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Prototyping, Testing, and Redesign of a Three-Wheel Trekking Wheelchair for Accessible Tourism Applications

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Abstract: This work is part of the project called "Gölem project", started in 2017, about special devices developed to enable the so-called Accessible Tourism. This project aims to design and develop a trekking wheelchair for people with impaired mobility. After an initial phase of design and prototyping, the testing phase has now begun. The objective is to validate several aspects of the design, concerning basic kinematics and dynamics, passenger comfort and physical effort of the carriers. This paper describes the development of qualitative tests for drivability and balance validation of this first prototype. At this stage, a list of features to be investigated was made, suitable trekking paths were chosen, and qualitative experimental field tests were performed. Then, the design of the prototype was modified according to these first experimental results, to improve the wheelchair characteristics. The prototype is now undergoing the modification phase, then further testing will be performed with the use of specific instrumental devices to evaluate the wheelchair itself and to perform the kinematic, dynamical, and comfort characterization.

Keywords: trekking wheelchair; hiking wheelchair; disabled people; design methods; experimental testing; user-centered design; assistive technologies; accessible tourism

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1. Introduction

Today, the development of new products is receiving more and more attention, especially regarding design aspects that are closely related to "design for all", "user-centered design", and "eco-design" methods [1–7]. In fact, several products are designed from scratch or redesigned to consider user's needs, inclusion, and general environmental sustainability aspects. In the field of medical device design as well as assistive technologies for people with disabilities, it is possible to observe a growing interest in the development of more functional and sustainable devices to be used in the context of Accessible Tourism (AT) initiatives. In this context, AT means all services and products used for tourism activities implemented with consideration of the needs of the full range of consumers, including disabled and elderly people. Indeed, AT requires the removal of attitudinal and institutional barriers in society and therefore includes accessibility to the physical environment, transport, information and communications, and other facilities and services [8]. The current situation sees a constant aging of populations, especially European ones, which is tackled by the continuous updating of the legislative framework, but also by the growing evolution of the available design and production techniques. This contributes to making AT increasingly popular and thus increasing the demand for further types of tourism activities and services [9,10].

The presented project fits into this context of growing interest in AT, and aims to describe the design, manufacturing, and testing of a special wheelchair for people with impaired mobility to use in AT activities, developed by the University of Brescia and named the "Gölem project" [11]. This peculiar name refers to the local dialect version of “Mount Guglielmo” (Brescia, Italy), the highest mountain (1957 m) on the University premises, and a very loved trekking destination for locals. The Gölem project considers the AT initiatives in mountain areas and specifically the activity of accompanying people with every major type of mobility issue on mountain trails, using dedicated wheelchairs. This should be implemented while considering an environmentally friendly production and use of the device. The literature analysis, combined with the market analysis described in previous work [11] highlighted the presence of several available technical solutions, as briefly reported in the following. Solutions can be divided into three main categories: self-propelled wheelchairs designed for developing countries; self-propelled off-road/all-terrain wheelchairs; and a new category of devices classified as trekking wheelchairs—ISO code 30.09.39 (according to ISO 9999:2016) [12–17]. The latter is the most promising and interesting for the development of devices suitable for AT initiatives. This class of products consists of a specific type of human powered trekking wheelchair similar to a sedan chair equipped with a wheel, conducted by at least two carriers managing the impaired boarded guest over rough terrain. Currently, there are only a few commercially available solutions of these trekking wheelchairs. The most well known are: Joëlette© and TrailRider©, presented in Figure 1 [16,17].

Figure 1. Examples of commercially available trekking wheelchairs: (**a**) Joëlette© and (**b**) TrailRider©, [16,17].

They are characterized by a single-wheel configuration with an ergonomic cushioned seat, equipped with safety belts. Each one has a back handle and a couple of front arms allowing the carriers to handle the vehicle properly and its precious load on challenging terrains. The use of these aids is mainly performed by charities organizing excursions along mountain trails for disabled guests; such activity has highlighted some objective limitations of these devices at the same time suggesting the direction for improvements.

