proportional to the human anthropometry. The Figure 1 and Table 1 present the general measurements of the human body in a seating position.

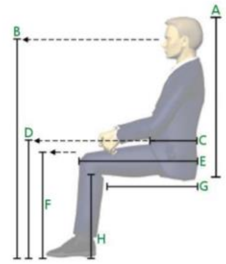


Figure 1 – Representative Scheme of Anthropometric Dimensions of a Seated Adult [7]

Table 1 – Values for 5th to 95th percentile for men and women in the sitting position (values in mm) [7]

Measurement	Letter	Woman 5° – 95° %	Man 5° – 95° %	Range 5° – 95° %
Sitting Height	A	795 – 909	853 – 973	795 – 973
Sitting Eye Height	B	1082 – 1240	1176 – 1336	1082 – 1336
Waist Depth	C	185 – 272	198 – 290	185 – 290
Thigh Clearance	D	533 – 622	584 – 681	533 – 681
Buttock-to-Knee	E	541 – 640	569 – 668	542 – 668
Knee Height	F	503 – 589	544 – 635	503 – 635
Seat Length/Depth	G	429 – 518	450 – 536	429 – 536
Popliteal Height	H	381 – 460	424 – 505	381 – 505
Seat Width	-----	368 – 457	353 – 437	353 – 457

3. Main characteristics

In order to understand which characteristics are the most important to the user, an online questionnaire was created and publish, mainly on social network. This inquiry was answered by individuals with reduced mobility and family members or partners of such individuals.

In total, 45 people answered. The answers show that about 50% of these individuals never used a beach wheelchair, either because they decided not to or because they never came across one. As it was expected, most of the ones who used these wheelchairs were not impressed with the comfort and had some troubles adjusting to the dimensions of the wheelchair.

From the results it was also clear that the three most important characteristics are: possibility of bathing at sea, ease of manoeuvring/driving the chair and the comfort. One other rather important feature consists in the easy transportation, in the case of owning a personal chair. At the end of the questionnaire, some suggestions were requested. One very interesting suggestion consists in the creation of a line of accessories to add to the wheelchair.

4. Design of the wheelchair

4.1. Public beach wheelchair

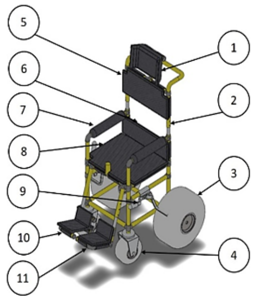
Considering the information of the previous chapters, it is possible to identify certain requirements and specifications, related to the main characteristics and the dimensions of a wheelchair, respectively (see Table 2).

Table 2 – Public chair requirements and specifications

Requirements	Specifications
Low cost	Sitting Height between 795 and 973 mm
Reduced weight	Seat Length/Depth between 429 and 536 mm
Adjustable size	Seat Width between 353 and 457 mm
	Leg rest length between 381 and 505 mm

Using the CAD program SolidWorks (SW), a 3D model was created (see Figure 2).

It is possible to identify the main components and dimensions of this beach wheelchair (see Figures 2 and 3 and Table 3).



Number	Component
1	Head rest
2	Main structure
3	Rear wheel
4	Caster wheel
5	Back cushion 1
6	Back cushion 2
7	Arm cushion
8	Seat cushion
9	Breaking system
10	Right leg rest
11	Left leg rest

Figure 2 – Main components of public beach wheelchair

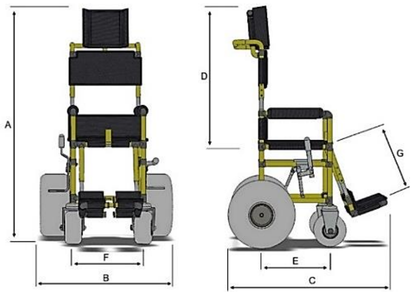


Figure 3 – Main dimensions of public beach wheelchair

Table 3 – Main dimensions of public beach wheelchair

Letter	Measurement	Value [mm]
A	Total height	1635 – 1715
B	Total width	1025
C	Total length	1132
D	Sitting height	857 – 937
E	Seat depth	510
F	Seat width	522
G	Leg rest length	380 – 480

The tubes that compose the main structure have an outside diameter of 33.4 mm and an inside diameter of 26.64 mm. The material of these tubes is rigid PVC [8]. The wheels' tires are in PUR [9]. The cushions' cover is *Texteline* [10] and its interior is a medium-density polyurethane foam [11].

