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FACULDADE DE ENGENHARIA MECÂNICA

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PROTOTYPE OF A SWIMMING POOL LIFT FOR PEOPLE WITH DISABILITIES

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Prototype of a swimming pool lift for people with disabilities

Thesis submitted to the Faculty of Mechanical Engineering in partial fulfillment of the requirements for the degree of Master of Science at the Federal University of Uberlandia.

Advisor: Prof. Dr. Cleudmar Amaral de Araújo

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ABSTRACT

One of the biggest concerns regarding safety for people with disabilities is transferring from one place to another, such as from a wheelchair to a swimming pool, especially for people who don't have enough resources. This work addresses the design, manufacture, and evaluation of a novel pool lift prototype. By combining new mechanisms and actuation systems, this work is a step towards closing the gap between Assistive Technology and the low-income population in Brazil. After extensive background research in patents, standards, and international markets, three benchmarks were selected to study and extract insights from the latest innovations. Several mechanisms were analyzed using kinematic and kinetic models, which allowed arriving at a design that substantially reduced the linear force required by the actuator. The linear actuator was replaced with an electric winch system, eliminating the dependence on importing it and lowering the cost of the final product. The dimensions of the pool lift were optimized to reach a distance of 400 millimeters from the edge. For this, a movement transmission mechanism was developed at the end of the lift arm - so that the seat automatically rotates on a Normal axis in relation to the deck's surface - when descending and ascending. Benchmarking analysis, FEA, and weight-loading tests validated the ideas and design. Finally, an operational environment validation test was carried out with focus group people, arriving at a prototype at TRL 7 level. The user study showed that the pool lift has a 68 score on the System Usability Scale. The result is a patented device to assist the transfer of people with reduced mobility between a pool deck and its water tank that complies with Brazilian and ADA Standards and comprises a column fixed to a base adjacent to the edge of the pool, activation that can be actuated by an electric motor, a protective cabinet that houses the metallic and electronic parts that are sensitive to environmental weather, a four-bar mechanism that is configured in such a way that it synchronizes the movement of the lifting arm with the seat during its locomotion, and an angular transmission mechanism that transfers the torque produced by the rotational movement of the lift arm. Thus, this work describes the development and validation process of this product.

Key-words: Transfer lifts. Assistive technology. Accessibility in swimming pools. Benchmarking.

RESUMO

Uma das maiores preocupações em relação à segurança das pessoas com deficiência é a transferência de um lugar para outro, como de cadeira de rodas para piscina, principalmente para pessoas que não dispõem de recursos suficientes. Este trabalho aborda o projeto, fabricação e avaliação de um novo protótipo de elevador de piscina. Ao combinar novos mecanismos e sistemas de atuação, este trabalho é um passo para fechar a lacuna entre a Tecnologia Assistiva e a população de baixa renda no Brasil. Após extensa pesquisa de antecedentes em patentes, padrões e mercados internacionais, três benchmarks foram selecionados para estudar e extrair insights das últimas inovações. Vários mecanismos foram analisados usando modelos cinemáticos e cinéticos, o que permitiu chegar a um projeto que reduziu substancialmente a força linear exigida pelo atuador. O atuador linear foi substituído por um sistema de guincho elétrico, eliminando a dependência de importação e diminuindo o custo do produto final. As dimensões do elevador da piscina foram otimizadas para atingir uma distância de 400 milímetros da borda. Para isso, foi desenvolvido um mecanismo de transmissão de movimento na extremidade do braço de elevação - para que o assento gire automaticamente em um eixo Normal em relação à superfície do convés - ao descer e subir. Análise de benchmarking, MEF e testes de carga de peso validaram as ideias e o design. Por fim, foi realizado um teste de validação do ambiente operacional com pessoas do grupo focal, chegando a um protótipo no nível TRL 7. O estudo do usuário mostrou que o pool lift tem uma pontuação de 68 na escala de usabilidade do sistema. O resultado é um dispositivo patenteado para auxiliar a transferência de pessoas com mobilidade reduzida entre o deck da piscina e sua caixa d'água que atende às Normas Brasileiras e ADA e compreende uma coluna fixada em uma base adjacente à borda da piscina, acionamento que pode ser acionado por um motor elétrico, um gabinete de proteção que abriga as partes metálicas e eletrônicas sensíveis às intempéries ambientais, um mecanismo de quatro barras configurado de forma a sincronizar o movimento do braço de elevação com o assento durante sua locomoção , e um mecanismo de transmissão angular que transfere o torque produzido pelo movimento de rotação do braço de elevação. Assim, este trabalho descreve o processo de desenvolvimento e validação deste produto.

Palavras-chaves: Elevador de transferência. Tecnologia assistiva. Acessibilidade em piscinas. Projeto Mecânico.

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND ACRONYMS

ABNT	Brazilian National Standards Organization (from Portuguese: *Associação Brasileira de Normas Técnicas*)
ADA	Americans With Disabilities Act
AT	Assistive Technology
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CINTESPBr	Brazilian Center of Reference in Technological Innovations for Paralympic Sports (from Portuguese: *Centro Brasileiro de Referência em Inovações Tecnológicas para Esportes Paralímpicos*)
DoF	Degrees of freedom
DOJ	United States Department of Justice
FDA	Food and Drug Administration
FEM	Finite Element Method
IBGE	Brazilian Institute of Geography and Statistics (from Portuguese: *Instituto Brasileiro de Geografia e Estatística*)
ICF	International Classification of Functioning, Disability and Health
INPI	National Industrial Property Institute (from Portuguese: *Instituto Nacional de Propriedade Industrial*)
ISO	International Organization for Standardization
SUS	System Usability Scale
TRL	Technology Readiness Level
USPTO	United States Patent and Trademark Office
WHO	World Health Organization

LIST OF SYMBOLS

T_n	Nominal torque
P_n	Rated power
n	Motor rotational speed
DC	Direct current
O_2	Fixed pivot
N	Number of DoF
B	Number of links
n_{j1}	Number of pairs having 1 DoF
n_{j2}	Number of pairs having 2 DoF
r	Length of the actuator link
p	Length of lift arm supporting actuator force
L	Distance between motor and pivot O_2
d	Length of the lift arm
F	Actuator force
W	User weight force
φ	Angle formed from the axis x to r
θ_2	Angle formed from the axis x to p
β	Angle formed from the axis x to W
γ	Angle formed from p and d
q	Position vector
$\dot{q}$	Velocity vector
$\ddot{q}$	Acceleration vector
$\dot{r}$	Derivative of r with respect to time
$\ddot{r}$	Derivative of $\dot{r}$ with respect to time

$\dot{\varphi}$	Derivative of ϕ with respect to time
$\dot{\theta}_2$	Derivative of θ_2 with respect to time
$\ddot{\varphi}$	Derivative of $\dot{\phi}$ with respect to time
$\ddot{\theta}_2$	Derivative of $\dot{\theta}_2$ with respect to time
A_x	x-component of the reaction force acting on the pivot O_2
A_y	y-component of the reaction force acting on the pivot O_2
F_x	x-component of the reaction force between the actuator and the link
F_y	y-component of the reaction force between the actuator and the link
m_b	Link mass
m_w	User mass
a_x	x-component of the the acceleration of the center of gravity of the link
a_y	y-component of the the acceleration of the center of gravity of the link
M_W	Moment due to force W
M_F	Moment due to force F
I	Moment of inertia of the link about the point O_2
ΔPE_{elec}	Battery potential energy
ΔV	Potential Difference of the battery
Q	Battery full electrical charge

CONTENTS

1 INTRODUCTION

One of the biggest dilemmas faced by people with disabilities and/or reduced mobility is related to safety when transferring from one place to another, for example, from a wheelchair to a swimming pool. There may be difficulties for the person transferring as well as the person helping with the transfer. There are several solutions to this problem, such as architectural designs in swimming pools and lifting and transferring equipment that make the process safer and more accessible.

A mechanism designed to assist in transferring persons with limited mobility or physical disabilities to a swimming pool is commonly referred to as a “pool lift.” This equipment usually includes an electronic transmission system, an articulated movement, an attachment base attached to the edge of the pool, and a seat for the user. Before pool lifts were invented in 1980, the biggest challenge in aquatic therapy centers was simply getting people out of the water safely and easily. They were transferred from their wheelchairs by attendants and carried into the water and then taken out of the water and back to their chairs. The first commercially successful pool lift dramatically changed this labor-intensive procedure as it eliminated dependence on such attendants, allowing more people with disabilities to participate in hydrotherapy.

This type of device stems from a multidisciplinary project in the areas of Engineering together with Physiotherapy for the development of Assistive Technologies that help these people, improving their quality of life. This task poses many challenges for researchers as they investigate new electromechanical designs and control strategies that might work in any architectural pool design and adapt to the mobility needs of the person with a disability. Common challenges faced in the field of lifting engineering include: securing the pool lift to the floor, transporting the pool lift between storage and use locations, providing a constant steering system to operate the pool lift, and providing stability for the pool lift seat to remain an upright position during movement and the incorporation of safety systems.

1.1 Motivation and Research Objectives

Although legislation and regulations in Brazil declare that the rights of individuals with disabilities to equality have been achieved, there is still a significant gap between this achievement and everyday life. People with disabilities in Brazil must deal with a variety of social, financial, and mobility challenges that are all related to their limited mobility. For individuals who are mostly from the lower socioeconomic classes, the issue is even worse. Many businesses in underprivileged areas of Brazil cannot afford to buy a powerful, motorized pool lift. Additionally, the Brazilian market's commercially available pool lift alternatives are of poor quality.

The justification for the development of a product is based on preliminary research involving physical therapy centers and manufacturers of medical equipment, which show that most clinics with swimming pools lack equipment that helps patients access the swimming pool for therapeutic purposes. In addition to the lack of equipment, this procedure of moving patients has other crucial characteristics, including the length of time, the level of risk, and the physical and mental exhaustion of physical therapists. Physical therapy clinics have limited the availability of these services, lowering the range of available treatments for patients with these needs. This is due to the poor supply of this kind of product on the national market and the high cost of importing high-quality ones.

This work's objective is to create a high-quality, reasonably priced pool lift using products made and offered on the Brazilian market. Wherein, this thesis is a continuation of Camilo (2019). As a result, it is possible to provide the population with limited resources with a national and accessible product. Numerous methods for getting a person between the pool and its deck were investigated as a solution to the issue at hand, and two of them were chosen for benchmarking since they were considered to be the most effective. This study introduces a new mechanism, shown in Fig. (1), that is, as far as is known, novel, while following the engineering design technique proposed by Norton (2010). To ensure the design's safety, power, and robustness, several analyses were carried out.

Figure 1 – Prototype of the presented pool lift.

Source: Elaborated by the author.

2 LITERATURE REVIEW

During this Chapter, basic concepts related to people with disabilities and the state of the art of transfer equipment for swimming pools are presented, as well as their importance as a tool to assist in rehabilitation processes.

2.1 People with Disabilities

Any condition that makes it more difficult for a person to engage in specific activities or enjoy equal access within a given society is referred to as a disability. Disabilities can be caused by cognitive, developmental, intellectual, mental, physical, or sensory issues. A person may be born with a disability or develop one throughout their lifetime. In the past, disabilities were only acknowledged if they met a specific set of requirements, although disabilities are not binary and might have individual features depending on the person. Like many social categories, the concept of "disability"is under heavy discussion amongst academia, the medical and legal worlds, and the disability community.

2.1.1 Concepts

Disability, according to the World Health Organization (WHO, 2012), is a generic term for disabilities, activity limitations, and participation restrictions. Deficiencies are problems that affect a body's structure or function; Activity limitations are difficulties to perform actions or tasks and participation restrictions are problems to participate in vital situations. Therefore, disability is a complex phenomenon that reflects an interaction between the characteristics of the human organism and the characteristics of the society in which they live.

The International Classification of Functioning, Disability and Health (ICF) (WHO, 2001) distinguishes between body functions, which are the physiological functions of organ systems (including psychological functions), and body structures, which are the anatomical parts of the body, such as organs, limbs, and their components. Deficiencies correspond to a deviation from what is generally accepted as the normal (standard) biomedical state of the body and its functions, which may vary over time. Activity is the performance of a task or action by an individual and participation is the involvement in a life situation.

2.1.2 Hydrotherapy

The swimming pool is an extremely important environment for the treatment of people with disabilities. Exercise in swimming pool water has long been recognized as a beneficial type of physical therapy for people with temporary and permanent disabilities. A study by Barassi et al. (2017) treated and evaluated 50 subjects who suffered from neuromotor impairment using aquatic rehabilitation techniques, the article reached positive conclusions about its effectiveness. According to the research, the physical characteristics of the aquatic environment can be explored by the rehabilitator to obtain specific muscle, neurological, and sensory recovery with different modalities and times compared to the techniques used in dry conditions, stimulating the reacquisition of impaired or even lost neuromotor-sensory skills. In addition, according to Porto, Simões e Moreira (2008), rehabilitation is an activity in which the expected results for the patient must be associated with increased independence and social autonomy, thus enabling a significant improvement in the quality of life of all those involved in the process.