This paper describes the preliminary testing phase of the prototype of our trekking wheelchair, reporting the description of qualitative tests, aimed at drivability and balance validation of this first “proof of concept” prototype. At this stage, a list of features to be investigated was made, suitable itinerary and paths to highlight each feature were chosen, and qualitative experimental field tests were performed. Consequently, the design of the prototype has been modified according to these first experimental results, to improve the wheelchair tested characteristics, in line with the proof-of-concept method adopted in our laboratory [18,19]. The prototype was returned to the workshop where it is undergoing modifications. Following tests are scheduled, with the use of specific instrumental devices to evaluate the device itself and to perform the kinematic, dynamical, and comfort characterization.

2. Materials and Methods

As introduced before, the main objectives of the Gölem project are the design, build, and testing of a new concept of trekking wheelchair that allows the mobility of disabled people on mountain trails or rough terrains that are not accessible by standard commercial self-propelled wheelchairs. The Gölem project started in 2017 and is still ongoing. The development of this project is divided into four macro-phases, as illustrated in Figure 2: idea, concept and design, prototyping and testing. The first two phases of the project—idea and concept design—have been completed and described in publication [11]. For the sake of clarity, they will only be summarized in Sections 2.1 and 2.2.

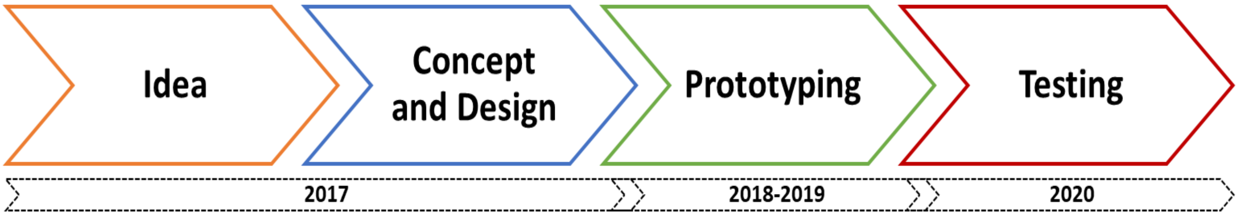


Figure 2. Flow of design process and timing of the Gölem project [11].

In this work we focus on the progress of the prototyping and testing phases. It should be remembered that they have suffered some delays due to the contingent pandemic situation.

2.1. Idea

In the phase called "idea", extensively described in [11], a careful analysis of the current marketed solutions was carried out, highlighting their advantages and disadvantages, also collecting comments of possible interested users and charities already using Joëlette© type trekking wheelchairs. In particular, this survey revealed some interesting operational limitations, as reported below:

- A certain difficulty was encountered by the people who carried the wheelchair (carriers) to keep it in lateral balance during a mountain trip, involving a considerable amount of energy and physical effort.
- A limited level of comfort for the transported, precluding this activity for people with a severe level or type of pathology.

Therefore, from this first phase, it was possible to define some technical specifications that the Gölem wheelchair needs to implement [11]. These specifications are shown in Table 1.

Table 1. Technical specifications of the Gölem wheelchair [11].

Technical Specification	Gölem Wheelchair
Wheel number	3
Layout	Double suspension system
Suspensions	Independent suspension
Steering system	Rear steering connected with rear handlebar
Seat and backrest width	With regulations
Frame material	Aluminum alloy
Mass	24 kg
Overall dimensions (L × W × H), in meters	2.4 × 0.6 × 1.4

2.2. Concept and Design

The second phase of the project involved the study and definition of the new concept with more emphasis on the definition of its new layout, materials, and its new suspension system. The results of this phase were the detailed drawings and 3D CAD modeling of the device and of its components. Figure 3 shows the main features of the new trekking wheelchair consisting of three wheels with independent suspensions, an adjustable and cushioned seat, a front handlebar, a back handle (with optional steering), and the aluminum frame. This phase of the overall project has been previously discussed and reported in [11].

