Development and testing of an all-terrain wheelchair built with light magnesium alloy to improve the mobility of the rural population

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Abstract

The objective of this work was to design and test an all-terrain wheelchair for the rural population, implementing an AZ31 magnesium alloy and a lever propulsion mechanism to reduce the effort made during mobility. Two wheelchair prototypes were evaluated under the ISO7176 standard and usability testing. To validate the fact that the wheelchair weight reduction represents a benefit, a repeated measures study was carried out to establish the effect of the material change on mobility efficiency. The tests were carried out in an academic campus in Colombia in an open space with a surface covered with grass, unevenness, and other obstacles to emulate the conditions of a rural environment. A convenience sample was used, randomly selecting 17 subjects from the academic community without disabilities or overweight. Two prototypes were manufactured, one in aluminum and the second in magnesium alloy. For the study of repeated measurements, each participant had to complete three tests with both prototypes: a short-distance test, an obstacles test, and a long-distance test, which were performed randomly. The magnesium alloy prototype achieved a 25% weight reduction. In ISO7176 testing, both prototypes maintained their structural integrity and functionality. Also, with a confidence of 95%, it was possible to establish that with the magnesium prototype, the users traveled a greater distance in the same time. The new design meets the needs of mobility, support, and comfort of users, making efficient use of magnesium alloy. Weight reduction in the wheelchair allows the user to save time on mobility or cover greater distances with less physical effort. This is a starting point to offer a contextualized and affordable product to the Latin American population.

Key words:
Usability; product design; physical disability; mobility efficiency; wheelchair testing.

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Desarrollo y validación de una silla de ruedas todoterreno construida con una aleación ligera de magnesio para mejorar la movilidad de la población rural

Resumen

Este trabajo tuvo como objetivo diseñar y probar una silla de ruedas todoterreno para la población rural, implementando aleaciones de magnesio AZ31 y un mecanismo de propulsión de palanca para reducir el esfuerzo realizado durante la movilidad. Se evaluaron dos prototipos de la silla de ruedas bajo la norma ISO7176 y pruebas de usabilidad. Para validar que la reducción de peso de la silla de ruedas representaba un beneficio, se realizó un estudio de medidas repetidas para establecer el efecto del cambio de material sobre la eficiencia de la movilidad. Las pruebas se desarrollaron en un campus académico en Colombia en un espacio abierto con una superficie cubierta de césped, desniveles y otros obstáculos para emular las condiciones de un entorno rural. Se utilizó un muestreo por conveniencia, seleccionando aleatoriamente 17 sujetos de la comunidad académica sin discapacidad ni sobrepeso. Se fabricaron dos prototipos, uno en aluminio y el segundo en aleación de magnesio. Para el estudio de medidas repetidas cada participante debía realizar tres pruebas con ambos prototipos: una de corta distancia, otra de obstáculos y otra de larga distancia, que se realizaban aleatoriamente. El prototipo de aleación de magnesio logró una reducción de peso del 25%. En las pruebas ISO7176, ambos prototipos mantuvieron su integridad estructural y funcionalidad. Asimismo, se pudo establecer con una confianza del 95%, que con el prototipo de magnesio los usuarios recorrieron una mayor distancia en el mismo lapso de tiempo. El nuevo diseño satisface las necesidades de movilidad, soporte y comodidad de los usuarios, haciendo un uso eficiente del material. La reducción de peso en la silla de ruedas permite al usuario ahorrar tiempo en su movilidad o recorrer mayores distancias con menor esfuerzo físico. Esto representa un punto de partida para ofrecer un producto contextualizado y asequible a la población latinoamericana.

Palabras clave:
Usabilidad; diseño de producto; discapacidad física; movilidad eficiente; pruebas de producto.

Abbreviations
Al: Aluminum.
HR: Heart rate
Mg: Magnesium
PCI: Physiological Cost Index
S: Speed

Introduction

An all-terrain wheelchair is a device adapted to allow people with disabilities to move safely over rough terrain. This type of wheelchair is ideal for providing mobility in rural areas with irregular surfaces, obstacles such as rocks and roots, and different types of soil, including dirt, sand, grass, and gravel. Under such conditions, people with disabilities can move safely over rough terrain using an all-terrain wheelchair. The operation of a conventional wheelchair compromises the stability and safety of users and may even require an additional physical effort that exceeds the capabilities of the user (Singh et al., 2008). For people who live in these contexts, an appropriate wheelchair is required to access health services, education, and decent work, allowing them to generate their livelihood. (Rispin & Wee, 2015).