The mechanism of adjustment consists on the same mechanism used in crutches. It has a locking pin which allows to adjust the height of the crutch in different positions (see Figure 5). This mechanism is incorporated in the back of the chair and in both leg rests. The interior tubes, where the locking pins are located, have a different material. These tubes are in aluminium (Al 6061-T6). The brake mechanism is based on a system by Ocelco: Health Equipments and Parts [12] (see Figure 4).

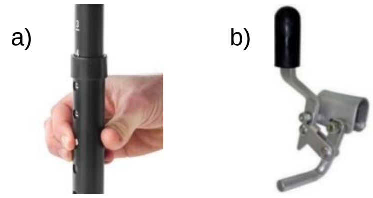


Figure 4 – a) Example of crutch mechanism [13]; b) Brake system [12]

4.2. Personal wheelchair

The second approach concerns the creation of a new non-public chair, which means it can and should be purchased for private personal use.

Certain improvements have been implemented to obtain a final model: possibility of bathing at sea; autonomy/independence for the user; possibility to use at the beach and in the city; possibility of placing the wheelchair in different positions; easy transportation. Considering these characteristics, it is possible to identify the requirements and specifications presented in Table 4.

Table 4 – Personal chair requirements and specifications

Requirements	Specifications
Reduced weight	Sitting Height between 795 and 973 mm
Adjustable size	Seat Length/Depth between 429 and 536 mm
Easy transportation	Seat Width between 353 and 457 mm
User autonomy	Leg rest length between 381 and 505 mm

A 3D model was created (see Figure 5), using the program SW.

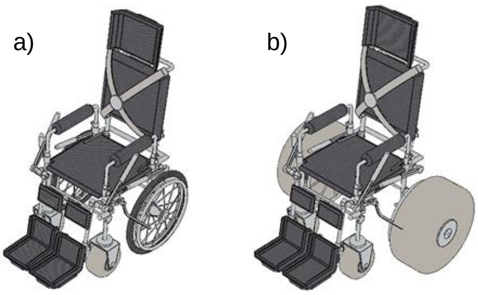
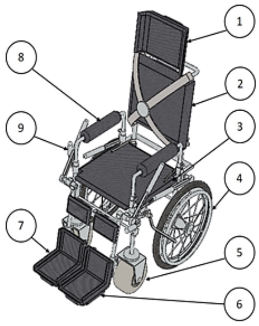


Figure 5 – 3D model of personal wheelchair: a) everyday version; b) beach version

It is possible to identify the main components and dimensions of this wheelchair (see Figures 6 and 7 and Table 5).



Number	Component
1	Head rest
2	Back
3	Seat
4	Rear wheel
5	Caster wheel
6	Left leg rest
7	Right leg rest
8	Arm rest
9	Break

Figure 6 – Main components of personal wheelchair

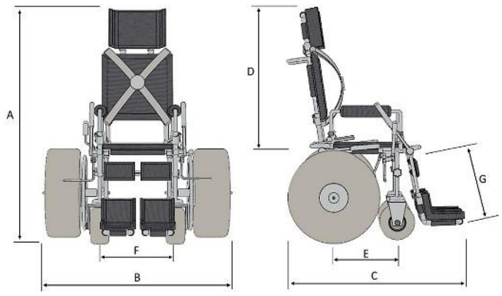


Figure 7 – Main dimensions of personal beach wheelchair

Letter	Measurement	Value [mm]
A	Total height	1452 – 1602
B	Total width	1319
C	Total length	1204
D	Sitting height	800 – 950
E	Seat depth	510
F	Seat width	500
G	Leg rest length	369 – 489