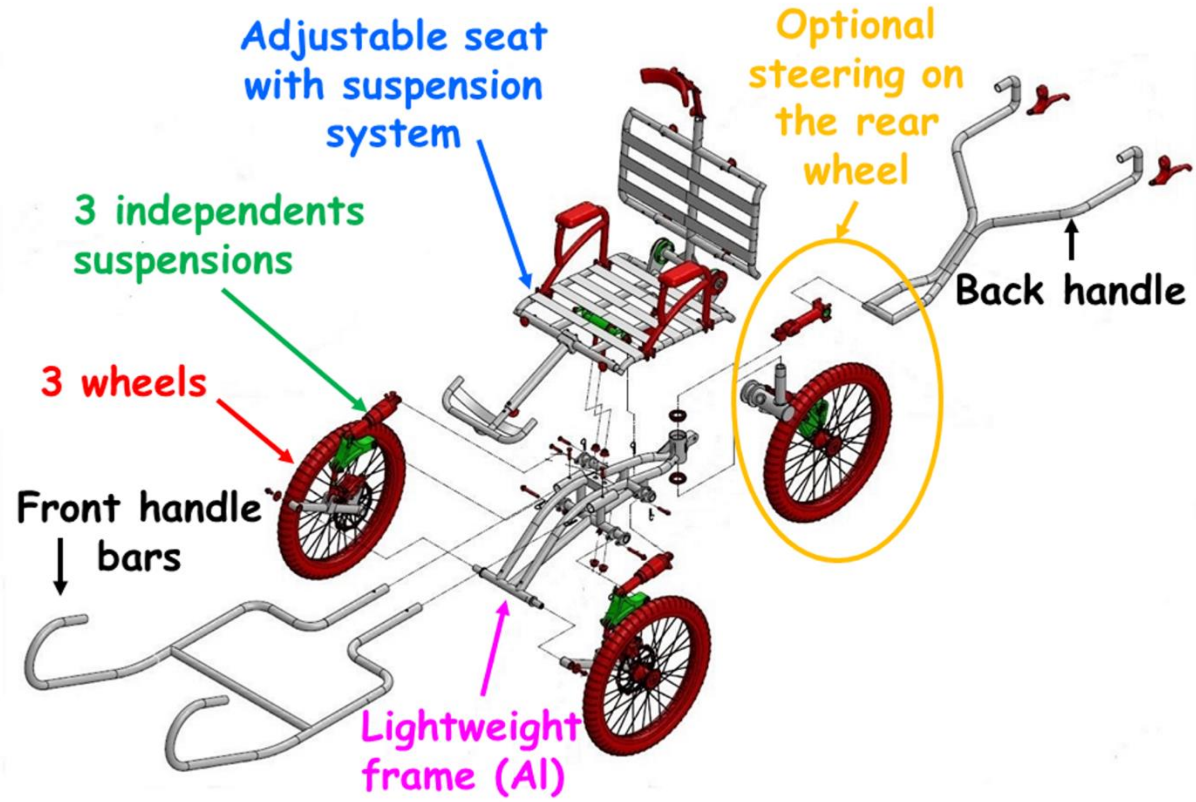


Figure 3. Main features of the proposed new trekking wheelchair [11].

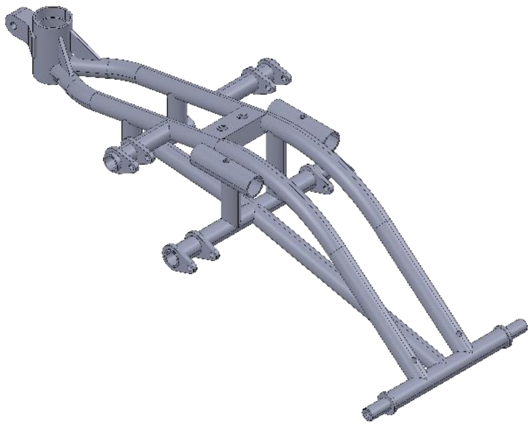
As aforementioned, the focus in this paper is on the work progress of the third and fourth phases.

2.3. Prototyping

The third phase of the project dealt with the realization of the first prototype of the new trekking wheelchair. To execute manufacturing of the prototype, a small factory with know-how both in the construction of Aluminum bicycle frames and in devices for disabled people (handbike), was chosen. Then, it was necessary to revise the project to adapt the structural elements of the prototype with respect to the available production process. As an example, Figure 4 shows modifications made to the frame: in Figure 4a the 3D CAD model is based on welded aluminum tubular; in Figure 4b the frame has been simplified and it is composed of a single load-bearing extruded element made of a hollow rectangular section profile.

Figure 5 shows the first prototype upon completion: the total mass of our three-wheeled wheelchair was less than 24 kg (23.68 kg), which represents a reduction of about 12% compared to the 27 kg mass of the one-wheeled model with fixed handlebars that can be found on the market.