Given this situation, the global market offers some models of all-terrain wheelchairs that provide greater stability, including manual propulsion systems to facilitate the movement of the vehicle on uneven surfaces (Flemmer & Flemmer, 2016). However, these models have some limitations, such as their high cost, the lack of established marketing channels in some regions, and the complexity of repairs that make them unaffordable for the vast majority of the Latin American population (Good Life Medical, 2018; GRIT Freedom Chair, n.d.; Invacare, 2018; Lasher Sport, 2017; Mountain Tirke, 2018; RGK, 2017; Trekinetic, 2018; Unicare Health, 2018). Although low-cost models exist, these are usually only available through donation or are not available in countries such as Colombia (Motivation, 2015; Whirlwind, 2018).

On the other hand, to offer greater stability, these wheelchairs are usually larger than conventional models, which increases their weight. This affects the amount of effort the user must exert to move the wheelchair, how easy it is to transport the wheelchair when it is not in use, and the ability of other people to help the user (Liu et al., 2008; Medola et al., 2014; Organización Mundial de la Salud, 2008). Likewise, the weight of the wheelchair directly affects the preservation of the upper limbs, on which most of the autonomy of its users depends (Medola et al., 2014).

In this type of product, some strategies have been used to reduce its weight, such as changing the shape and using light materials such as aluminum alloys, titanium, and carbon fiber reinforced polymers (Medola et al., 2014). Researchers have barely explored the use of lighter alloys, such as magnesium (Mg) alloys. However, this is a material with high-performance for this type of application thanks to its properties, such as a high strength-to-weight ratio and high vibration absorption, which makes it suitable for achieving a significant reduction in the weight of the wheelchairs (Pan et al., 2016).

Until recently, magnesium alloys were only used in specialized applications that required an excellent strength-to-weight ratio, mainly in the aerospace and aeronautical industries. However, its availability in commercial presentations has increased, and competitive prices can be found compared to aluminum, expanding its application possibilities (You et al., 2017). The machining processes of this material are usually simple, fast, and effective, given its low weight and malleability (Berrio-Betancur et al., 2017). In addition, low environmental impact surface treatment processes have been developed to improve its corrosion and wear resistance, increasing its application potential (Zuleta et al., 2017).

This work represents the second part of the design process for an all-terrain wheelchair previously made (Chacon et al., 2020a; Chacon et al., 2020b) by the work team. The aim of this study is to design an AZ31 magnesium alloy all-terrain wheelchair with a magnesium alloy frame that reduces the weight of the system, an efficient propulsion mechanism for uneven terrain, and its adaptation to the ergonomic requirements of users that meets usability and technical tests established in the ISO 7176 standard (International Organization for Standardization, 2014, 2015). For the manufacturing process, the conditions and technology available in Latin America were considered thus proposing an affordable alternative for this population.

Materials and methods

Design Process

A user-centered design approach was used to develop the wheelchair. Initially, the design requirements were defined considering previous works (Flemmer & Flemmer, 2016.; Medola et al., 2014; Rispin & Wee, 2015.; Stanfill & Jensen, 2017) analyzing commercial products, and conducting interviews and focus groups with wheelchair users. Subsequently, the ideation process was carried out which provided the necessary information for digital modelling. Then, a structural analysis using Finite Elements Analysis (FEA) we performed and, finally, commercial components and systems and the detailed design of the frame, levers, and interfaces were selected.

To validate the design, two full-scale prototypes were built. One was constructed from aluminum alloy (6061-T6), and the other from magnesium alloy (AZ31B). Both prototypes were subjected to structural and usability testing to compare their design performance and to define the benefits obtained using magnesium alloy as a structural material.

Wheelchair prototypes

Both prototypes had the same structural design and drive mechanism. The only difference between the two wheelchairs was the material and, with it, the total weight of the prototype. This strategy was used to assess the impact of magnesium alloy on the structural performance and usability of the wheelchair.