Table 5 – Main dimensions of personal beach wheelchair

Two types of tubes are used in the structure of the different components: one has an outside diameter of 30 mm and an inside diameter of 26 mm and the other has an outside diameter of 24 mm and an inside diameter of 20 mm. The material of these tubes is aluminium (Al 6061-T6). However, there is also the possibility of using titanium or a composite material (carbon fibre). The wheels' tires are in PUR [9]. The cover of the cushions is *Sunbrella* [10] and its interior is a high-density polyurethane foam [11].

The mechanism of size adjustment consists on a telescoping mechanism, where an inner tube slides inside an outer tube [14]. To fix the two tubes a clamp is used (see Figure 8). This mechanism is incorporated in the back of the chair, in both leg rests, in the head rest and in the arm rest.

Figure 8 – Clamp used in telescoping mechanism [14]

The mechanism that allows the position adjustment consists of a screw that is integral with the back or the leg rest, a lever-like part that acts as a nut, and a rubber that is between the components to be connected (see Figure 9). The fixation of the components is achieved due to the tightening and friction between the parts.

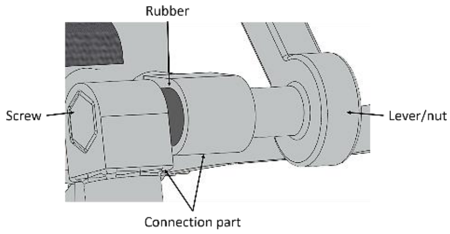


Figure 9 – Position mechanism

In order to change the rear wheels between everyday use and beach version, a *Quick release* mechanism is used [15] (see Figure 10).

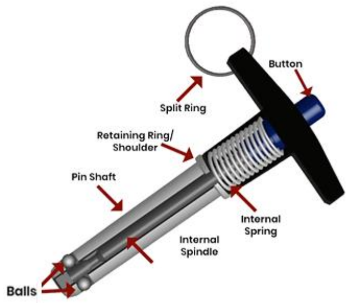


Figure 10 – Quick release [15]

The brake mechanism is the one used in the public wheelchair. In order to be able to attach some accessories to the chair, a claw mechanism is used, based on Ram Mounts mechanism RAM® TOUGH-CLAW™ [16] (see Figure 11).

Figure 11 – RAM® TOUGH-CLAW™ mechanism [16]

To facilitate the task of transportation, it is possible to partly disassemble the wheelchair. It is intended that the final configuration may have smaller dimensions (see Figure 12).

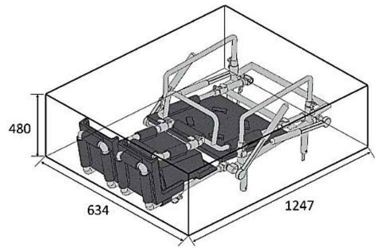


Figure 12 – Final configuration and measurements (mm)

Following a suggestion given in the online questionnaire, several accessories were created (see Figure 13): sun umbrella holder; tray; cup holder; cell phone holder; seat belt; floats.

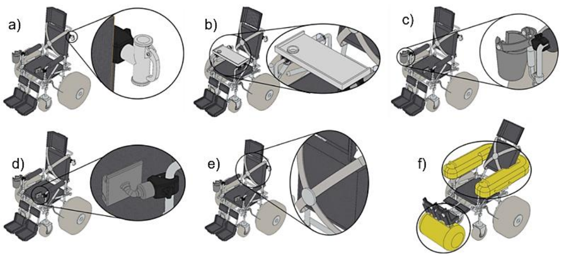


Figure 13 – Accessories: a) sunhat holder; b) tray; c) cup holder; d) mobile phone holder; e) seat belt; f) floats

5. Analysis and results

5.1. Public beach wheelchair

5.1.1. Materials and properties

The main material used in tubes is rigid PVC. However, the smaller diameter tubes on the back of the main frame and the leg rests are aluminium tubes (Al 6061-T6).