2.1.3 Accessibility Legislation

In Brazil, the Federal Constitution guarantees every citizen their social rights, including the right to come and go freely, and fundamental guarantees for the human person, which include all individuals regardless of their physical or mental conditions. The main Brazilian law that governs this issue is the Accessibility Law - Decree of Law nº 5296, of December 2, 2004, which regulates Law nº 10.048/2000, which gives priority to care for people with disabilities, and Law nº 10.098/2000, which establishes general norms and basic criteria for the promotion of accessibility for people with disabilities or reduced mobility. As it is federal, it is valid in all states of the country. Nevertheless, States and municipalities still have their local legislation dealing with accessibility.

With regard to accessibility in swimming pools, article 18, sole paragraph of Federal Decree 5296/2004, provides for the construction of multifamily private-use buildings, and the construction, expansion, or renovation of buildings for collective use must comply with the precepts of accessibility. In the interconnection of all parts of common use or open to the public, according to the standards of the technical standards of accessibility of ABNT.

Among the regulations outlined in this Decree, it is worth mentioning the obligations regarding the formalization of buildings, such as the issuance of the "*Habite-se*"letter and the granting of a business license, as well as its renewals when the document was issued prior to Decree 5296/ 2004 - in order to obtain such documents, the accessibility rules provided for in this Decree and in ABNT’s technical accessibility standards must be observed and certified.

2.1.4 Assistive Technology

More than one billion people around the world live with some form of disability. In the coming years, disability will be an even greater concern as its incidence has increased. This is due to aging populations and the increased risk of disability in the older population, as well as the global increase in chronic diseases such as diabetes, cardiovascular disease, cancer, and mental disorders (WHO, 2012). In Brazil, approximately 45 million people are living with some type of disability. Of these, about 13 million have motor disabilities (IBGE, 2010b).

In general, people with disabilities face numerous social, economic, and mobility difficulties, all associated with reduced mobility. Facility-related obstacles include inaccessible parking areas, inadequate access to buildings, poor signage, narrow doors, internal steps, and inadequate sanitation facilities. A survey carried out in 41 Brazilian cities on architectural barriers in primary health care units concluded that about 60 % of them do not allow adequate access for people with functional difficulties. Among these numerous barriers, swimming pools, in general, are inaccessible to most of these people (SIQUEIRA et al., 2009).

The elimination of access barriers in the streets, buildings, and means of transport deserved the attention of those who thought and drafted the Constitution and the equality of people with disabilities, at least before the law, is guaranteed as a possibility of integration of these people in the city allowing its circulation and the fulfillment of its spatial needs. Laws and norms announce the achievement of the rights of people with disabilities to equality, but the distance between this achievement and reality is still wide. The reality of people with disabilities in Brazil and the world reveals few opportunities to engage in sports activities, whether for recovery, leisure, or competition. There are still numerous physical barriers, such as narrow sidewalks, with deteriorated pavement and obstacles that are difficult to detect by people with visual impairments; doors too narrow for a wheelchair to pass through; inaccessible stairs in buildings; small elevators without braille signage; inaccessible buses, trains, and planes; telephones and light switches placed out of reach or in the absence of adapted restrooms. These barriers are the result of the lack of concern and unpreparedness of technicians in different areas (COHEN, 1998).

Assistive Technology (AT) encompasses equipment and services that aim to promote functionality, related to the activity and participation of people with disabilities, disabilities, or reduced mobility, aiming at autonomy, independence, quality of life, and social inclusion. In the case of accessibility in swimming pools, the most recent assistive technologies are in the development of transfer lifts. In Brazil, many resources developed in universities are not incorporated into the market, the variety of products manufactured in the country is small, and most imported devices do not have tax exemption, significantly increasing the cost of AT available for sale. Therefore, Brazil needs to encourage the development of low-cost AT products and services to serve the less favored social classes and thus apply the concept of social sustainability, raising the quality of life of the entire population. There are many bottlenecks ranging from the training of scientists and researchers to the strengthening of the infrastructure necessary for the full development of their activities, through an economic environment that is more conducive to innovation. All, or most of these aspects, can be influenced or improved by the implementation of adequate and intelligent public policies (NEGRI, 2018).

2.2 Pool Lifts

Swimming pool lifts are a type of patient lift that allows an individual to be transferred from the pool deck to the pool and back to the pool deck. There are several ways to transfer a person into and out of a pool. This section will go over the history and evolution of swimming pool lifts, as well as information on the design and use of these devices. The goal is to give the reader a better understanding of the various types of lifts and their respective advantages in providing pool access.

2.2.1 Standards

On an international level, the existing standard for patient lifts is ISO 10535:2006. This standard not only specifies design and manufacturing requirements but also categorizes patient lifts into different groups. Patient lifts or hoists are divided into two categories: stationary hoists and mobile hoists.[1] A stationary hoist is a piece of equipment that lifts, transfers, or moves people within a predetermined area. Stationary hoists can be fastened to a wall, ceiling, or floor, or they can be free-standing on the floor, installed in an allied device such as a deck anchor. A mobile hoist is a piece of equipment with a device or devices (e.g. wheels) that can travel freely over the floor and raise, transfer, or move a person without the use of a fixed installation or another allied device. Design types and test protocols appropriate for all patient lifts are contained in ISO 10535:2006 (S.R. SMITH LLC, 2012).

In Brazil, ABNT NBR 9050 is the standard that establishes criteria and technical parameters to be observed in the design, construction, installation, and adaptation of urban and rural environments, and of buildings to accessibility conditions. This standard require that newly constructed or altered pools have means of accessibility, which also include specific requirements for pool lifts: location, seat size, lift capacity, and floor space. This standard also classifies and standardizes the methods of accessing swimming pools (ABNT, 2015).

In the United States, the Food and Drug Administration (FDA) regulates patient lifts. Any company in the United States that manufactures a regulated product must register with the FDA and demonstrate that its manufacturing facility follows current "good manufacturing practices"in its operations. The application of a dominant standard in the design and manufacture of such products is one of the requirements of a good manufacturing process. The Americans with Disabilities Act (ADA) is a civil rights law

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[1] In the publication of ISO Standards, the terminology "hoist"is used internationally to describe these products, whereas "lift"refers to an elevator.

that prohibits discrimination against people with disabilities. Individuals with disabilities must be able to access and use newly constructed and altered state and local government buildings, places of public accommodation, and commercial facilities under the ADA.

The Department of Justice (DOJ) issued new regulations under the ADA in 2010. These rules incorporated the 2010 Standards for Accessible Design (2010 Standards), which include precise accessibility standards for a variety of recreational facilities, including swimming pools, wading pools, and spas, for the first time. The ADA Accessibility Requirements are applied to public swimming pools starting March 15, 2012. Accessibility criteria for various types of aquatic facilities are outlined in Section 242 of the amended Regulations. Section 1009.2 of the ADA Regulations establishes requirements for swimming pool lifts in order to maintain operational consistency across the various products on the market. Swimming pool lifts are listed in Section 1009.2 as having nine separate elements. Some of the elements are design-specific, which means they must be incorporated into the lift's design. The remaining components are specific to the lift's installation (DOJ, 2012).

The ADA Accessibility Guidelines (ADAAG) is the standard applied to buildings and facilities. According to the US Access Board (2003), recreational facilities, including swimming pools, wading pools, and spas, are among the facilities required to comply with the ADA. For swimming pools, the primary means of entry must be either a sloped entry into the water or a pool lift that is capable of being independently operated by a person with a disability. The secondary means of access could be a sloped entry, transfer wall, transfer system, or pool stairs. It is recommended that where two means of entry are provided, they be different types and be situated on other pool walls.

Transfer walls are walls built on the edge of the pool, at the height of the wheelchair seat. They have one or two rods that allow the individual to leave their chair and go to the pool. They are usually used in conjunction with another access device, such as a ramp. It does not involve mechanical mechanisms and does not require frequent maintenance. It is an interesting option for users who want practicality and agility to access the pool. However, the transfer walls do not serve people who have difficulty moving, permanently or temporarily, or with an effective reduction in their mobility, flexibility, and motor coordination (US Access Board, 2003).

Pool ramps usually start at the pool's deck level and slope down to the water's surface. They can be built into the pool or placed in the main pool area or a swim-out section that feeds into the main pool area. These ramps are made to the same standards as handicapped accessibility ramps. Handrails are required on both sides of the ramp. Conventional wheelchairs are not recommended for submerged use. However, this type of project is limited by the size of the site, the budget available and the type of activity to be carried out there. Even though architectural adaptations in the pools offer certain advantages, they are still limited, so people with limited mobility are not able to get around independently (US Access Board, 2003).

Pool Stairs, unlike ladders, enable progressive entry into the pool. They can be a permanent feature of the pool, such as integrated into the pool tank or the pool wall, or they can be removed and moved around. Stairs can be narrow or wide depending on the situation. They are an option for people who can walk (US Access Board, 2003).

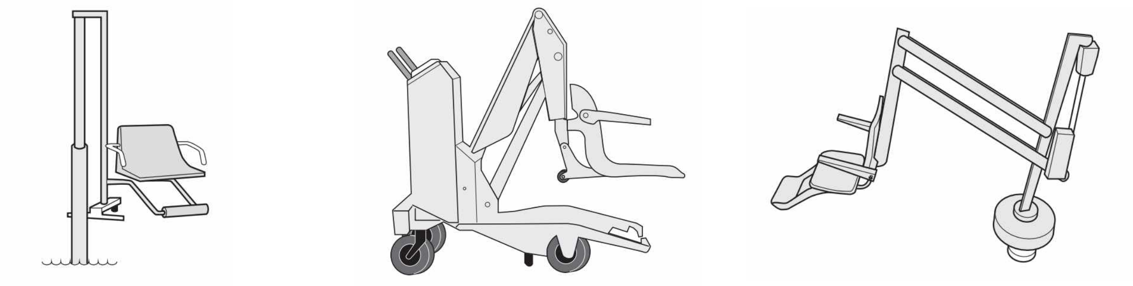
Platforms are Pool floors that may be raised or lowered to any depth by moving the part of the pool floor. When the floor is raised to the deck level, users can either walk or roll their wheelchairs onto the pool floor and be lowered to the appropriate water depth (US Access Board, 2003).

Pool lifts are mechanical devices that allow a person to enter and exit a pool. Some lifts are permanently built, while others are movable and can be moved into place or mounted on a deck. Lifts may need a transfer from a wheelchair to the lift seat, or they may include a sling seat that allows the individual to go from a wheelchair to the water directly. Some lifts are powered, while others are manually operated; some can be used by the user freely, while others require assistance (US Access Board, 2003).

2.2.2 Classification

Currently, there is a wide range of pool lifts. For practical purposes, in this work, not all existing types are reviewed, but only the models of devices of interest to this research, which are widely used and commercialized. Thus, to facilitate understanding, the classification proposed by S.R. SMITH LLC (2012) is presented in three main groups: Non-Cantilevered, Non-Rotational Cantilevered, and Rotational Cantilevered, as shown in Fig. (2).

Figure 2 – Illustration of each pool lift classification.



(a) Non-Cantilevered (b) Non-Rotational Cantilevered (c) Rotational Cantilevered

Source: (S.R. SMITH LLC, 2012)

First, Non-Cantilevered pool lifts provide a seat that is attached and rotates around an anchor point. The use of non-cantilever lifts is limited to simple pool designs that feature no gutters or recessed gutters. Water-powered lifts are good examples of non-cantilever lifts. These types of lifts are usually fixed to the edge of the pool but can, in some cases, be placed on a deck anchor. The limitation is that these types of lifts always need to be connected to a water supply. In addition, hydraulically operated lifts can be slow to lower or lift, which can cause some difficulty in times of emergency.

Second, Non-Rotational Cantilevered pool lifts provide an extension or seat directly from the loading. Just like non-swing lifts, they have a range of motion. Overall, they are most effective with the simple gutterless pool edge design.

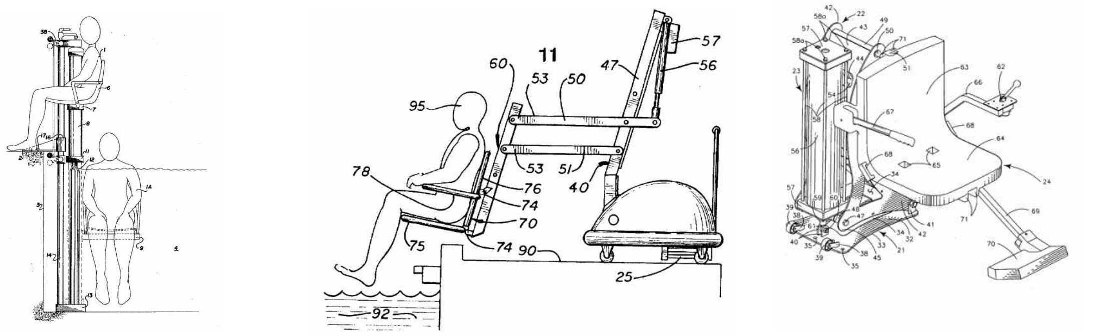
Finally, Rotational Cantilevered pool lifts can lift and rotate the seat position over the deck and extend the seat out of the anchor point and over any obstacles on the way to the water. This feature allows secure transfers, whether independent or assisted. Rotational cantilevered lifts can work effectively in virtually any type of pool design. They can be fixed, anchored, or free-standing.