(**a**)



(**b**)

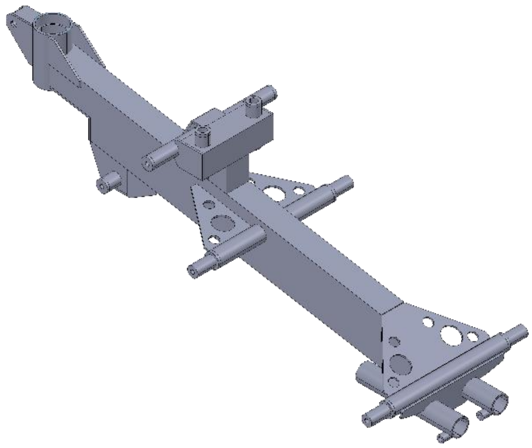


Figure 4. (**a**) Ideal 3D CAD model of the frame; (**b**) 3D CAD model of the adapted and simplified frame.

Figure 5. Prototype of the Gölem wheelchair upon completion.

2.4. Testing

After the realization of the first prototype, the preliminary testing phase started. This was a very important phase because its output consisted of obtaining important information and data for further optimization of the design.

As shown in Figure 6, the prototype will need to undergo several types of tests. These tests have been divided into two groups. A first group of qualitative tests to assess the overall drivability and balance of the wheelchair and a second group of quantitative tests aimed at assessing the dynamical response of the wheelchair, the comfort of the passenger, and the physical effort of the carriers.

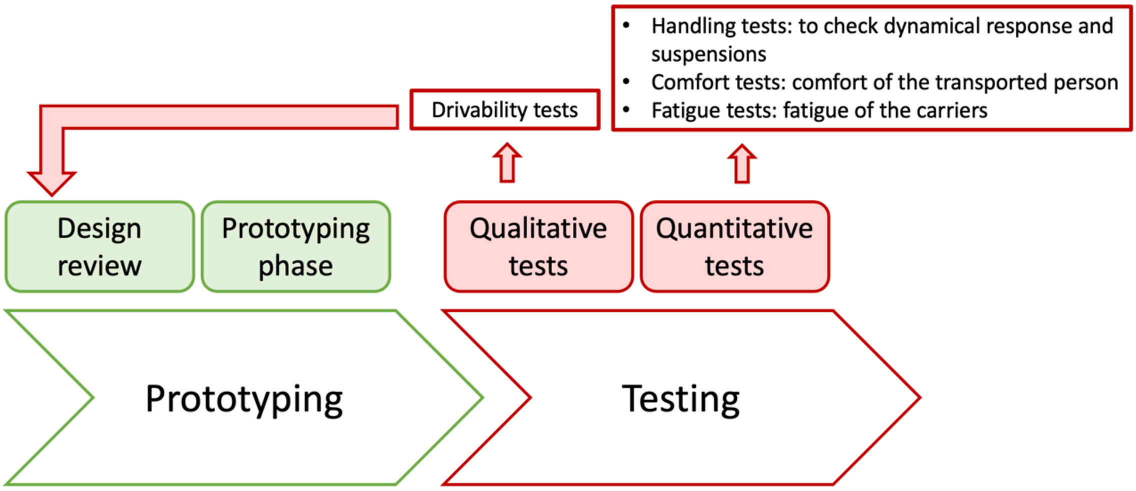


Figure 6. Prototyping and testing phases of the Gölem project.

At this point, it is important to emphasize that, compared to the other wheelchairs on the market with one or two wheels, the proposed solution, with three wheels can be considered as a real vehicle with its own geometry and set-up. In these situations, it is therefore useful to carry out qualitative tests by skilled testers, aimed to professionally evaluate and highlight any macro-modifications that need to be made to the prototype. This is necessary even before carrying out quantitative tests aimed at more specific investigations

2.4.1. Early Qualitative Evaluation

At this moment, the first group of qualitative field tests have been carried out to assess drivability, looking at the device from the carrier's point of view, although with some delay due to the pandemic situation. These tests were carried out by a group of expert designers and some members of BrAL (Brixia Accessibility Lab) and were performed in a park and on some simple mountain bike trails nearby (Figure 7). There were always two carriers, from a pool of three people who worked on the wheelchair development, alternating in their role (both in the rear and front positions). In these tests, the passenger was a non-disabled person.