Usability testing

Usability testing was developed in Colombia. The location for field tests of the wheelchairs was selected considering the characteristics of a non-uniform rural terrain. An open space with a surface covered with grass, unevenness, and other obstacles, such as small rocks and roots, was chosen inside an academic campus. The routes to be covered by the participants on this space were traced using wooden stakes. Figure 1 shows the terrain and the elements used for the demarcation of the routes.

Figure 1. The terrain in which the tests were carried out with (a) marks for slalom and race routes and (b) marks for the 6-minute test route.

A convenience sample was used, randomly selecting 17 subjects from the academic community without disability or overweight and 53% of the participants were male. The average age of the subjects was 22 (17-39) years, and their average height was 174cm (156cm-182cm). The subjects voluntarily agreed to participate in the study and signed informed consent and authorization for the use of photographs and videos recorded during the tests. Participants were free to withdraw at any time and knew the purpose of the test and how their information would be used.

A repeated measures study was carried out to validate that weight reduction in the wheelchair represents a benefit for the user and to establish the effect of material change on the Physiological Cost Index (PCI), on the distance traveled by the user, and on the speed achieved. The studies carried out by Rispin & Wee (Rispin & Wee, 2015), Sasaki & Rispin (Sasaki & Rispin, 2017), Stanfill & Jensen (Stanfill & Jensen, 2017) and Marszałek et al. (Marszałek et al., 2018) were taken as references to define the experimental procedure of the repeated measures of this study.

Three different tests were proposed: the short distance test (race), the obstacle test (slalom), and the long-distance test (six-minute test). The race test consisted of running a straight course 20 m-long at the maximum possible speed. The slalom test consisted of tunning a zigzag route of 20 m-length at the maximum possible speed. In addition, the six-minute test consisted of driving around a 10m-long quadrilateral road for six-minute at a comfortable self-selected speed. Each participant had to complete the three tests with the two prototypes. Considering the type of test and the type of wheelchair as independent variables, six experiments were configured. These were randomly assigned for each participant to guarantee the assumption of independence of observation.

The initial and final heart rates were recorded in each run using a Polar M200 wrist monitor placed on the left hand. For the race and slalom tests, the travel time was recorded in seconds with a manual stopwatch, and for the six-minute test, the distance traveled in meters was recorded with measuring tape. A rest time was established for the participant between each test until their heart rate returned to the initial resting state. Photographic and video records of the tests and the aforementioned measurements were recorded.

The Physiological Cost Index (PCI) was calculated with the recorded information for each test using Equation 1, where HR_f is the final heart rate, HR_i is the initial heart rate or at rest, and S is the average speed during the test (Rana & Pun, 2015; Rispin & Wee, 2015). This index is an accepted indicator to quantify and compare the physical effort made by a person when performing a task.

$$PCI = \frac{HR_f - HR_i}{S}$$

Equation 1. Physiological Cost Index

Statistical analysis of the data was performed using the JAMOVI software (The Jamovi Project, 2021). A descriptive analysis was performed, and the assumption of normality for the dependent variables was verified using the Shapiro-Wilk test. The dependent variables analyzed were the distance covered in the six-minute tests, the speed reached in the race and slalom tests, and the PCI of all tests. For the comparative analysis of the test the results with each type of chair, the t-student test was used for paired samples, with a significance level of 5% (α=0.05).

Technical testing

Technical tests were carried out following the ISO7176 part 1 and part 8 standard (International Organization for Standardization, 2014, 2015). In chronological order, tests were carried out rearward stability, lateral stability, static resistance, impact resistance, drop resistance, and fatigue tests were carried out. This order is established by the ISO standard. The stability and static resistance tests were carried out on a universal furniture test bench that was conditioned to carry out the tests according to the standard.

As it was a three-wheeled wheelchair, the rearward and lateral stability tests were performed. A platform with adjustable inclination adapted to the universal test bench was built in such a way that its inclination could be progressively increased. Two wheelchair configurations were used to test the angle in the most stable configuration and in the least stable configuration. These configurations are described in Table 1. Two runs were made for each configuration, with 75 kg, and 100 Kg. Figure 2a and 2b show the setup for the stability tests.

Table 1. Wheelchair configurations for stability tests.