2.2.3 State of the Art

Before pool lifts were invented in 1980, the biggest challenge in aquatic therapy centers was simply getting people out of the water safely and easily. They were taken out of their wheelchairs by attendants and carried by those attendants into the water and then taken out of the water and back to their chairs. The first commercially successful pool lift dramatically changed this labor-intensive procedure as it eliminated dependence on such attendants, allowing more people with disabilities to participate in hydrotherapy.

The historical evolution of swimming pool lift development can be traced back to the invention patented by Nolan (1980) and shown in Fig. (3a). This device vertically transports people in a helical path in and out of the pool. Its mechanism consists of a hydraulic cylinder fitted on a guide to follow an elongated helical cam as the cylinder extends vertically. Like several other patents from this era, it is powered by a hydraulic pump.

Figure 3 – Historic pool lift patents.



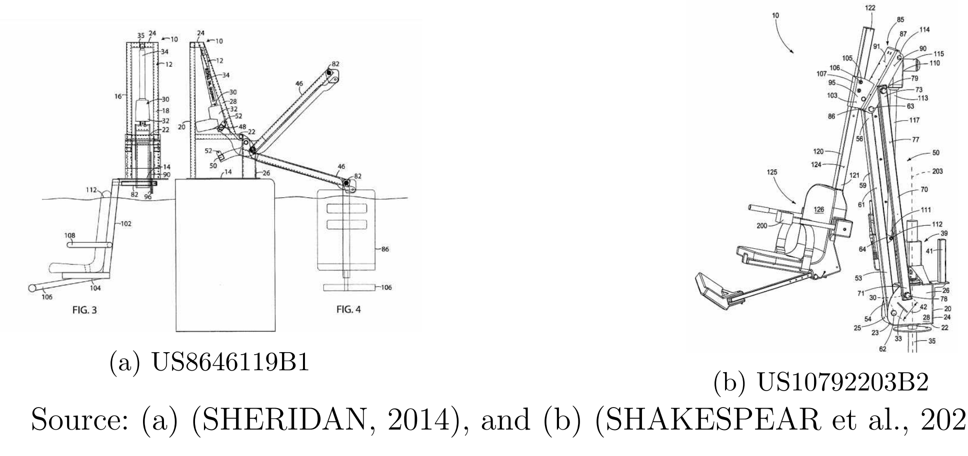
(a) Hydraulic pool lift (b) Linear actuator pool lift (c) Fixed Non-Rotational Cantilevered pool lift

Source: (a) (NOLAN, 1980), (b) (CADEN; RESCH; SANDER, 1998), and (c) (TERZO, 2005).

In 1998, the next generation of pool lifts was invented and helped overcome many of the limitations of the first design. These new pool lifts were self-supporting and battery-powered, designed to work with more contemporary pool designs. The device patented by Caden, Resch e Sander (1998), Fig. (3b), illustrates these advances. It can be seen that the bar mechanism is driven by an electric linear actuator, which is silent, non-toxic, and energy efficient. Compared to hydraulic and pneumatic systems, this linear actuator solution is much easier to install. It takes up less space as there are no hoses and pumps that require routine maintenance to prevent safety hazards and oil leaks. In addition, it has a long lifespan with little maintenance. This guarantees a lower total cost of operation compared to other systems. Several patents have been filed for new designs of Non-Rotational Cantilevered type transfer devices. Figure 3c shows one of the first patents in this category - registered by Terzo (2005). This is a device in which the particular movement and arched shape of the lift frame of this pool lift allow it to be smaller, simpler, and more compact in nature than previous pool lifts.

These pool lifts, on the other hand, have traditionally been designed for use in controlled environments such as club pools, therapy pools, and elder care facilities where employees can easily undertake maintenance, setup, and usage supervision. If utilized outside, the aforementioned pool lifts may need to be removed and stored to guard against adverse weather or surroundings or special additional temporary protection. Furthermore, these existing pool lifts feature risky mechanical actions that could crush, squeeze, or hurt a user if they are not adequately protected. Sheridan (2014) presented the device depicted in Fig. (4a), which is electrically driven and has an enhanced motor system that limits the mechanical movement of electronics, actuators, and mechanical linkage. The installation of a fixed protective physical cover for the electronics and movement drive system solves the problem of mechanical anterior lifting movement. The device satisfies the new ADA standards for being appropriate for harsh environmental conditions while also offering critical security enhancements for general public use in such settings.

Figure 4 – Latest pool lifts patents.



(a) US8646119B1

(b) US10792203B2

Source: (a) (SHERIDAN, 2014), and (b) (SHAKESPEAR et al., 2020)

The most recent patents for swimming pool lifts are concerned with reducing the force required by the linear actuator, thus saving on the cost of the equipment. For instance, the patent US10792203B2 divulges a mechanical manipulator arm, shown in Fig. (4b) that differs from existing pool lifts by including a lift frame made up of three parallel, spaced-apart lift members. Additionally, the present invention utilizes the mechanical advantage provided by a fulcrum lever link that connects the proximate end portions of the spaced-apart lift members to provide a mechanical advantage that enables the use of a fulcrum.

Recently, there has been a new trend in the market: pool lifts that can be fixed a long distance from the edge. Figure 5 shows two examples of newly launched pool lifts by two of the largest companies in this industry in the United States. Compared to the previous generation, it can be seen that the lifting arms are pretty large and go beyond the seat backrest, which allows for greater arm reach.

Figure 5 – Latest pool lifts.

(a) MULTILIFT™2 POOL LIFT

(b) The Mighty 600

Source: (a) (S.R. SMITH LLC, 2022), and (b) (AQUA CREEK PRODUCTS LLC, 2022)

3 METHODOLOGY

The engineering design in this research work was carried out using the Norton (2010) methodology, which consists of ten steps: Identification of Need, Background Research, Goal Statement, Performance Specifications, Ideation and Invention, Analysis, Selection Detailed Design, Prototyping and Testing, and Production. As a result, the phases of the product development cycle, the tools utilized to construct this project, as well as the tools used to build the prototype presented in this thesis are discussed in the following sections.

3.1 Identification of Need

This is the first phase of the methodology, in which the fundamental need that kicks off the process is stated. This project aims to address the need for persons with disabilities to be able to visit pools independently and at a reduced cost. According to the research conducted by Cerqueira et al. (2010), most rehabilitation clinics in Brazil with a therapeutic swimming pool lack equipment that aids in the placement and removal of patients from the pool, restricting the availability of such treatments.

3.2 Background Research

The second phase of the design methodology, considered by Norton (2010) as the most important in the process, is the Background Research. It is wanted to learn about the problem by studying existing products.

A systematic background research was carried out in the scientific literature using the Scopus, PubMed, and Google Scholar databases on pool transfer lifts. The query search keywords were organized into two categories: technology (lift, hoist, crane, apparatus, device), application area (pool, water, spa, bath, aquatic), and purpose limitation (disabled persons, ADA, mobility, access). It was searched in titles, abstracts, and keywords of the documents.

The full search query was: (TITLE-ABS-KEY (pool OR aquatic) AND TITLE-ABS-KEY (disabled OR mobility OR access OR ADA) AND TITLE-ABS-KEY (lift OR crane OR hoist OR device OR apparatus)), and there was no search period limitation

A patent search was carried out with the American Patent and Trademark Office (USPTO) and the National Institute of Industrial Property (INPI). We also used Google Patents, which is a Google search engine that indexes patents and patent applications. All patents in category A61G7/1005 were sought, which is: Devices for lifting patients or people with disabilities, e.g., special adaptations of hoists specially adapted for specific applications mounted in, or in combination with, a swimming pool.

An extensive market survey of pool lift prices in the North American region was published in (ALTERGO, 2013). Nevertheless, it was carried out a competition research in the market of products similar to the prototype developed in this work in the United States of America (USA) and Brazil, shown in Table 1. This research showed that not all commercialized products had a patent, and many of these were similar to patents from other competitors.

Table 1 – Pool lifts competition research.

Product	Country	Type	Price
ELIT 150	Brazil	RC	BRL 11,500.00
Freedom	Brazil	RC	BRL 29,000.00
Fluidra	Brazil	NC	BRL 42,300.00
Cajumoro Guarujá	Brazil	RC	BRL 19,800.00
Cajumoro Ipanema	Brazil	NRC	BRL 22,500.00
S.R. Smith ML 300	USA	NRC	USD 3,171.10
Pool Lift Patriot Portable AT1	USA	NRC	USD 3,800.00
Harmar P350	USA	NRC	USD 3,475.00
Global R-450R Rotational	USA	RC	USD 5,099.00

Source: Elaborated by the author.

Note: Abbreviations: NC = Non-Cantilevered, NRC = Non-Rotational Cantilevered,and RC = Rotational Cantilevered

Analyzing the Table, it is noticeable that Fixed Non-Rotational Cantilevered pool lifts are the most cost-effective. This is due to its lesser complexity and, as a result, fewer moving parts. For the following subsection, two pool lift models were selected from among the assessed ones to conduct a complete examination of each component, a procedure known as benchmarking.

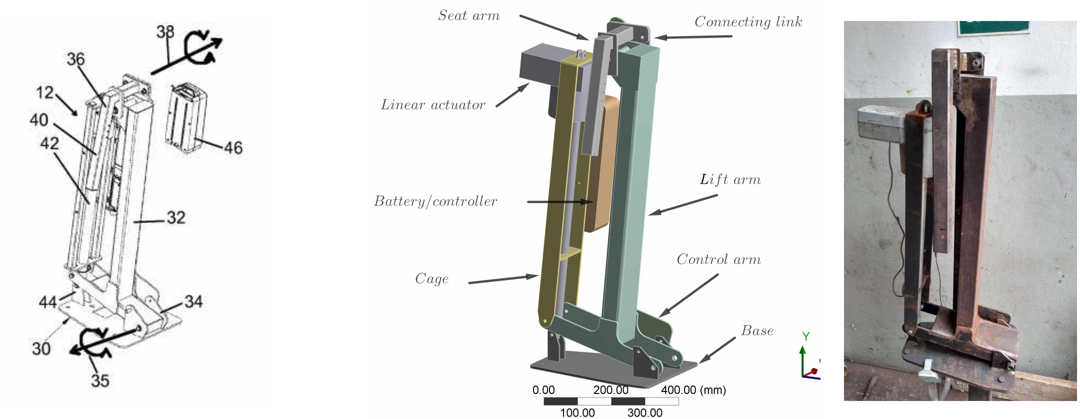
3.2.1 Benchmark I

S.R. Smith LLC’s ML 300 pool lift has a patent registered with the USPTO number US 2014/0101839. A prototype was designed and built based on this product to learn about this type of pool lift operation. This lift is referred to as "Benchmark I"in this thesis. The device’s design is shown in Figure 6a, which is accessible in the patent publication.

This pool lift’s base is right next to the pool’s edge. An elongated arcuate lifting frame pivots along an axis parallel to the pool’s edge on the base. To pivotally move a chair support, carried by the lift frame and oriented in a direction parallel to the edge of the adjacent pool, from the pool deck to the pool cavity. An electromechanical linear actuator extends into the hinged interconnection between the base and the medial portion of the arched lift frame. During the movement of the chair, a guide arm keeps the user’s support in the horizontal orientation of the seat.

This pool lift is not made in Brazil. Thus the importation of this product, including taxes and shipping, was budgeted at around BRL 50,000.00 with a local import company representing the brand in Brazil. Because this price is prohibitive for our study, the only other choice for benchmarking was to build a prototype based on designs found on the internet. A 3D model was created using CAD files and other technical drawings provided on the company's website. The electrical equipment and the linear actuator, which has a nominal linear force of 10,000 N, were imported from HIWIN. The metallic structure was fabricated, and the final assembly was completed in a local mechanical workshop. The 3D model of Benchmark I and the manufactured prototype are shown in Figs. (8b) and (6c), respectively.

Figure 6 – Benchmark I.



(a) Patent drawing.

(b) 3D model

(c) Manufactured prototype

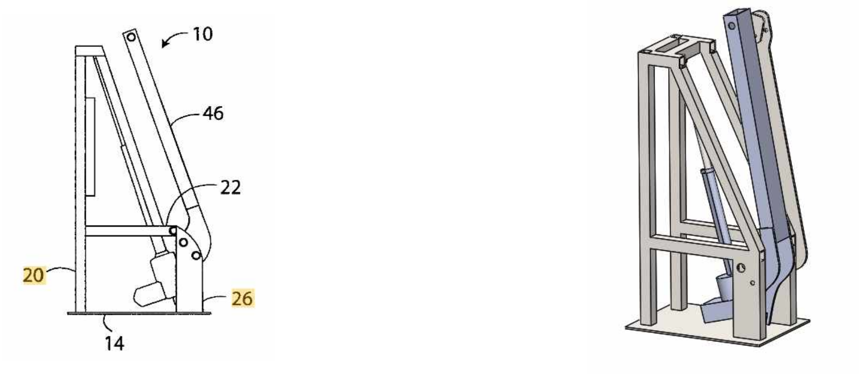
Source: (a) (S.R. SMITH LLC, 2014), (b) and (c) elaborated by the author.

3.2.2 Benchmark II

A model proposed by Sheridan (2014), a patent registered with the USPTO number US 8,646,119, and depicted in Fig. (7a), proved to be interesting for the study. This lift is referred to as the benchmark II prototype in this work. During the market study, no commercially accessible product based on this invention was found out. A 3D model was developed based on available patents to learn about the operation of this type of pool lift, and the result is displayed in Fig. (7b).