These kinds of tests have the purpose of giving technical information about the wheelchair behavior, as an actual vehicle test. They come in a pre-engineering phase as completion of the prototyping phase; therefore, a high number of carriers are not required, rather it is required that the carriers know the phenomenon on which they must make a judgment. For this, the three designers who worked on the development of the wheelchair were chosen as carriers and can be considered as actual test drivers [20–23].

1. In reference to the considerations on the use of the device as discussed in [11] (relating the wheelchair design choices to its scope of use), nine types of maneuvers and routes were chosen to characterize the drivability and the balance of the device single step (the step is approximately 150 mm high), Figure 7a;
2. long curve;
3. tight curve;
4. flat path on grass Figure 7b;
5. grass track with ups and downs, Figure 7d;
6. uphill mountain track (with deep potholes both dry and muddy);
7. downhill mountain track (with deep potholes both dry and muddy) Figure 7c;
8. uphill hairpin bend (with deep potholes both dry and muddy);
9. downhill hairpin bend (with deep potholes both dry and muddy).

These nine types of tests were chosen between typical maneuvers that carriers may encounter during trekking activities on trails. Two routes were identified: maneuvers 1 through 4 were performed on the easy path represented by the lawn of the university parking lot, while maneuvers 5 through 9 were performed on a more MTB demanding trail.

(**a**)
(**b**)
(**c**)

Figure 7. *Cont*.

(**d**)

Figure 7. Example of field tests: (**a**) single step test; (**b**) flat path on grass; (**c**) grass track with ups and downs; (**d**) downhill mountain track.

In general, in trekking wheelchairs, the role of the two carriers is different and well defined: the front carrier tows the wheelchair, the rear carrier maneuvers, contributing less to the pushing effort, being more focused on equilibrium. From a technical point of view, it should also be noted that, in our prototype the rear bar can be configurable in two versions: (1) configuration with steerable handlebars; (2) configuration with the handlebars rigidly connected to the frame, with a pivoting rear wheel ("caster wheel"). The steerable handlebar has been designed to obtain increased maneuverability in tight bends. In current commercial solutions, the rear bar is only rigidly connected to the frame. For this reason, in this first series of qualitative tests the prototype was tested only in the configuration with steerable handlebars. This was conducted to verify the effectiveness of the new proposal (steerable handlebar) for the functions of drivability and balance. The qualitative tests carried out involved alternating three carriers in the front and rear positions and assessing their feelings about drivability and balance. Drivability is meant as ease of maneuver (e.g., tight bend, wide bend) and balance is meant as the effort required to keep the device balanced.

2.4.2. Quantitative Tests

The results of these qualitative tests were useful to modify the prototype design and the realized prototype itself. Once the new prototype will be ready, it will be equipped with accelerometers, potentiometers, and GPS, while the carriers will be equipped with a wearable metabolic system to perform quantitative tests of passenger comfort, dynamical behavior of the wheelchair and to measure carrier physical effort and performance. These quantitative tests will have three different purposes: (i) to verify the physical effort of the carriers through the monitoring of their oxygen consumption during the transport activity; (ii) to verify the comfort of the passenger using sensors on the cycling structures and on the seat of the wheelchair; and (iii) to verify the performance of the wheelchair suspensions.

To ensure comparability of results, the same maneuvers and routes chosen for the qualitative tests will be repeated after equipping the wheelchair with the following instrumentation:

- Triaxial accelerometer attached to the seat to check the comfort of the passenger.
- Potentiometers mounted on the shock absorbers to check the suspension's shaking.
- GPS.
- Wearable metabolic system to check the oxygen consumption of guides (therefore their performance assessment and energy expended).

The quantitative tests will be performed in two different vehicle configurations: (1) steerable handlebars, and (2) the handlebars rigidly connected to the frame, with a pivoting rear wheel.

3. Results

In this section, qualitative field test results are reported. They allowed authors to collect some initial interesting macro-indications from the carriers, which were chosen with different physical characteristics (Table 2) to collect as many considerations as possible.

Table 2. Carriers physical characteristics.

	Gender	Age	Height [m]	Mass [kg]
C1	Male	48	1.73	72
C2	Male	48	1.82	71
C3	Male	41	1.90	88

Tables 3 and 4 show the results of the nine qualitative tests performed and the average ratings of the three carriers (C1, C2, C3) who alternated in the two positions of front tow and rear handlebar.

Table 3. Drivability test scores.