Test	Most stable configuration	Least stable configuration
Rearward stability	Smallest angle between the backrest and the seat (85°) Footrest in lowest possible position (420mm)	Greater angle between the back and the seat (105°) Footrest in highest possible position (340mm)
Lateral stability	Smallest angle between the backrest and the seat (85°)	Greater angle between the back and the seat (105°)

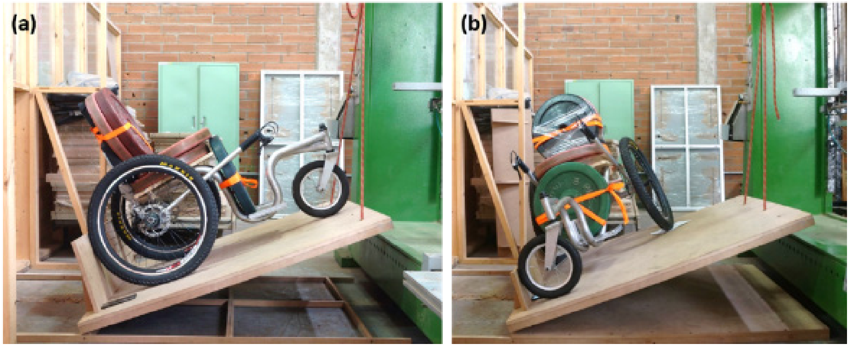

Figure 2. Stability test set-up (a) rearward and (b) lateral.

Static strength tests were applied to the footrests and performed on the universal test bench. The resistance to downward forces was tested with a load of 980N. The static upward resistance test was performed with a mass of 100 kg. At the end of each test, the wheelchair was inspected for visible cracks, fractures, separations between elements, deformed components, free movements, and loss of adjustments that affect the performance or misalignment in the brake position. Figure 3a and 3b shows the configuration for static strength tests.

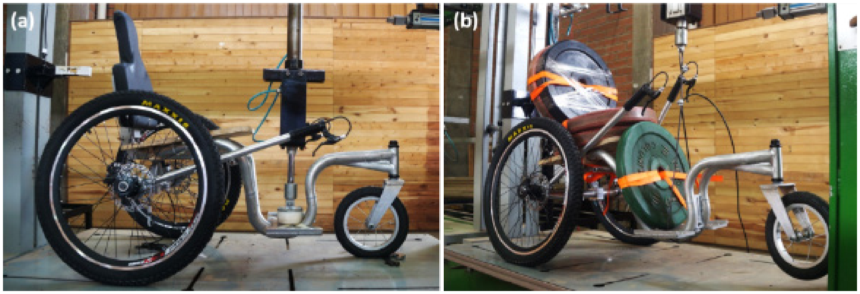

Figure 3. Static resistance test setup for (a) resistance to downward forces and (b) resistance to upward forces.

A special device was locally built for the fatigue test. This device was equipped with three 250mm diameter rollers with two 12mm high protrusions separated every 180°. These rollers rotate at a speed of 1m/s while the wheelchair rolls continuously. The test was performed with a 100 kg load and 200,000 cycles, equivalent to 110 hours. The mentioned configuration can be seen in Figure 4a. For the drop test, the device included a cam mechanism that raised the wheelchair 5cm above the ground and allowed it to fall freely. The wheelchair was tested with a 100 kg load and 6666 cycles or drops. Figure 4b shows the configuration for the drop test.

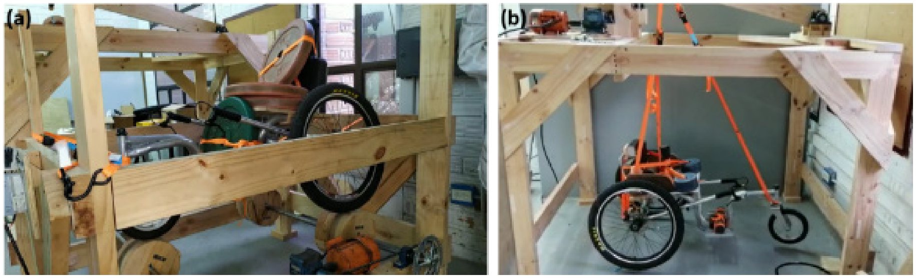

Figure 4. Configuration for (a) fatigue and (b) drop tests.