Table 6 – Materials and mechanical properties [17][18]

Material	Density ρ [kg/m³]	Yield strenght S_y [MPa]	Ultimate strenght S_u [MPa]	Young's modulus E [GPa]
PVC	1300 - 1490	41,4 - 52,7	41,4 - 52,7	2,48 - 3,3
Al 6061-T6	2700	276	310	68,9

5.1.2. Centre of mass

To calculate the centre of mass of the set wheelchair + user, it is first necessary to calculate the individual centre of mass of each. Calculation of the user's centre of mass [19]:

$$L_H = A \times h\,(cm) + B \times m\,(lb) + C \qquad (1)$$

This calculation is applied for each component (x, y and z). However, only the x component is needed in future calculations (L(x)). In the case of a person seated, the values of A, B and C are 0,080, 0,010 and 4,450, respectively [19]. The values of the user's height and weight are assumed (h=1,8m=180cm; m=80kg=176,4lbs). Appling these values in (1) gives $L_H(x)$=206,14mm.

The centre of mass of the wheelchair is obtained using SW and its value is $L_C(x)$=173,05mm. The centre of mass of the set wheelchair + user is given by:

$$L(x) = \frac{\sum x_i \times m_i}{\sum m_i} \qquad (2)$$

Considering $x_1 = L_H(x)$, $m_1 = m_{user}$=80kg, $x_2 = L_C(x)$ and $m_2 = m_{chair}$=14,5kg, the centre of mass is L(x)=201,06mm.

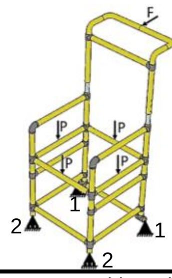
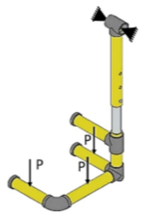
5.1.3. Load scenarios

Using the program Siemens NX, a finite element mesh is created. This mesh is needed to perform a static numerical analysis and obtain results concerning stress and displacement. By identifying the maximum stress (σ_{VM}), this value is then compared to the yield strenght of the material (see Table 6) and a factor of safety is obtained. This safety factor is calculated as follows:

$$n = \frac{S_y}{\sigma_{VM}} \qquad (4)$$

Both the main structure and the leg rest were studied in several load scenarios. It is verified that in all those cases, the maximum stress, obtained from the numerical analysis, does not surpass the yield strength of the respective material. In fact, the lower safety factor obtained is n=1,38, in a scenario where the main structure is subjected to the weight of the set (user + wheelchair) and to a pushing force on the hold. Regarding the leg rest, the lower safety factor corresponds to a scenario where the user stands up in the leg rests. However, this safety factor is still quite high (n=4,6), presenting no problem (see Table 7).

Table 7 – Load scenarios and results for the public chair

Scenario	Loads and constrains	Maximum stress	Safety factor
Structure subjected to weight of the set and pushing force 	Loads: F=300N P=214,6N Constrains: $Ux_1=Uy_1=$ $=Uz_1=0$ $Uz_2=0$	σ_{VM}=60,92MPa On back Al tube σ_{VM}=30MPa On back PVC tube	n=4,53 n=1,38
Leg rest subjected to weight of the user 	Loads: P=131N Constrains: Ux=Uy= =Uz=0 θx=θy= =θz=0	σ_{VM}=15,32MPa On Al tube σ_{VM}=9MPa On PVC tube	n=18,02 n=4,6

5.1.4. Critical cases

Since the security is verified in all studied load cases, the other critical situation considered is the turning of the chair (see Figure 14).