It is important to note that Benchmark I has a flaw: its preservation. A rigorous maintenance schedule must be followed to ensure its integrity. This involves keeping all electronics clean and dry at all times, as well as maintaining the console/battery cover in place at all times to prevent moisture from gathering in the control box and battery, which can impact the device's operation. The lift's battery and hoist can fail, resulting in battery failure and/or the lift's inability to operate. Finally, because the lift was installed outside, an external cover was required. As a result, the lift published by Sheridan (2014) was chosen because it overcomes the maintenance problem in the benchmark prototype I since it provides permanent coverage of the electronic components, which reduces predictive maintenance if the lift is operated outside. The operating principle is similar to that of benchmark I in that it uses an electromechanical linear actuator attached to the metallic structure to produce the same angular movement.

Figure 7 – Benchmark II.



(a) Patent drawing

(b) 3D model

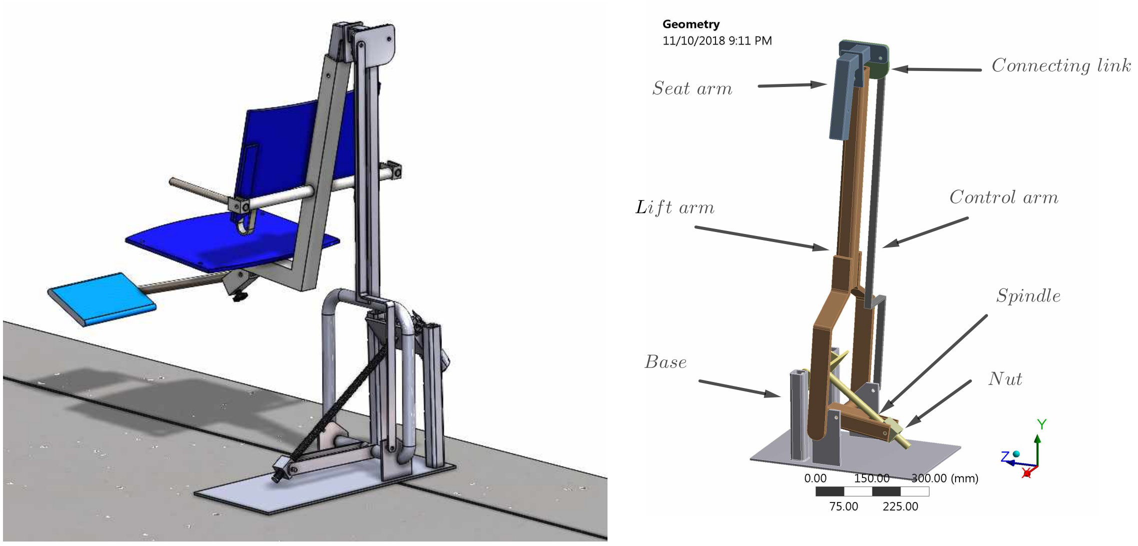
Source: (a) (SHERIDAN, 2014), and (b) elaborated by the author.

3.2.3 Benchmark III

The last benchmark selected was the pool lift developed by (CAMILO, 2019), as shown in Fig (8a). This lift has the same proposal as the current one proposed in this thesis, but uses a set of power screw and nut as actuation mechanism, as shown in Fig (**??**). The advantage of this pool lift is its low cost and reduced volume compared to the other benchmarks, but at the expense of its performance.

This pool lift is supported by a base adjacent to the edge of the pool, which, in turn, is above the water level. A metallic structure is fixed on this base. A tertiary link is rotationally connected, in its central portion, to a support point located in the metallic frame, working as a lever. A seat is supported on the end of the lifting arm that is towards the pool to perform a swiveling movement around an axis of the seat, oriented parallel to the axis of the fulcrum. The opposite end of the lift arm is connected to a nut by a rotational joint. The nut is connected to a threaded spindle by a helical joint. Through an electronic controller, the user controls the activation of the electric motor, moving the pool lift. The four-bar mechanism arms hold the chair in an upright position during the pivoting movement of the lift arm.

Figure 8 – Benchmark III.



(a) 3D model

(b) 3D model

Source: (CAMILO, 2019)

3.3 Goal Statement

After thoroughly understanding the theory involved in the problem in the preliminary research section, the problem can be redefined into a more precise objective. This objective must meet three criteria, according to Norton (2010): it must be concise, be general, and not be defined by any terms that predict the solution.

The first requirement was to *develop a great pool lift.* According to Cohen (1998), most people with physical disabilities are from lower socioeconomic groups. A powerful and inexpensive motorized pool lift is out of reach for many establishments in Brazil's poorer regions. The commercial pool lift alternatives offered in Brazil do not fulfill the ADA Standards, implying that they are of inferior quality. With this in mind, another goal was re-established: *to develop an affordable, secure, and motorized method of transporting people to swimming pools.*

After examining a variety of options for getting a person from the pool to the deck, it was determined that transfer lifts with fixed Non-Rotational Cantilevered mechanisms are often less expensive. Preliminary investigation also revealed that the equipment required for this type of mechanism is only manufactured outside of Brazil and that importing it is costly. As a result, developing with national equipment directly results in designing cheaply.

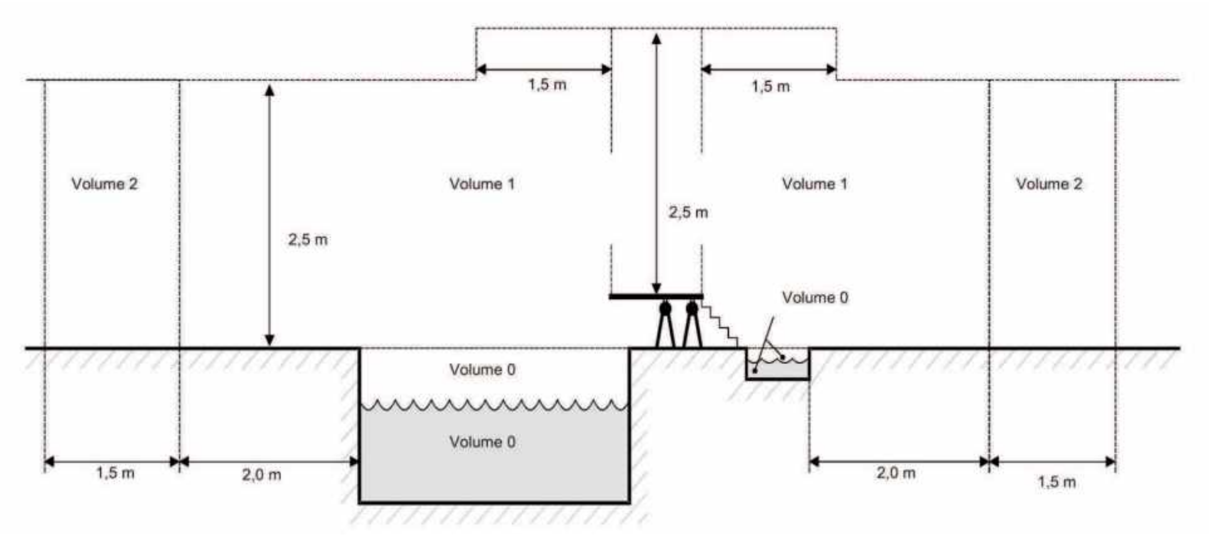
3.4 Design Specifications

Design specifications define how it must do it In general, they must meet the rules that regulate their operation. Below are listed and detailed the parts of interest of the standards to be followed.

1. Must meet the 2010 ADA Standards for Accessible Design (DOJ, 2010):
    - Seat Location: In the raised position, the centerline of the seat shall be located over the deck and 405 mm minimum from the edge of the pool.
    - Clear Deck Space: On the side of the seat opposite the water, a clear deck space shall be provided parallel with the seat. The space shall be 915 mm wide minimum and shall extend forward 1220 mm minimum from a line located 305 mm behind the rear edge of the seat;
    - Seat Height: The height of the lift seat shall be designed to allow a stop at 405 mm minimum to 485 mm maximum measured from the deck to the top of the seat surface when in the raised (load) position;
    - Seat Width: The seat shall be 405 mm wide minimum;
    - Footrests and Armrests: Footrests shall be provided and shall move with the seat. If provided, the armrest positioned opposite the water shall be removable or shall fold clear of the seat when the seat is in the raised (load) position;
    - Seat Height: The height of the lift seat shall be designed to allow a stop at 405 mm minimum to 485 mm maximum measured from the deck to the top of the seat surface when in the raised (load) position;
    - Operation: The lift shall be capable of unassisted operation from both the deck and water levels;
    - Submerged Depth: The lift shall be designed so that the seat will submerge to a water depth of 455 mm minimum below the stationary water level; and
    - Lifting Capacity: Single person pool lifts shall have a weight capacity of 136 kg minimum and be capable of sustaining a static load of at least one and a half times the rated load.
2. Must meet the ABNT NBR Standards:
    - The only requirement according to ABNT NBR 9050 is, when the transfer equipment is installed, the approach and transfer areas must be guaranteed, similarly to the ADA Standard; and
    - ABNT NBR 5410 considers the existence of three volumes, as indicated in Fig. (9), which are referred to as volumes 0, 1, and 2. According to the horizontal

distances and defined verticals, volume 0 corresponds to the interior of the reservoir (pool or foot wash), and volumes 1 and 2 are next to it. Only extra-low voltage, with electrical isolation, installation at voltages not exceeding 12 V in alternating current and 30 V in direct current is permitted for volumes 0 and 1. Installation in low voltage is permitted for volume 2 if the same type of installation in extra-low voltage is not used, provided that the circuits have equipotential connections and are protected by RCDs (residual differential current not exceeding 30 mA). Also, in volume 1, the electrical installation components must have at least the following degrees of protection: IPX5 (Ingress Protection rating 5) (IPX4 for small indoor pools that are not normally subjected to washing with pressure water jets).

Figure 9 – Volumes of pools according the ABNT NBR 5410.



Source: (ABNT, 2004)

3.5 Performance Specifications

The system's performance specifications specify what it must do. These requirements limit the design without limiting the designer's freedom; in other words, they help characterize the problem as completely and broadly feasible, as well as give contractual definitions of what is to be achieved, as discussed by Norton (2010). The performance specifications are listed below:

1. The lift components must be corrosion resistant;
2. The lift must transport users safely and smoothly from the ground to the pool;

3. The lift manufacturing cost must not exceed BRL 9,000.00;
4. The lift must be easy to use;
5. The lift cannot damage the pool area during operation or installation;
6. The lift must move one user at a time;
7. The lift must sustain long periods of use;
8. The lift should ideally have an easy maintenance; and
9. The lift must be able to adapt to various pool configurations.

3.6 Ideation and Invention

According to Norton (2010), the idealization phase is associated with both enjoyment and frustration. In fact, multiple iterations were carried out as problems were discovered, but they were crucial since they permitted the development of new design ideas.

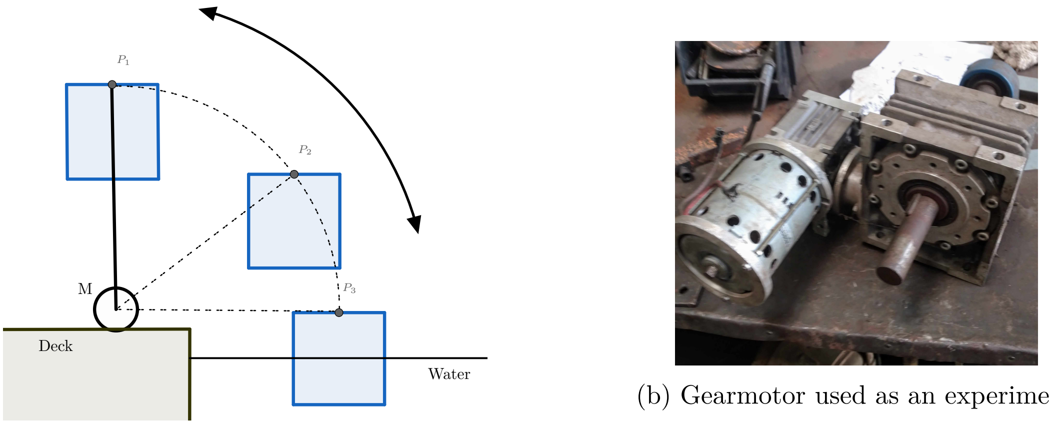
All of the idealized ideas are described in this section. It's important to note that this was an iterative process, meaning that in addition to developing the 3D model, additional analyses were conducted for each of these projects, and when problems were discovered, a new solution was established.

3.6.1 Lifting Arm

One of the most important aspects of this project is that the device has the simplest feasible mechanism, which means that its kinematics have the fewest degrees of freedom and, as a result, the transfer steps to the mechanism are as small as possible. Given this, the most basic and straightforward mechanism would be a circular movement of a fixed arm adjacent to the pool, with the first angular position being with the arm facing the deck and the user seated in the chair, and the second angular position being with the arm submerged in the water. The angular movement of the arm is performed by the rotation of the motor shaft, which is placed on the base of the arm by a revolution joint. The idealized working principle is depicted in Fig. (10a).

For example, the Bosch® F 006 B10 273 DC motor operates on 24 V and produces 550 W of power, 3300 RPM, and 10 N-m of torque (nominal). The mechanism, when combined with a 1:2000 reduction, generates a torque of 20,000 N-m on the arm shaft, which is sufficient to complete the task. Figure 10b depicts the experimental setup, which measured current values in the 35 A range. The battery must have a capacity of at least 35 Ah to provide 30 operational cycles.