Finally, for the impact resistance test, a pendulum-type device was built to impact the wheelchair with a 10 kg mass. According to the ISO standard, an impact was produced on the caster wheel while the chair remained static and loaded with 100 kg. The pendulum was raised at an angle of 46° and dropped to hit the caster wheel. Figure 5 shows the configuration. At the end of each test, the wheelchair was inspected to detect visible defects, separations, deformed components, free movements, and loss of adjustments that affect the operation or misalignment of the brakes.

Figure 5. Impact resistance test setup showing (a) the position of the chair and (b) the impact point of the pendulum

Results

The aluminum prototype weighed 20 kg. This prototype was made of 6061 T6 aluminum tubing with an outer diameter of 38mm and 1.63mm thickness. The magnesium prototype weighed 15 kg. This prototype was made of AZ31B magnesium tubing with an outer diameter of 38 mm and 2.65 mm thickness. The lever propulsion system included a freewheel and a disc brake commercially available for bicycles. The design of this system focused on developing lightweight and compact components that would allow lever propulsion without adding excessive weight. The design of the seat, backrest, and footrests consisted of rigid surfaces made of 6.35 mm thick AZ31B magnesium sheets. This design allows constumizing the size of the backrest and seat and vary the height of the footrests according to the anthropometric characteristics. Figure 6a and 6b show the prototypes being used during the tests.

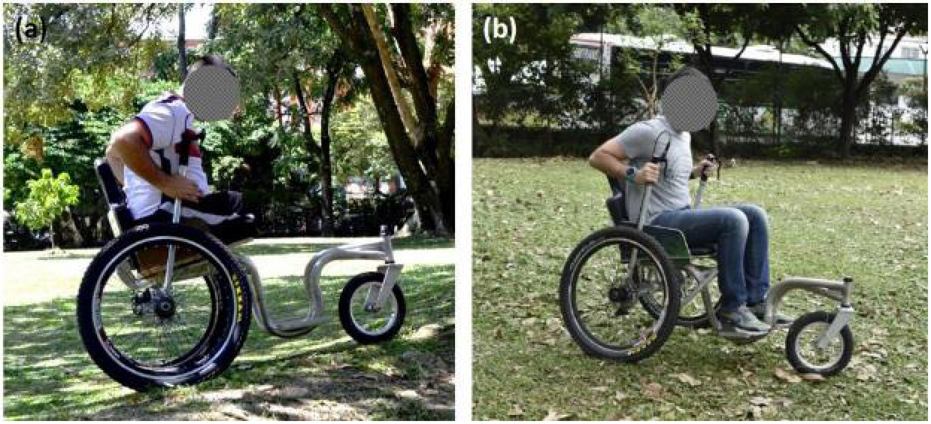

Figure 6. Prototypes manufactured in (a) 6061 T6 aluminum and (b) AZ31 magnesium alloy.

For usability test data, the assumption of normality of dependent variables was verified using the Shapiro-Wilk test. It was found that all, except the speed in the slalom course with the Mg wheelchair, had a normal distribution (p-value>0.05). Table 2 and Table 3 show the results for all the dependent variables.

Table 2. Shapiro-Wilk test for the dependent variables of distance and speed.

Variable	6 min test distance Mg wheelchair	6 min test distance Al wheelchair	Race test speed Mg wheelchair	Race test speed Al wheelchair	Slalom test speed Mg wheelchair Me(P25-P75)	Slalom test speed Al wheelchair
N	17	17	17	17	17	17
X(SD)	184 (45,2)	152 (38,2)	0,91 (0,22)	0,85 (0,25)	0,66 (0,56 - 0,69)	0,62 (0,19)
Shapiro-Wilk p	0,592	0,367	0,549	0,370	0,006	0,334

Table 3. Shapiro-Wilk test for dependent variables associated to PCI.

Variable	6min test PCI Mg wheelchair	6min test PCI Al wheelchair	Race test PCI Mg wheelchair	Race test PCI Al wheelchair	Slalom test PCI Mg wheelchair	Slalom test PCI Al wheelchair
N	17	17	17	17	17	17
X(SD)	91,2 (24,7)	103 (32,9)	31,3 (17,9)	32,3 (15)	42,5 (19,8)	50,1 (21,1)
Shapiro-Wilk p	0,750	0,665	0,331	0,473	0,105	0,849

Consequently, the comparative analysis was performed using the t-student test for paired samples. The mean distance traveled in the six-minute test with the magnesium wheelchair was 184m (45.2m), while with the aluminum wheelchair, it was 152m (38.2m). With a p-value <0.001, it can be stated that there is a statistically significant difference between these two variables, showing higher values for the distance traveled with the magnesium wheelchair. With 95% confidence, the additional distance traveled is expected to be between 20.1 and 43.9m for the study population, with an expected mean of 32m. For the other comparisons, no statistically significant differences were found (p-values>0.05). Table 4 shows the results of the comparative analyses.