#	Type of Test	Drivability							
		Front Position				Rear Position			
		C1	C2	C3	Average	C1	C2	C3	Average
1	Single step	5	5	5	5	5	5	5	5
2	Long curve	5	5	5	5	4	4	5	4.3
3	Tight curve	3	4	4	3.7	3	3	3	3
4	Flat path on grass	5	5	5	5	5	5	5	5
5	Grass track with ups and downs	3	4	5	4	4	4	4	4
6	Uphill mountain track	3	3	3	3	2	3	3	2.7
7	Downhill mountain track	2	3	3	2.7	2	3	2	2.3
8	Uphill hairpin bend	2	2	2	2	2	2	2	2
9	Downhill hairpin bend	1	2	2	1.7	1	2	1	1.3

Table 4. Balance test scores.

#	Type of Test	Balance							
		Front Position				Rear Position			
		C1	C2	C3	Average	C1	C2	C3	Average
1	Single step	5	5	5	5	5	5	5	5
2	Long curve	5	5	5	5	4	4	5	4.3
3	Tight curve	4	4	4	4	2	3	3	2.7
4	Flat path on grass	5	5	5	5	5	5	5	5
5	Grass track with ups and downs	4	4	4	4	3	3	3	3
6	Uphill mountain track	3	3	3	3	2	3	3	2.7
7	Downhill mountain track	3	3	3	3	2	3	2	2.3
8	Uphill hairpin bend	2	2	2	2	1	2	1	1.3
9	Downhill hairpin bend	1	2	1	1.3	1	1	1	1

The rating scale uses a range from 1 to 5, where 1 is the least satisfactory score and 5 is the most satisfactory (1 = very poor; 2 = poor; 3 = fair; 4 = good; 5 = very good). The two considered aspects were: the drivability (Table 3) and the balance (Table 4), differentiating between the rear and front positions. Before starting the test session, the three carriers were instructed about the evaluation grid and the purpose of the test and of the survey.

Tables 3 and 4 present the scores of drivability and balance tests, respectively, as they are felt by the carriers, showing the collected data and their average value, for each maneuver. Figure 8 illustrates these results, plotting the average values obtained in the nine different maneuvers, considering the front and rear positions. Looking at Figure 8, it is possible to observe that: (i) in the single step (maneuver 1), there are very good levels of drivability and balance, both in the front and rear positions; (ii) in the long curve (maneuver 2), drivability and balance are both very good in the front position and they are both good in the rear position; (iii) in the tight curve (maneuver 3), the front balance is good, the front drivability is quite good, the rear drivability is fair, and the rear balance is quite fair; (iv) in the flat path on grass (maneuver 4), there are very good levels of drivability and balance, in both the front and rear positions; (v) in the grass track with ups and downs (maneuver 5), drivability and balance are both good in the front position and they are both fair in the rear position; (vi) in the uphill mountain track (maneuver 6), drivability and balance are both fair in the front position and they are both quite fair in the rear position; (vii) in the downhill mountain track (maneuver 7), balance is fair in the front position and is quite poor in the rear position, drivability is quite fair in the front position and is quite poor in the rear position; (viii) in the uphill hairpin bend (maneuver 8), drivability is poor both in the front and rear position, balance is poor in the front position and it is very poor in the rear position; (ix) in the downhill hairpin bend (maneuver 9), drivability is quite poor in the front position and very poor in the rear position, balance is very poor in both the front and rear positions.