Figure 10 – Idealized operating principle.



(a) Schematic representation

(b) Gearmotor used as an experiment

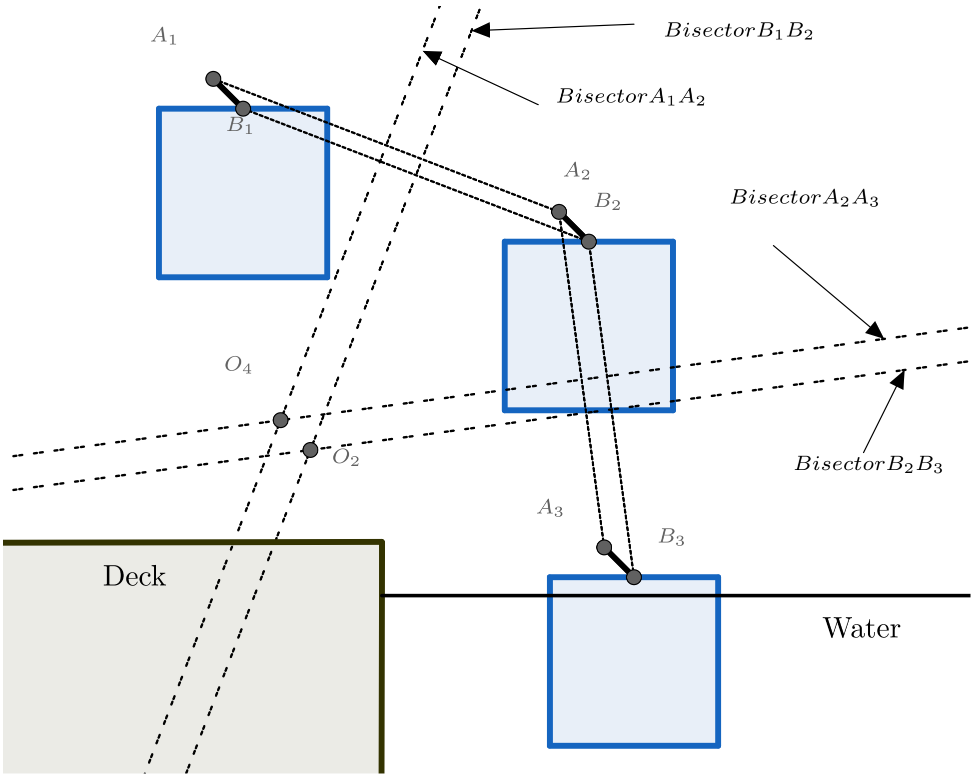
Source: Elaborated by the author.

Considering the performance requirements, the arm must be at least one meter and must be able to sustain a load of 1400 N, which generates a torque provided at the end of the arm, i.e. its nominal torque T_n, is approximately 1,400 N-m. Other requirements are that the motor operates at up to 24 V DC and that the operating time is a maximum of 60 seconds for the descent or rise, that is, to travel an amplitude of $\approx 120°$, in other words, $\approx 0,33$ RPM. Therefore, the maximum rated power required P_r, calculated by $P_r = 2\pi n T_n/60$, is $\approx$ 49 W, disregarding friction and other losses. Therefore, this apparatuses would required to provide such a high demand for energy are overlarge and costly. To address this issue, a novel mechanism was developed to maximize mechanical advantage and hence reduce energy demand.

3.6.2 Four-bar Linkage

The three positions (1, 2, and 3) used to generate the design are shown in Fig. (11). The bold numbers in blocks 1, 2, and 3 represent the chair that places the user in three important locations. The first position is where the user sits in the chair. In position 2, the chair is on the edge of being submerged in water. The chair is submerged in water in end position 3. Such position criteria can be satisfied by a circular motion. In addition, the chair must remain upright throughout the movement, necessitating the use of an auxiliary movement control system in addition to the main lifting arm. Norton (2010) demonstrated how to design the configuration of a four-bar mechanism to achieve the desired movement using the three-position synthesis approach with specified pivots. The fixed pivots O_2 and O_4 are discovered in this way.

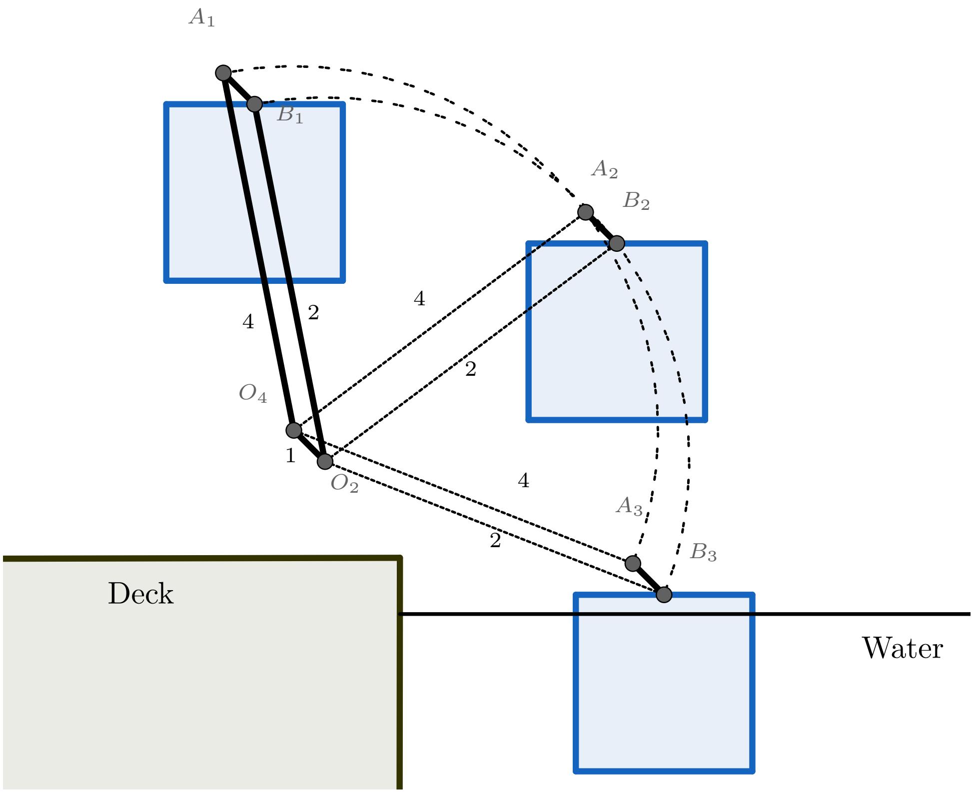
Figure 11 – Three positions graphical synthesis.



Source: Elaborated by the author.

Figure 12 depicts the creation of linkages 1, 2, 3, and 4. Link 1 is the lift's base and does not move while it is in motion. The lift arm is the second link that links the seat to the base. Because Link 3 maintains its angular position in regard to the horizontal during seat movement, it can be considered the seat in a simplified manner. The control arm, or Link 4, is the arm that regulates the movement. All of the joints (A, B, O_2, and O_4) are rotational.

Figure 12 – Linkages synthesis.



Source: Elaborated by the author.

The design specifications determined the dimensions of the pool lift. The frame must take up as little room as possible in the pool area, which is a crucial necessity. At the same time, the device must be robust enough to transfer an adult securely. These opposing goals impose tight size and weight constraints.

Following the selection of the lift arm movement type and consideration of the performance parameters, a position analysis can be conducted to determine the structure's dimensions. These dimensions are necessary to determine the lifting arm's range of angular movement in order to completely immerse the user within the pool and set it at ground level at a suitable height so that it can transfer to the pool, in this case, a wheelchair. An initial sketch of the pool lift's geometry was created in CAD software for this purpose. Performance parameters were defined, and after several iterations, a design that met the requirements was found.

3.6.3 Lifting Mechanism

In benchmark prototypes I and II, the power transmission system is provided by a linear actuator. This choice makes a lot of sense as electric linear actuators represent the perfect solution when you need safe, linear motion with smooth, precise motion control. This provides accurate position feedback and control over acceleration and velocity. However, for several reasons already discussed, this solution is expensive, especially in Brazil.

The most obvious alternative is to replace it with a power screw, which has the working principle of a linear actuator, is cheaper and takes up less space. Therefore, benchmark III devised a mechanism that made use of a spindle, inspired by Scotch Yoke actuators. This type of mechanism transforms a linear movement, in the case of the spindle, into a rotary movement, in the case of the lifting arm. Its main advantage is space saving. However, the fact that the power is transmitted by slip limits the load capacity. Also, for a stationary spindle, this application is limited to about ¼-turn rotary mechanisms. That is, the angular movement of the lift arm cannot exceed 90°, limiting the displacement of the seat (CAMILO, 2019).

For the power transmission system of the proposed pool lift, it was decided to replace the linear actuator and the power screw with a tractioned cable system, as they are cheaper equipment in the Brazilian market.

3.7 Analysis

Analyzes were performed by analytical methods and validated by computational methods. This section details the analyzes made to study the proposed pool lift and the benchmarks. At the end of the section, the experimental evaluation and the focus group satisfaction survey methodology are explained.

3.7.1 Kinematic Analysis

First, a simplified model of the lift was elaborated that had the mechanism operating in a plane. The Kutzbach criterion can be used to calculate the number of DoFs of this device, according to Eq. (1).

$$N = 3(B-1) - 2n_{j1} - 2n_{j2} \tag{1}$$

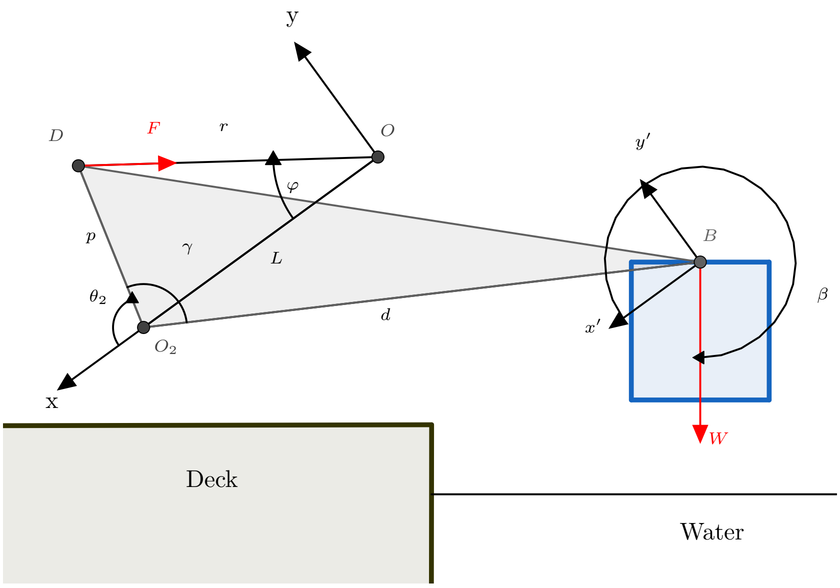
Where:

- N: Number of DoF;
- B: Number of links;
- n_{j1}: Number of pairs having 1 DoF; and
- n_{j2}: Number of pairs having 2 DoF.

There are seven bodies, including the ground and counting twice the linear actuator, and eight joints with one DoF. Substituting these values in Eq. (1), it results in two DoFs for the mechanism, which is related to rotation around two axes normal to the plane in which the mechanism schema is contained: one at the pivot in the connection of the lift arm with the base and the other in the direction opposite, at the top axis in the connection of the lift arm with the connecting link.

Figure 13 shows the schematic configuration of the mechanism, where r is the length of the actuator. This set is controlled by a motor coupled at the point O. L represents the distance between O and O_2. The lifting arm is given by the ternary link represented by the triangle DBO_2, where O_2 is the support center (fulcrum). p is the length of the arm that sustains the powerful force F and d is the length of the lever arm of the resisting force W. The coordinate system is positioned with the coincident origin at point O and with axis x parallel to L. The angle φ represents the angle formed from L to r. The angle θ_2 is the angle formed from x to p. This mechanism can be fully described using the position vector $q \equiv (r, \varphi, \theta_2)$. The independent variable is r, so that leaves the angles φ and θ_2 to find.

Figure 13 – Kinematic diagram of the proposed pool lift mechanism.



Source: Elaborated by the author.

Therefore, the closed loop vector equation is:

$$\mathbf{r} - \mathbf{p} - \mathbf{L} = 0 \tag{2}$$

These vectors can be represented in Polar and Cartesian coordinates, respectively in Eq. (3) and Eq. (4):

$$re^{i\varphi} - pe^{i\theta_2} - Le^{i0} = 0 \tag{3}$$

$$r(cos\varphi + isen\varphi) - p(cos\theta_2 + isen\theta_2) - L(cos0 + isen0) = 0 \tag{4}$$

Equation 4 can be separated into real and imaginary parts and each set equal to zero, resulting in the following system:

$$\begin{cases} real : rcos\varphi - pcos\theta_2 - L = 0 \\ imaginary : rsen\varphi - psen\theta_2 = 0 \end{cases} \tag{5}$$

which can be solved for φ and θ_2.