Regarding stability tests, the maximum angles recorded are shown in Table 5. The angles reached remain above the maximum specified for access ramps according to the Colombian technical standard NTC 4143 (ICONTEC Internacional, 2009), except the angle recorded for the least stable position in the rearward stability test.

No visible problems affecting the functioning of the wheelchair or the brakes were observed in the static stress tests. At the end of the impact test, no cracks or fractures were observed, validating that the wheelchair maintained its integrity. Likewise, after finishing the fatigue and drop tests, no damage to the components and the adjustments between them were identified.

Table 4. Results of the t-student test for the comparative analysis.

Variable #1	Variable #2	T-student p-value	Mean difference	95% Confidence Interval	
				Inferior	Superior
6min test distance Mg wheelchair	6min test distance Al wheelchair	<.001	32.024	20.11	43.93
Race test speed Mg wheelchair	Race test speed Al wheelchair	0.259	0.088	-0.048	0.17
Slalom test speed Mg wheelchair	Slalom test speed Al wheelchair	0.256*	0.035	-0.35	0.11
6min test PCI Mg wheelchair	6min test PCI Al wheelchair	0.152	-11.584	-27.92	4.75
Race test PCI Mg wheelchair	Race test PCI Al wheelchair	0.834	-0.991	-10.85	8.87
Slalom test PCI Mg wheelchair	Slalom test PCI Al wheelchair	0.311	-7.668	-23.21	7.87

* Calculated with Wilcoxon rank because variables have a different distribution other than normal

Table 5. Values for the stability test.

Test	Configuration	Weight (Kg)	Maximum angle (°)	Corresponding tilt (%)
Rearward stability	Most stable configuration	75	14	24,9
		100	11	19,4
	Least stable configuration	75	10	17,6
		100	4	7
Lateral stability	Most stable configuration	75	22	40,4
		100	19	34,4
	Least stable configuration	75	23	42,4
		100	22	40,4

Discussion

The results of the statistical analysis allow affirming that, with the use of magnesium in the wheelchair frame, people were able to travel a greater distance in the six-minute test. This type of test is commonly used in similar studies since it allows studying the effect that the wheelchair can have during a long distance journey (Gagnon et al., 2016). In this way, the Mg wheelchair affects the efficiency of mobility, allowing users to travel a greater distance at the same time or, in other words, to travel the same distance in less time. This may be because the reduced weight of the wheelchair may cause less fatigue in users, allowing them to maintain a higher speed. Nevertheless, it is advisable to delve deeper into this result in greater depth, by carrying out tests with wheelchair users.

Although no statistically significant difference was found for the other comparisons, it is observed that the values with the magnesium chair showed desirable trends. Speed values for the race and slalom tests tended to be higher with the Mg wheelchair as the mean difference showed positive values. On the other hand, the mean difference in all PCIs shows that this indicator was lower in all tests with the Mg wheelchair. These results may indicate that physical fatigue could have been less when testing with this prototype. However, since no statistically significant difference was found, it cannot be concluded in this regard, but exploring it in future research is recommended.

The results of the technical tests made it possible to validate that the structure of the frame and the adjustment conditions between components have an adequate behavior. The integrity of the structure and the preservation of the functional characteristics of the wheelchair are the criteria defined in the standard mentioned above to consider that it meets the conditions for safe operation. Visual and tactile inspection carried out at the end of the technical tests confirmed a positive result. This validates that the proposed design withstands the rough conditions of its use.

Regarding the result of the rearward stability test in the less stable configuration, it is suggested to explore the possibility of using the greatest angle of the backrest without compromising the stability of the system. This can be achieved by allowing adjustments in the position of the rear wheels or backrest to move forward the location of the center of mass of the system. Installation of anti-tip devices may also be considered.