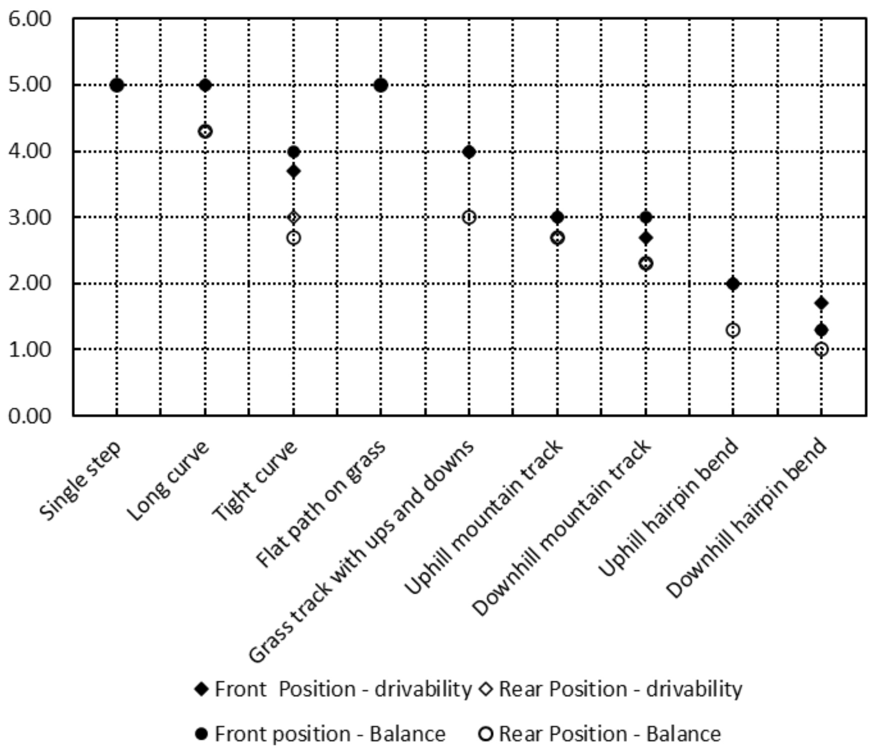


Figure 8. Plot of the average values obtained in the nine different maneuvers considering the front and rear positions.

4. Discussion

Analyzing and reviewing the design choices of our new concept of trekking wheelchair [11] and considering the received feedback from the carriers, a highlight on the high geometrical trail value of the rear steering wheel was found, as indicated by the drivability/stability and balance effort expressed by testers. Although this choice guarantees the maximum kinematic maneuverability of the device, especially in tight curves, balance is compromised due to the variation of the footprint of the vehicle, which is the triangle located by the contact patches of the tires. Hence, the center of gravity (CG) projection on the ground can fall dangerously near the stability perimeter. Moreover, this behavior is worsened by the asymmetric compression of the suspension related to the shift in the CG position, which in turn causes roll and subsequent further CG projection shift (CG is quite high for passenger safety reasons). It is important to remember that the three wheels layout with proper transversal roll resistance was chosen to help carriers' efforts, so it was mandatory regarding balance vehicle behavior towards this side. Considering all these reasons, a slight redesign of the prototype was carried out.

In particular, the first prototype of the wheelchair highlighted the difficulty for carriers to execute some maneuvers and to keep the wheelchair balanced, especially in tight turns, as well as on dirt roads with deep potholes (maneuver 7, 8, and 9). Therefore, the design of the prototype was modified to reduce this problem, and thus improve drivability by excluding the danger of overbalancing. As a result, two components of the device were modified: the frame was lengthened, and the rear suspension bracket was redesigned. Figure 9 shows the prototype configuration of the wheelchair before the qualitative tests, while Figure 10 shows the modification implemented in the design of the prototype on the frame and suspension. The blue steering axis (blue mark in Figures 9 and 10) was moved 200 mm back, and 145 mm high, to comply with the new geometry (keeping the desired vertical wheel excursion). As a result, the rear wheel trail was decreased from 225 mm to 25 mm, equal to the ground position of the steering axis relative to the wheel contact patch center (steer axis is vertical). This was a trade-off, sacrificing part of the former extreme agility towards a more manageable vehicle.