Likewise, the velocity vector $\dot{q} \equiv (\dot{r}, \dot{\varphi}, \dot{\theta_2})$ and the acceleration vector $\ddot{q} \equiv (\ddot{r}, \ddot{\varphi}, \ddot{\theta_2})$ are defined as a function of the time derivatives of the position vector, and therefore being represented in polar form as:

$$(\dot{r} + ir\dot{\varphi})e^{i\varphi} - (\dot{p} + ip\dot{\theta}_2)e^{i\theta_2} - (\dot{L} + iL\dot{0})e^{i0} = 0 \tag{6}$$

$$(\ddot{r} + i2\dot{r}\dot{\varphi} + ir\ddot{\varphi} - r\dot{\varphi}^2)e^{i\varphi} - (\ddot{p} + i2\dot{p}\dot{\theta}_2 + ip\ddot{\theta}_2 - p\dot{\theta_2}^2)e^{i\theta_2} - (\ddot{L} + i2\dot{L}\dot{0} + iL\ddot{0} - L\dot{0}^2)e^{i0} = 0 \tag{7}$$

Performing the same procedure used to find φ and θ_2 from the position vector, it is possible to solve for $\dot{\varphi}$, $\dot{\theta}_2$, $\ddot{\varphi}$ and $\ddot{\theta}_2$. The angular acceleration at the point O_2 will be used in dynamic analysis and its expression is calculated as:

$$\ddot{\theta}_2 = -\frac{r\ddot{\varphi}^2 - 2\ddot{r} - 2p\dot{\theta_2}^2 cos(\varphi - \theta_2) + r\dot{\varphi}^2 cos(2\varphi) + r\dot{\varphi}^2 sen(2\varphi)}{2psen(\varphi - \theta_2)} \tag{8}$$

3.7.2 Kinetic Analysis

Based on the diagram of Fig. (13), and assuming that the weight and moment of inertia corresponding to the links are small, causing negligible normal forces when compared to the module of the user's weight force and the driving force of the actuator. The equilibrium equations of force are

$$A_x + F_x = m_b a_x \tag{9}$$

$$A_y + F_y - W = m_b a_y \tag{10}$$

$$M_F + M_W = I\ddot{\theta}_2 \tag{11}$$

where A_x,A_y are the components of the reaction force acting on the pivotal link at point O_2; F_x,F_y are the components of the reaction force between the power screw and the nut; m_b is the mass of the link; a_x and a_y are the components of the acceleration of the center of gravity of the link; I is the moment of inertia of the link about point O_2 which is defined as $I = m_w d^2$ for a rotation of a point mass, m_w, at end of the link, with length d, rotating about O_2; M_F and M_W are, respectively, the moments due to the useful force, F, and user weight, W, on O_2 and are given by

$$M_F = Fcos(\varphi + \pi)psen(\theta_2) + Fsen(\varphi + \pi)pcos(\theta_2) \tag{12}$$

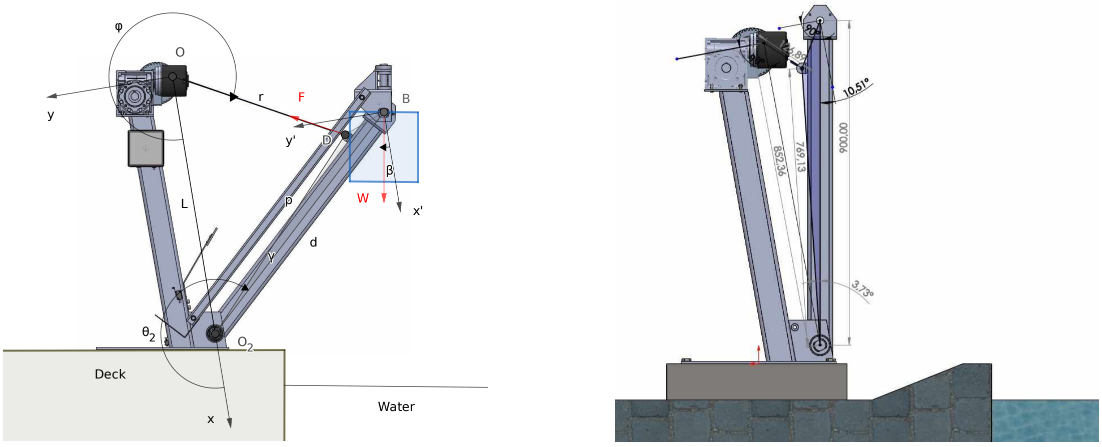
$$M_W = Wsen(\beta)dcos(\theta_2 + \gamma) + Wcos(\beta)dsen(\theta_2 + \gamma) \tag{13}$$

Substituting I and Eqs. (12), (13), and (8) into Eq. (11) it is obtained the load force **F** acting on the actuator, that is,

$$F = \frac{\begin{matrix} -(d(Wpcos(\gamma - \beta + \varphi) - Wpcos(\beta - \gamma + \varphi - 2\theta_2) - 2dm\ddot{r} \\ + dm\dot{\varphi}^2 r - 2dmp\dot{\theta_2}^2 cos(\varphi - \theta_2) + dm\dot{\varphi}^2 rcos(2\varphi) + dm\dot{\varphi}^2 rsin(2\varphi)) \end{matrix}}{p^2(cos(2\varphi - 2\theta_2) - 1)} \tag{14}$$

This mathematical model was applied to the three benchmarks. A rigid body dynamic analysis is implemented using ANSYS Workbench and SolidWorks. The simulation was validated by comparing the actuator linear force from the simulation to the analytical expression derived of the kinematic analysis. It was used SolidWorks to evaluate the dimensions of the models on their initial position, i.e. in the loading position. Figure 14 shows the kinematic diagram superimposed on our 3D model and dimensions, as an example of the calculations procedure.

Figure 14 – Kinematic diagram superimposed on the proposed lift's 3D model and dimensions.



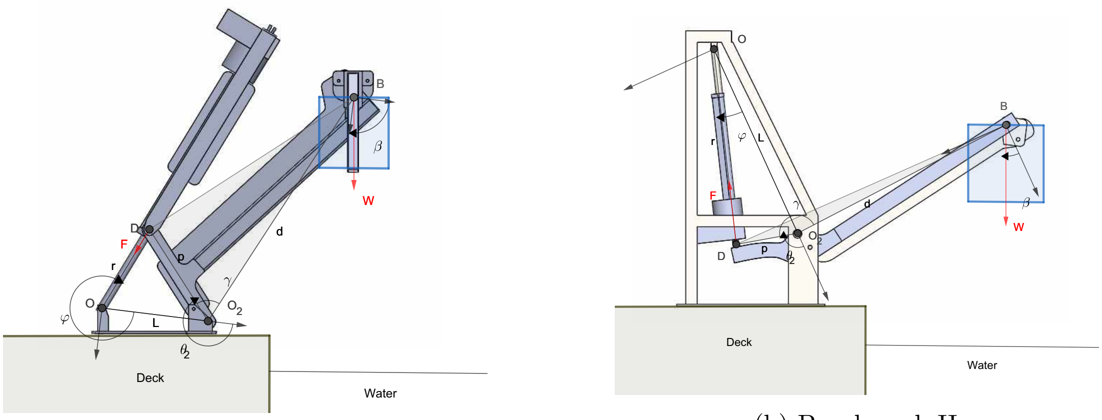
(a) Ours

(b) Dimensions of the parameters

Source: Elaborated by the author.

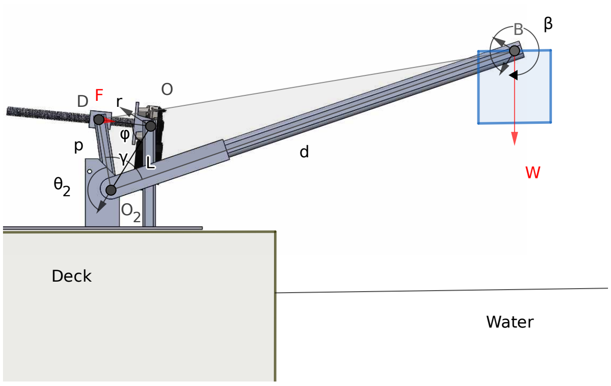
Figure 15 shows the kinematic layout superimposed on the 3D models of the studied benchmarks. The dimensions used in these models are shown in Table 2.

Figure 15 – Kinematic diagram superimposed on the 3D models of the studied benchmarks.



(a) Benchmark I

(b) Benchmark II



(c) Benchmark III

Source: Elaborated by the author.

Table 2 – Parameters used in the calculations and simulation.

Parameter	Benchmark I	Benchmark II	Benchmark III	Proposed lift
W (N)	1400	1400	1400	1400
L (N)	0.37263	0.89935	0.15465	0.85809
p (m)	0.37767	0.27374	0.15000	0.76913
r (m)	0.05536	1.15236	0.27298	0.12689
$\dot{r}$ (m/s)	0.01	0.01	0.005	0.03
$\ddot{r}$ (m/s^2)	0	0	0	0
d (m)	0.93791	1.03539	1.00000	0.90000
γ (rad)	1.1353	2.8023	1.658063	0.06510
β (rad)	1.4502	0.4185	5.84441	0.18343

Source: Elaborated by the author.

3.7.3 Finite Element Analysis

It was used Finite Element Analysis (FEA) in conjunction with Computer-Aided Engineering (CAE) tools. This strategy allows for rapid iteration in project development by identifying likely breakpoints. The FEA simulation of the model was done using the computational package ANSYS Workbench. To begin, a Rigid Body Dynamics Analysis is used to assess joint connections and determine maximal joint forces in order to identify potentially problematic movement positions. The mechanism's deformation and stress in the most critical position are then verified using a Static Analysis. The simulation was carried out in five fundamental steps that will be detailed later in this section:

i. The geometry was imported into ANSYS;

ii. The properties of the materials were defined;

iii. The boundary conditions were defined within the software;

iv. The mesh was generated;

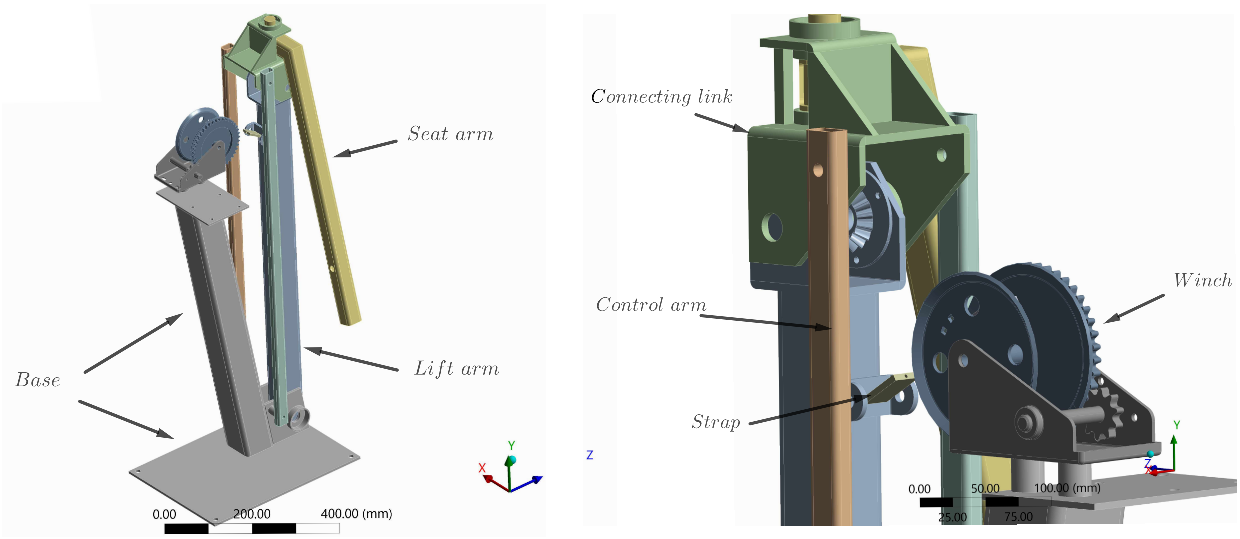
v. The values of stress in the structure were obtained;

vi. The mesh was refined at the stress concentration points; and

vii. Converged values were obtained.

First, the simplified CAD model made in SolidWorks was imported. The start position is when the seat is in the user loading position, on the deck above the floor surface, and the final position is when the seat is in the user unloading position, submerged under water. Fixed contact conditions were deleted, and joint conditions were created. Table 3 lists the elements' joint type. Figure 16 show the location of the joints in the ANSYS model. It is important to emphasize that the contact between the gear teeth was defined as frictional, with a coefficient of 0.15, and with an augmented Lagrangian formulation.

Figure 16 – Model in ANSYS in the initial position and the denomination of each body.



(a) Big picture

(b) Detail

Source: Elaborated by the author.

Table 3 – List of types of joint types and connected bodies.

Joint	Body 1	Body 2	Type
1	Ground	Base	Fixed
2	Base	Winch	Fixed
3	Winch	Strap	Revolution
4	Strap	Strap	Translation
5	Strap	Lift arm	Revolution
6	Lift arm	Base	Revolution
7	Lift arm	Control arm	Revolution
8	Lift arm	Connecting link	Revolution
9	Connecting link	Control arm	Revolution
10	Connecting link	Seat arm	Revolution
11	Seat arm	Lift arm	Contact

Source: Elaborated by the author.