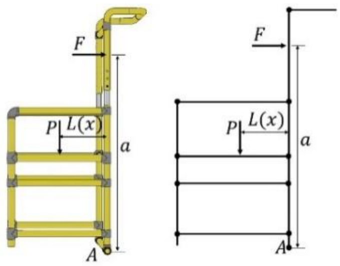


Figure 14 - Scheme and free body diagram of the chair subjected to weight of the set and back pulling force

In this case, the data is: P=784,8N; a=1090mm; L(x)=201,06mm. To calculate the maximum force F the point A is analysed in terms of equilibrium:

$$\sum M_A = 0 \Leftrightarrow P \times L(x) - F \times a = 0 \qquad (5)$$

Solving, a maximum force of 145N is obtained. This value only corresponds to approximately a fifth of the user's weight, so special attention should be paid to this critical situation.

One other situation to consider is the possible inclination of the ground in which the wheelchair is been used. It is necessary to calculate the maximum inclination possible for the chair not to turn (see Figure 15).

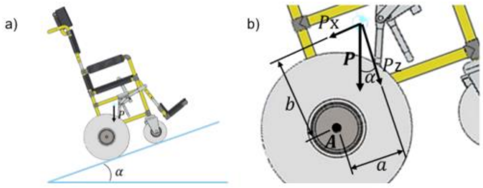


Figure 15 – a) Scheme of the wheelchair in an inclined ground and b) detail and decomposition of the weight

Calculating the moment in point A (Figure 15 b)) and knowing that P=927,05N, a=201,06mm and b=687,2mm, a maximum inclination of α=16,3° is obtained.

5.2. Personal wheelchair

5.2.1. Materials and properties

The material used is aluminium (Al 6061-T6). However, there is also the possibility of using titanium (Ti-6Al-4V) or carbon fibre (Toray T700).

Table 8 – Materials and mechanical properties [18][20]

Material	Density ρ [kg/m³]	Yield strenght S_y [MPa]	Ultimate strenght S_u [MPa]	Young's modulus E [GPa]
Al 6061-T6	2700	276	310	68,9
Ti-6Al-4V	4430	880	950	113,8
T700S	1800	4900	4900	230

5.2.2. Centre of mass

The centre of mass of the user is the same as the one obtained for the public wheelchair: $L_H(x)$=206,14mm.

The centre of mass of the wheelchair is once again obtained using the CAD software SW and its value is $L_C(x)$=136,20mm.

Therefore, the centre of mass of the set wheelchair + user is L(x)=193,35mm.

In this chair, however, a new situation is presented, in the case of having the back of the chair reclined. For this position it is once again necessary to calculate the centre of mass of the user and of the chair.

The user's centre of mass is obtained using a 3D model, in SW, of a human body ($L_H(x)$=77,10mm).

The centre of mass of the chair is obtained using SW again ($L_C(x)$=124,64mm).

Therefore, the centre of mass of the set is L(x)=85,54mm.

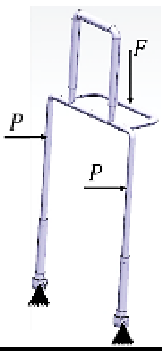
5.2.3. Load scenarios

Once again, after creating a finite element mesh, it is possible to obtain results concerning stress and displacement, by means of a numerical analysis.

After analysing the results, it is, once again, calculated the factor of safety as shown in (4). In this case for each possible material (see table 8). The calculations and analysis are made for the structure of the seat, the back and the leg rest.

It is again verified that the maximum stress in each scenario is lower than the yield strength of the materials. In fact, in all those cases, the safety factor is relatively high, being the lowest the case in which the back of the wheelchair is subjected to the weight of the user's back and a vertical force on the handle, with a safety factor of n=4,08, considering the aluminium alloy as the material (see Table 9).