Conclusion

The magnesium alloy prototype achieved a weight reduction of 25% compared to the aluminum prototype, a reduction of up to 32% compared to similar models in other structural materials. In addition, the technical tests showed that the proposed design has an appropriate structural behavior and that the conditions of adjustment between the components of the wheelchair are suitable for this application.

The resulting design of the wheelchair includes a three-wheel configuration to improve stability and a lever system to aid in the efficiency of the ride. This design responds to the needs of mobility, support, and comfort of users, making efficient use of the proposed material. Similarly, in the usability tests, it was possible to validate that the weight reduction achieved positively affected the efficiency of the wheelchair, demonstrating that a greater distance was traveled with the magnesium chair.

The design of the AZ31 magnesium alloy wheelchair was fabricated entirely in Latin America, which is a starting point for offering a contextualized product at an affordable cost for the conditions of this region. To move forward in this way, it is suggested that future studies address usability tests with permanent wheelchair users who live in rural areas, as well as the development of scaling conditions for their production at an industrial level.

References

Berrio-Betancur, L. F., Echeverry-Rendón, M., Correa-Bedoya, E., Zuleta, A. A., Robledo-Restrepo, S. M., & Castaño-González, J. G. (2017). Development of the magnesium alloy industry in Colombia - An opportunity. *DYNA*, *84*(203), 55–64.

Chacon-Cifuentes, P., Zuleta, A. A., Sevilla, G., Valencia-Escobar, A., Correa-Bedoya, E., & Echeverria-Echeverria, F. (2020a). Human factors in all-terrain wheelchair design for rural population. In Advances in Usability and User Experience: Proceedings of the AHFE 2019 *International Conferences on Usability & User Experience, and Human Factors and Assistive Technology*, 2019, 899-910.

Chacon-Cifuentes, P., Zuleta-Gil, A., Cadavid, G. S., Valencia-Escobar, A., Correa-Bedoya, E., & Echeverria-Echeverria, F. (2020b). Interdisciplinary Approach of the Design Process for the Application of New Materials in Wheelchair Design. *In Advances in Interdisciplinary Practice in Industrial Design: Proceedings of the AHFE 2019 International Conference on Interdisciplinary Practice in Industrial Design*, 2019, 75-82.

Flemmer, C. L., & Flemmer, R. C. (2016). A review of manual wheelchairs. *Disability and Rehabilitation: Assistive Technology*, *11*(3), 177–187. https://doi.org/10.3109/17483107.2015.1099747

Gagnon, D. H., Roy, A., Verrier, M. C., Duclos, C., Craven, B. C., & Nadeau, S. (2016). Do Performance-Based Wheelchair Propulsion Tests Detect Changes among Manual Wheelchair Users with Spinal Cord Injury during Inpatient Rehabilitation in Quebec? *Archives of Physical Medicine and Rehabilitation*, *97*(7), 1214–1218. https://doi.org/10.1016/j.apmr.2016.02.018

Good Life Medical. (2018). *Quickie GT*. Retrieved on:(2021) and From: https://www.goodlifemedical.com.au/products/manual-wheelchairs/quickie-gt/

GRIT Freedom Chair. (n.d.). *GRIT Freedom Chair - All Terrain Wheelchair*. Retrieved on: (2019) and From: https://www.gogrit.us/

ICONTEC Internacional. (2009). *NTC 4143 Accessibility To Physical Environment. Buildings and Urban Spaces Fixed Ramps Adequate and Basic* (Issue 571).

International Organization for Standardization. (2014). *International Standard ISO 7176-1* (Vol. 2014). ISO. https://doi.org/10.1109/IEEESTD.2007.4288250

International Organization for Standardization. (2015). *International Standard ISO 7176-8* (Vol. 2015). ISO.