The majority of pool lifts on the market are made of carbon and/or stainless steel. The usage of carbon steel necessitates the application of anti-corrosion paint. To prevent corrosion on carbon steel, anti-corrosion paint can be applied relatively cheaply instead of using corrosion-resistant materials. For these reasons, as well as the fact that it is less expensive, carbon steel was chosen for the complete construction in this project. The mechanical properties of the chosen material are shown in the table 4.

Table 4 – Material properties used in the ANSYS model.

Property	AISI 1045 Steel
Young's Modulus [GPa]	200
Poisson's ratio	0,27
Density [kg/m^3]	7.850
Yield Strength [MPa]	310
Ultimate Strength [MPa]	585

Fonte: (ASM INTERNATIONAL, 1990)

To simulate the user's weight, a point mass of 140 kg was applied on the surface of the seat arm. Gravity was included to account for the weight and inertia of the mechanism, which in this model is in the -Y direction. To simulate the engagement of the gear teeth, a translational displacement of 50 mm was set on the strap.

Based on the results obtained by the Rigid Body Dynamic Analysis, a Static Analysis of the pool lift was performed in its most critical position, that is, the angular position at the maximum linear force in the actuator. This position is where the lever arm is greatest, that is, when the user's weight is farthest from the base of the attachment on the deck, horizontally. The model in the most critical position during Dynamic Rigid Body Analysis was imported into ANSYS Workbench to perform the Static Analysis. The same designations of materials and connections were preserved. Figure 34, in the appendix C, show the model to be studied and its boundary conditions.

A study of the degree of refinement was carried out in order to analyze the sensitivity of the mesh, in view of the optimized option between the computational cost and the precision of the results. An initial simulation was performed with the mesh automatically generated by the software, utilizing the tetrahedron meshing method. After that, the mesh was recreated with a denser distribution of elements in the structural element where the maximum equivalent von-Mises stress was located. This was done by progressively changing the finite element size. The process was repeated until the results converged satisfactorily, that is, with a change smaller than 5 % in relation to the previous result. All simulation results shown below refer to the most refined meshes. Figure 36, in the appendix C, show the final mesh.

3.7.4 Focus Group Prototype Evaluation

The evaluation research was be carried out at the co-participating institution SESI Uberlândia – Clube "Virgílio Galassi"(Gravatás). The process of recruiting subjects follows inherently the needs of the research, that is, it has as a criterion the selection of people with reduced mobility. Once the candidates meet the research conditions, favoring the attainment of results that allow the evaluation of the proposed methodology and its effects, the inclusion criterion will be satisfied. Therefore, no other form of discrimination (by gender, ethnicity, age, socioeconomic status etc) in the selection of individuals can occur.

Initially, the participant was greeted with a brief explanation about the equipment and the nature of the activities to be carried out. Then, the subject was provided with a document that described the purpose and conditions of the study. Thus, after agreeing with the purpose of the study, the participant signed a Free Consent Term authorizing the use of the data obtained. In addition, in the initial stage, the participant provided personal information necessary to compose the sample profile.

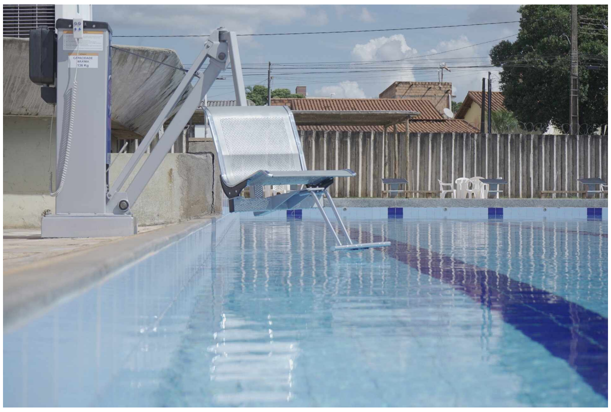
Then study subjects used the pool elevator to transfer to the pool and return to the deck. To deal with the difficulties encountered, the participant must identify areas for improvement at this stage through some type of assessment and choose how to approach these areas for improvement. This experiential test was recorded by a camera. Immediately after the completion of the test, a questionnaire was provided to the participant so that he could provide a subjective assessment of the usability of the system, as well as comments and suggestions for improving the equipment. Also, all subjects were required to complete a Sociodemographic Questionnaire, which is a standardized tool for gathering general data about the participant group. The proposed questionnaires are in the appendix D.

SUS was chosen because it is one of the most popular usability assessment methods in the literature, mainly due to its desirable psychometrics, including high reliability and validity (BANGOR; KORTUM; MILLER, 2008). The SUS is a questionnaire that addresses a global view of subjective usability estimates. The questions consist of ten statements using the Likert scale format, where the intensity of agreement is measured within a five-point scale. Some sentences were adapted to the reality of this research, making necessary modifications to the scoring method. Usability testing, a procedure in which members of the focus group take part, was employed in this study to determine how well an interface satisfies specified usability standards. Finding actual issues with the product or the process used to generate it is the main goal of usability testing.

4 RESULTS

Figure 17 shows the prototype installed at the SESI's pool, ready to be operated under real-world conditions in its environment. In this chapter, it is outlined the mechanical characteristics of the complete system, supplemented by a description of the electronic configuration. Given the inventive steps, novelty, and other aspects identified in the design of this pool lift, a patent application was made, as shown in the last annex.

Figure 17 – End result of the prototype.

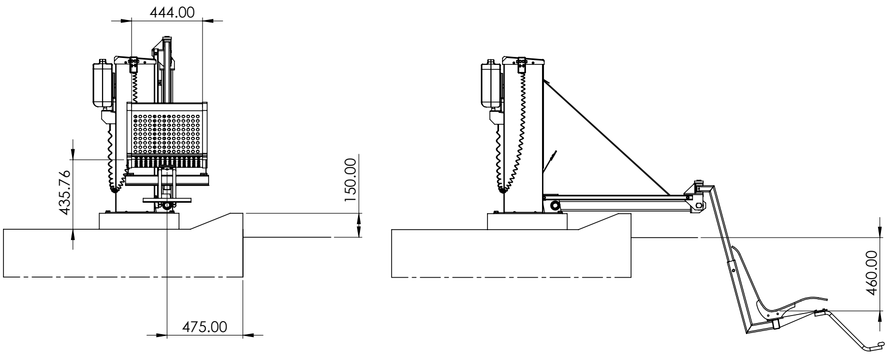


Source: Elaborated by the author.

4.1 Mechanical Design

Figure 18 shows the side view of the pool lift proposed by this work in a retracted and extended position. The device achieves the desired kinematics and positions for the chair as established by the ADA. The design was created using the engineering design technique proposed by Norton (2010). After numerous iterations of the project, a design of the structure was reached.

Figure 18 – Final main dimensions of the proposed pool lift.



Source: Elaborated by the author.

The proposed pool transfer lift comprises a support frame, a lift assembly, a gearbox, and a seat assembly. The lift assembly is articulately connected to the support frame and performs the raising and lowering of the seat assembly, which allows a user to be transferred between a stowed position, above the deck, and an extended position, inside the tank of a pool.

The support structure is formed by a base-type structure that includes a column. The column has an inclination with respect to the axis normal to the ground plane, away from the pool, which provides additional structural strength against the tangential force acting on it — preventing deflection.

The base plate has two mounting tabs, which have mounting holes, with a lower pair of mounting holes receiving a special threaded screw at the end, adequately mounted using washers and nuts. The bolt also passes through the bushing located at the lower end of a lift arm, supporting its rotation. The top pair of mounting holes on the mounting tab is pinned and mounted using snap rings. The pin also passes through the hole located at the lower end of a control arm.

The support structure may further include an anchoring system comprising threaded bushings embedded in a concrete slab. A set of screws can be threaded through holes located in the base plate. Figure 19 shows the anchoring base and concrete slab being mounted at the edge of the pool. This metal structure was galvanized, a process in which a coating of zinc is applied to offer protection and prevent rusting. The sizing of the concrete slab deck was made based on the anchoring-to-concrete pool lift specifications manuals provided by S.R. Smith LLC (S.R. SMITH LLC, 2019).

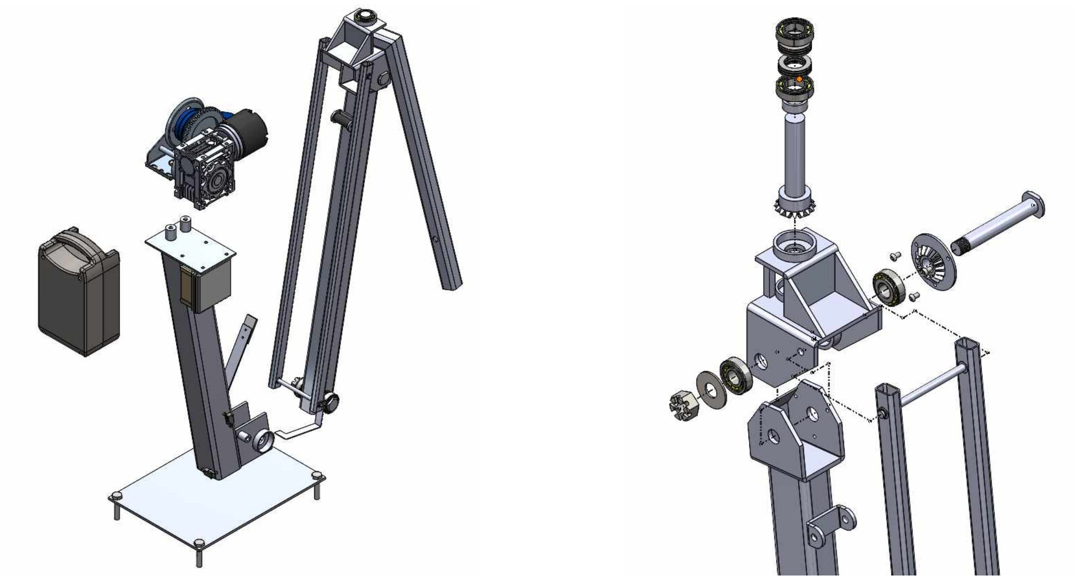
Figure 19 – Anchoring base and concrete slab being mounted in the edge of the pool.

Source: Elaborated by the author.

With reference to Fig. (20a), the lifting assembly comprises the lifting arm. A lower end of the lift arm is pivotally mounted via the mounting tabs, allowing the lifting arm to rotate around the support axis. An upper end of the lift arm is rotatably mounted to the gearbox to lift a person in and out of the pool. The top end of the lift arm includes a pair of mounting holes. The upper end of the lift arm is a U-bracket. The lift arm is inclined slightly towards the pool so that the user's center of gravity forms a lever arm with respect to the support axis, necessary to exert a torque that will move the pool lift down to the pool. A spring is fixed to the column and gives the initial impulse to the lifting arm when it is in its initial retracted position.

Now referring to Fig. (20b), the control arm maintains the chair in a substantially level position with respect to the ground along the path of movement between the initial position and the final position of the lift arm. The control arm forms a four-bar mechanism with the lifting arm, a connecting link, and the mounting tab. The control arm has a lower end that is rotationally connected to the mounting tab. The upper end of the control arm is rotatably attached to the connecting link, passing through the holes through a pin, suitably mounted by the use of snap rings.

Figure 20 – Exploded view of the mechanical frame.

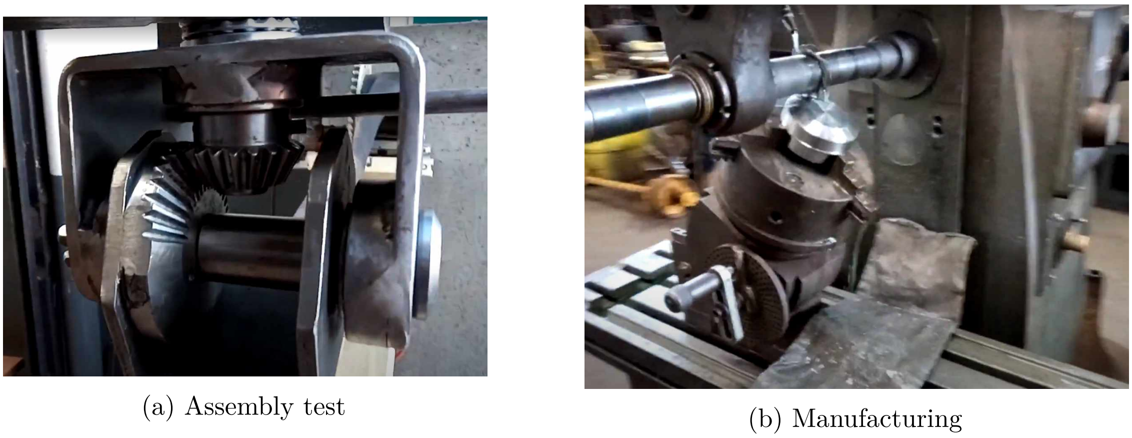


(a) Mechanical frame and adjacent components (b) Detail of the transmission system

Source: Elaborated by the author.

The gearbox is connected to the upper end of the lift arm and includes the link. The gearbox includes a pair of bevel gears, which transmit the pivotal movement of the connecting link to the vertical shaft, suitably supported by a set of bearings, as shown in Fig. (21a). Figure 21b shows the manufacture of 1:2 ratio bevel gears, which were a Z40 with a Z20, Module 2. There is a jamb to press a support arm of the seat against the connecting link, causing the seat to remain firm, i.e., decreasing wobble in the seat due to gear teeth backlash. The upper end of the lift arm is rotatably mounted to the connecting link with a nut and bolt combination with washers, through the pair of mounting holes, supporting its rotation.