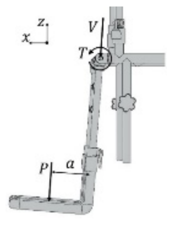
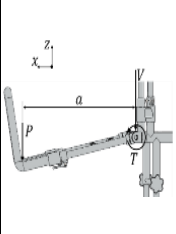
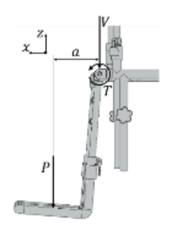
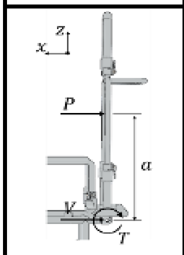
Table 9 – Load scenarios and results for the personal chair

Scenario	Loads and constrains	Maximum stress	Safety factor
Back subjected to back weight and force on the handle 	Loads: F=294,3N P=196,2N Constrains: Ux=Uy= =Uz=0	σ_{VM}=78,30MPa	Al: n=4,08 Ti: n=13,00 T700S: n=72,40

5.2.4. Analysis of connections

Besides the numerical analysis, it is also necessary to analyse the connections between the seat and the leg rest and between the seat and the back (see Table 8). For the following calculations, it is analysed the forces and stresses in the screw (assumed as a pin for this section) of the connection.

Table 10 – Load scenarios and results for the connections

Scenario	Data	Maximum stress	Safety factor
	P=137,34N a=112,4mm T=15,44Nm V=137,34N	τ_V=0,911MPa τ_T=19,198MPa σ_{vM}=33,29MPa	<u>Al:</u> n=8,29 <u>Ti:</u> n=26,43 <u>T700S:</u> n=147,19
	P=137,34N a=458,85mm T=63,02Nm V=137,34N	τ_V=0,911MPa τ_T=78,359MPa σ_{vM}=135,73MPa	<u>Al:</u> n=2,03 <u>Ti:</u> n=6,48 <u>T700S:</u> n=36,10
	P=392,4N a=111,3mm T=15,44Nm V=392,4N	τ_V=2,602MPa τ_T=54,84MPa σ_{vM}=95,09MPa	<u>Al:</u> n=2,9 <u>Ti:</u> n=9,25 <u>T700S:</u> n=51,53
	P=196,2N a=474,8mm T=93,16Nm V=196,2N	τ_V=1,301MPa τ_T=115,835MPa σ_{vM}=200,64MPa	<u>Al:</u> n=1,38 <u>Ti:</u> n=4,39 <u>T700S:</u> n=24,42

Once again, the safety is verified in all cases.

5.2.5. Critical cases

Since the security is verified in all studied cases, one other critical situation considered is the turning of the chair. As calculated previously, the centre of mass of the set in the case where the back is reclined is L(x)=85,54mm. This value is not small enough for the wheelchair to turn. Although the turning does not happen in this case, if the user puts too much of their weight in the back the chair will turn.

Once again, it also necessary to calculate the maximum inclination of the grounds so that the wheelchair does not turn (see Figure 16).

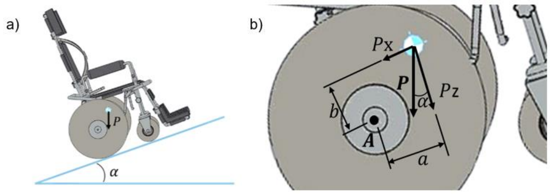


Figure 16 – a) Scheme of the wheelchair in an inclined ground and b) detail and decomposition of the weight

Calculating the moment in point A (Figure 16 b)) and knowing that P=960,4N, a=153,35mm and b=660mm, a maximum inclination of α=13,1° is obtained.

Considering the case where the back of the chair in totally inclined, the maximum inclination obtained is α=4°, which corresponds to a low inclination, making this chair inadequate to use in inclined surfaces when the back is in this position.

Another situation is the strength of the connection. It is important to understand whether the force applied on the back is enough to yield the bond. For the connection to give in, the friction between the surfaces must be overcome by the torque resulting from the force P on the back (see Figure 15). This means that the sum of both friction torques created by each friction force must not surpass the torque T for the connection to hold.