Invacare. (2018). *Invacare Top End Crossfire All Terrain*. Retrieved on: (2020) and From: http://www.topendwheelchair.com/product/crossfire-all-terrain-wheelchair

Lasher Sport. (2017). *Lasher Sport_ BT-Mg*. Retrieved on: (2019) and From: http://www.lashersport.com/pages/chairs/btmg/btmg.html

Liu, H., Cooper, R. A., Pearlman, J., & Connor, S. (2008). Evaluation of titanium ultralight manual wheelchairs using ANSI / RESNA standards. *Journal of Rehabilitation Research & Development*, *45*(9), 1–20. https://doi.org/10.1682/JRRD.2007.12.0204

Marszałek, J., Kosmol, A., Mróz, A., Wiszomirska, I., Fiok, K., & Molik, B. (2018). Physiological parameters depending on two different types of manual wheelchair propulsion. *Assistive Technology*, *00*(00), 1–7. https://doi.org/10.1080/10400435.2018.1529005

Medola, F. O., Elui, V. M. C., Santana, C. D. S., & Fortulan, C. A. (2014). Aspects of Manual Wheelchair Configuration Affecting Mobility: A Review. *Journal of Physical Therapy Science*, *26*, 313–318.

Motivation. (2015). *Motivation Rough Terrain*. Retrieved on:(2020) and From: https://www.motivation.org.uk/rough-terrain

Mountain Tirke. (2018). *Mountain trike*. Retrieved on:(2019) From: http://www.mountaintrike.com/products/mountain-trike

Organización Mundial de la Salud. (2008). Pautas para el suministro de sillas de ruedas manuales en entornos de menores recursos. *Pautas Para El Suministro de Sillas de Ruedas Manuales*, 137.

Pan, F., Yang, M., & Chen, X. (2016). A Review on Casting Magnesium Alloys: Modification of Commercial Alloys and Development of New Alloys. In *Journal of Materials Science and Technology* (Vol. 32, Issue 12, pp. 1211–1221). https://doi.org/10.1016/j.jmst.2016.07.001

Rana, B. S., & Pun, M. (2015). Estimation of Physiological Cost Index as an Energy Expenditure Index using MacGregor's Equation. *JNMA; Journal of the Nepal Medical Association*, *53*(199), 174–179. https://doi.org/10.31729/jnma.2786

RGK. (2017). *RGK Tiga TX I Made to Measure All Terrain Wheelchair*. Retrieved on: (2019) and From: https://www.rgklife.com/wheelchairs/daily-wheelchairs/all-terrain-wheelchair.html

Rispin, K., & Wee, J. (2015). Comparison between performances of three types of manual wheelchairs often distributed in low-resource settings. *Disability and Rehabilitation: Assistive Technology*, *10*(4), 316–322.

Sasaki, K., & Rispin, K. (2017). Assessment of physiological performance and perception of pushing different wheelchairs on indoor modular units simulating a surface roughness often encountered in under-resourced settings. *Assistive Technology*, *29*(4), 173–180. https://doi.org/10.1080/10400435.2016.1216473

Singh, S. K., Arya, K. N., & Nagar, R. (2008). To compare the physiological effects of standard and light weight wheelchair design during propulsion by persons with spinal cord injury (SCI). *The Indian Journal of Occupational Therapy*, *39*(3), 73–78.

Stanfill, C. J., & Jensen, J. L. (2017). Effect of wheelchair design on wheeled mobility and propulsion efficiency in less-resourced settings. *African Journal of Disability*, *6*(0), 1–9. https://doi.org/10.4102/ajod.v6i0.342

The Jamovi Project. (2021). *jamovi (Version 1.6)*.

Trekinetic. (2018). *Trekinetic K-2*. Retrieved on:(2020) and From: http://www.trekinetic.com/K2.php

Unicare Health. (2018). *Bushranger*. Retrieved on:(2019) and From: https://www.unicarehealth.com.au/shop/5060-wheelchair-bushranger-manual

Whirlwind. (2018). *Whirlwind Rough Ride*. Retrieved on:(2020) and From: https://whirlwindwheelchair.org/product/roughrider

You, S., Huang, Y., Kainer, K. U., & Hort, N. (2017). Recent research and developments on wrought magnesium alloys. *Journal of Magnesium and Alloys*, *5*, 239–253. https://doi.org/10.1016/j.jma.2017.09.001

Zuleta, A. A., Correa, E., Castaño, J. G., Echeverría, F., Baron-Wiecheć, A., Skeldon, P., & Thompson, G. E. (2017). Study of the formation of alkaline electroless Ni-P coating on magnesium and AZ31B magnesium alloy. *Surface and Coatings Technology*, *321*, 309–320. https://doi.org/10.1016/j.surfcoat.2017.04.059

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