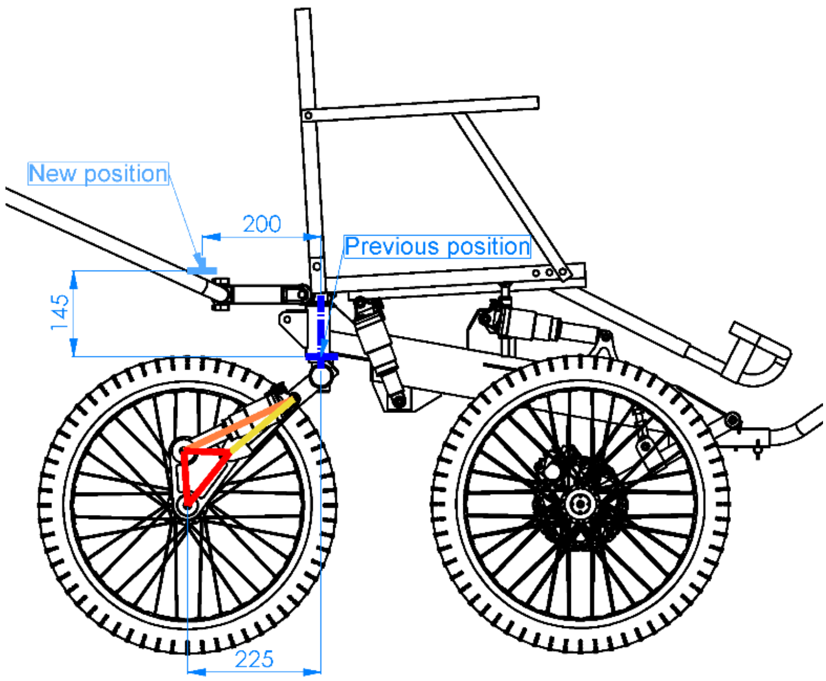


Figure 9. Design of the first prototype.

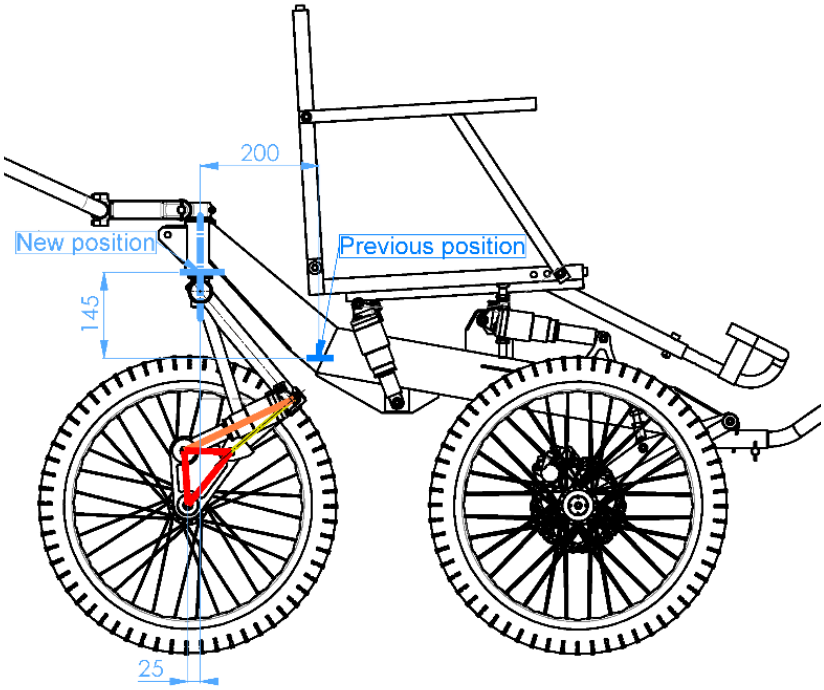


Figure 10. Modifications made to the prototype after drivability and balance tests.

This solution decreases the natural self-aligning effect of the wheel (which is not strictly needed in such vehicles) and slightly increases the curvature radius, but greatly improves the problem of the lateral variability of the vehicle footprint during maximum steering and therefore the stability of the entire wheelchair. It should be noted that the changes did not directly affect the rear suspension components (in red, orange, and yellow in Figures 9 and 10). These components have remained identical in both solutions. By calculations, we expect to set-up rear suspension behavior of this second prototype only by means of shock adsorbers and air spring regulations. At this time the prototype is back to the manufacturing company to be modified.

5. Conclusions

This paper presented the progress of the Gölem project concerning the construction of a trekking wheelchair to transport disabled people along mountain paths.

The initial stages of the project development have been briefly described. More emphasis was given to the description and explanation of the prototyping and testing phases. In particular, the qualitative drivability and balance tests were described, illustrating the method for their execution, and discussing the results obtained. These tests revealed drivability problems in some conditions. Consequently, design modifications have been made to improve the balance of the device without affecting the suspension scheme and therefore without affecting the vibrational comfort perceived by the passenger. The wheelchair prototype is now at the manufacturer's facility to make the appropriate structural modifications.

The next step to further optimize the proposed new model will be to perform quantitative field tests, to verify experimentally the comfort of the passenger, the performance of the suspensions, the handling and drivability of the wheelchair and the energy consumption values of the carriers.

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