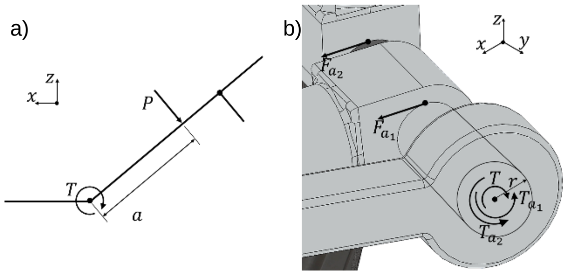


Figure 17 – a) Free-body diagram of the wheelchair with reclined back and b) respective frictional forces and forces on the connection

$$T \le T_{a_1} + T_{a_2} \Leftrightarrow P \times a \le F_{a_1} \times r + F_{a_2} \times r \qquad (7)$$

The forces F_{a1} and F_{a2} are given by:

$$\begin{cases} F_{a_1} = \mu_{e_1} \times N \\ F_{a_2} = \mu_{e_2} \times N \end{cases} \Leftrightarrow \begin{cases} F_{a_1} = \mu_{e_1} \times F_i \\ F_{a_2} = \mu_{e_2} \times F_i \end{cases} \qquad (8)$$

The force F_i is the preload applied in the screw of the connection [21]:

$$T_i = K \times F_i \times d \Leftrightarrow F_i = \frac{T_i}{K \times 2 \times r} \qquad (9)$$

Knowing that the friction coefficient is 0,3 for the surface 1 [22] and 1 for the surface 2 [23], the force P has a value of 196,2N and the torque coefficient K is assumed as 0,2 [21], after some calculations, it was determined that, for the connection to hold, the torque applied on the lever (T_i) must be at least 28,66Nm (see Figure 16).

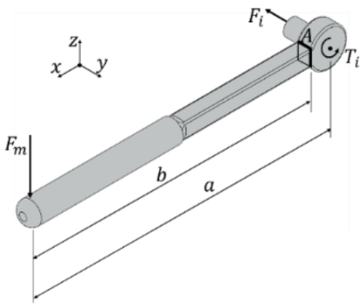


Figure 18 – Coupling mechanism lever diagram

Knowing that a=400mm, the force F_m, applied on the lever by the user, is calculated as follows:

$$T_i = F_m \times a \Leftrightarrow F_m = 71{,}66N \qquad (10)$$

Since a person can apply 130N on a lever [24], this value presents no obstacle.

The remaining calculation concerns the analysis of the critical section A (see Figure 18).

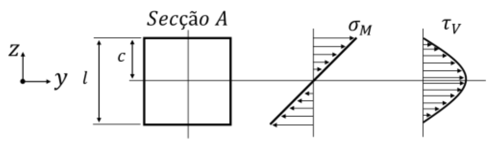


Figure 19 – Section A scheme and respective efforts

Given b=375mm, c=10mm and l=20mm, it is possible to calculate the bending moment and the shear stress in the section: σ_M=20,15MPa; τ_V=0,27MPa. The von Mises stress is then given by:

$$\sigma_{vM} = \sqrt{26{,}215^2 + 3 \times 0{,}35^2} = 20{,}16\ MPa \qquad (11)$$

Therefore, the safety factor is n=13,69, which means that the lever safety is verified.

6. Conclusions

The main objective of this dissertation is to develop two wheelchair designs.

One of the projects aims to create a beach-specific chair, which allows size adjustment. In the second project, it is intended to create a more complex wheelchair, whose improvements are based on the characteristics considered most important by the user in an online questionnaire.

The public chair is the simplest chair, with a size adjustment mechanism equal to the one used in certain equipment, such as crutches.

The personal chair has several improvements. Like the previous one, it allows for size adjustment, in this case by means of a telescope mechanism. It also allows the inclination of the back and elevation of the leg rests, removal and replacement of the rear wheels and partially disassemble, to facilitate transportation and storage.

After several analyses it was concluded that both chairs meet the safety requirements.

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