Figure 21 – 1:2 bevel gear pair.



(a) Assembly test

(b) Manufacturing

Source: Elaborated by the author.

The seat mounting assembly comprises a seat, which is supported on the support arm that is positioned towards the pool to perform a pivotal movement around an axis of the seat, oriented orthogonally to the support axis. This rotational movement can be 90° or 180°, depending on the gear transmission ratio. The figure 38, in the annex B, shows the dimensions of the pair of bevel gears with a 1:2 ratio used in the first version of this prototype.

A protective enclosure covers the support structure, electric motor, spool, and all associated electronic control, e.g., command center, battery, and so on, and is spatially stationary, as shown in Figure. This protective case provides protection as a safety barrier against unintentional human interaction with the spool during its mechanical movement. The top cover allows access to the interior of the case.

Figure 22 – Protective enclosure.

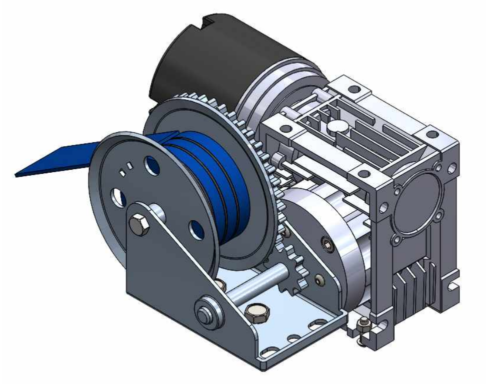
(a) Front view

(b) Back view

Source: Elaborated by the author.

An actuator is fixed to the column. The actuator can be any device that creates rotary motion. This prototype includes an electric motor that is mechanically connected to rotate the spool through a worm gear reducer, taking advantage of its self-locking feature to stop the reverse movement of the lifting arm. The spool winds a pull strap. The strap is connected to the lift arm via a U bracket, through a combination of pin and latches. Figure 23 shows the final assembly of the gearmotor used in this work.

Figure 23 – Actuator assembly.



Source: Elaborated by the author.

The actuator is connected to a control center and powered by a battery. Figure 24 shows the battery being recharged and battery assembly. It was decided to use a commercial battery charger because it is easily found in the Brazilian market and at a low cost. The battery is also easily found, but it comes in its cubic form. In order to adapt to the pool lift, a case was made by additive manufacturing. This case is specially designed for these batteries and includes side attachments to fit into the pool lift cover.

Figure 24 – Battery assembly.

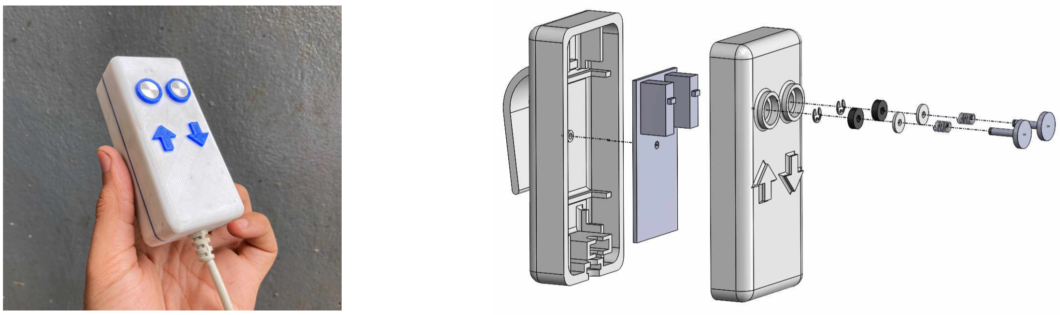
(a) Final assembly with the charger

(b) Exploded view

Source: Elaborated by the author.

Optionally, the command center can preferably be operated by a wired remote control, but it can also be performed by a wireless remote control or pushbutton, as shown in the Fig. (25). Initially, several remote control quotes were carried out, but its high cost is not viable for the project since it seeks to optimize its cost reduction. Therefore, a control was made in which the electrical circuit is enclosed by a case made by additive manufacturing. The pushbuttons were locally manufactured in stainless steel and are secured to the case by a series of snap rings and O-rings. Two limit switches restrict the movement of the lift arm between the initial position and the final position and are placed in the column of the base, so when the lift arm reaches one of them, the movement stops.

Figure 25 – 3D printed wired control.



(a) Final assembly

(b) Exploded view

Source: Elaborated by the author.

There are attachment brackets for securing seat belts in order to ensure the stability of the user. There is also a fixed footrest connected to the seat. This particular prototype does not includes a pair of armrests attached to the seat, but it is recommended and may be fixed, retractable, or rotating. Future versions will include this feature.

4.1.1 Operation and Maintenance

To ensure the proper functioning of the pool lift and also to prolong its useful life, it is essential that all the manufacturer's instructions are followed when using the lift.

It is the responsibility of the pool lift owner to ensure that the correct safety procedures are implemented and a risk assessment is carried out. If a user is mentally impaired or has physical disabilities, these issues should be taken into account to determine the number of people needed to complete the transfer to the seat and the number of people needed to be in the water ready to receive the user. Only people healthy enough for water activities should use the pool lift. Users should consult their physician to determine if water activities are appropriate. Fingers and hands should be kept away from the lift arms during use. Caution with long loose hair, which must be tied back.

Once the unit is positioned for use, the procedure for transferring the user from the seat to the water is as follows:

i. Check the battery level to ensure that the charge is adequate for operation (at least 50 % recommended charge).

ii. Use the buttons on the controller to raise the seat to the loading/unloading position on the deck.

iii. Transfer the user to the seat, ensuring the user's weight is centered on the seat. The armrests can be rotated if necessary.

iv. Fasten seat belt.

v. Use the buttons on the controller to lower the seat into the water.

vi. Loosen seat belt.

vii. When finished, return to the seat, ensuring that the user's weight is centered on the seat.

viii. Fasten seat belt.

ix. Use the controller buttons to return to the load/unload position on the deck.

x. Loosen seat belt.

xi. Seat transfer.

In order to prolong the life of the pool lift, it is necessary to carry out predictive maintenance of the equipment. A protective frame covers the metal frame, motor, battery and controller. An opening allows handling these electrical equipment, such as removing the battery for charging. To ensure that all electrical equipment is safe, this cover should be kept closed whenever not in use. Table 5 presents the maintenance schedule that must be performed to ensure proper operation with the daily items performed before each use:

Table 5 – Maintenance table.

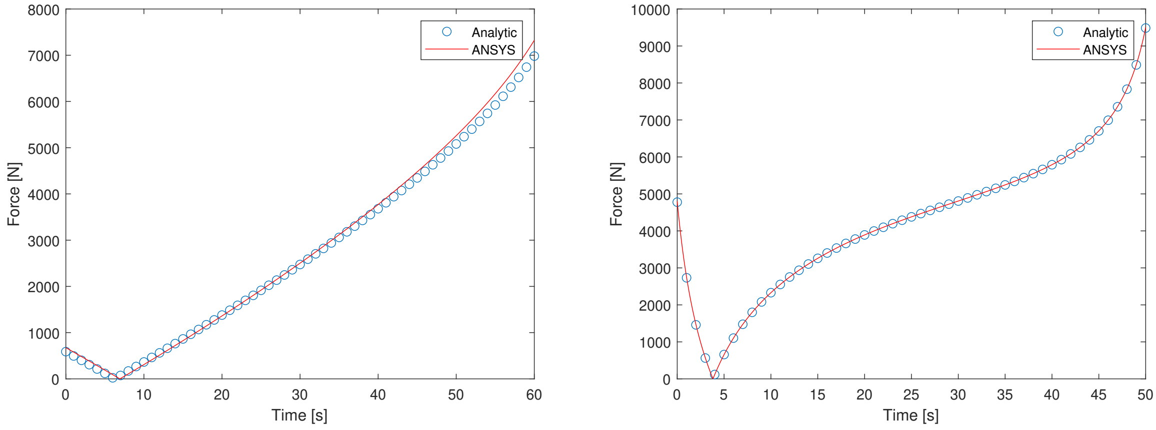
Maintenance Performed	Daily	Weekly	Monthly
Check the battery level before each use	✓		
Clean the battery connection with a clean, dry cloth	✓		
Examine the pool lift for any damage or missing hardware	✓		
Test for normal operation	✓		
Make sure the cover is closed	✓		
Inspect the pool lift frame for rust			✓
Clean all battery connections with a nylon sponge		✓	
Clean all metal surfaces with a cleaning wax			✓
Lubrication of the bevel gears			✓

Source: Elaborated by the author.

4.1.2 Kinetic Analysis

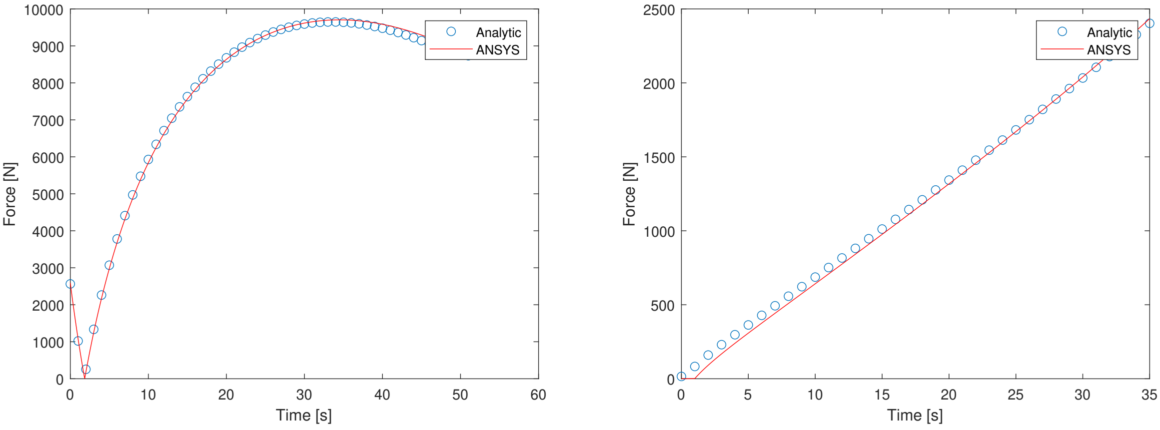
Appendix A contains the MATLAB scripts developed to symbolically solve the systems of equations of the Kinetic Analysis of the swimming pool lift. Figure 26 shows the comparison of the simulation results with analytical calculations for the force of the linear actuator in each of the benchmarks and in the proposed project. The analytical results are represented in the continuous blue curve, whereas the numerical results are plotted in red circles. The kinematic and kinetic analytical model was validated using numerical simulations comparing the force values of the actuator connection joint from the Rigid Body Dynamic Analysis at ANSYS.

Figure 26 – Confrontation of simulation results with analytical calculations for the linear actuator force.



(a) Benchmark I

(b) Benchmark II



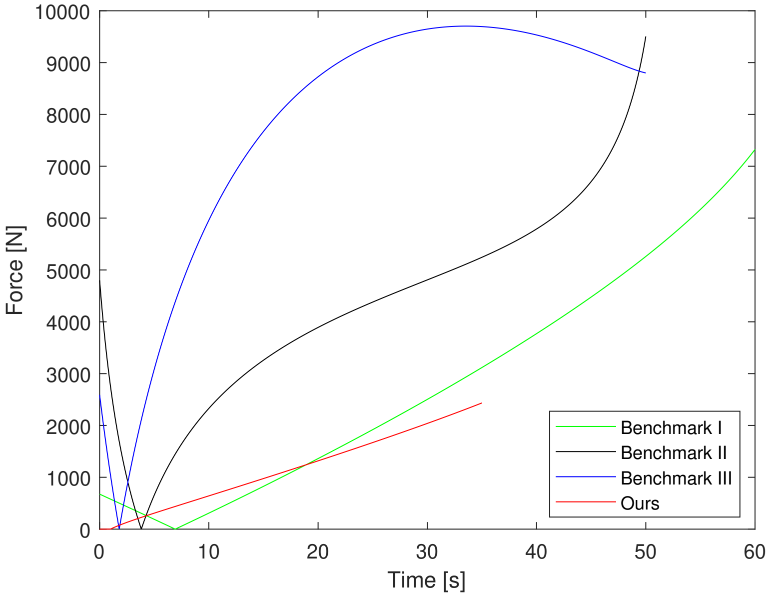
(c) Benchmark III

(d) Proposed lift

Source: Elaborated by the author.

Figure 27 shows the graph of the linear force required as a function of operating time for each one in one cycle of operation as means of comparison between them. It is possible to note a substantial reduction in the linear force required by the proposed mechanism of the pool lift, represented by the red curve. This is possible because it utilizes a greater mechanical advantage, as it utilizes a longer lever arm. It is also possible to observe that the operating time of the proposed pool lift is smaller than the benchmarks.

Figure 27 – Comparison between the forces required by the linear actuator for a load of 1400 N.



Source: Elaborated by the author.

For comparison purposes, the maximum force required by the power screw of benchmark III, represented by the blue curve, is about 35 % greater than that of benchmarks I and II. Benchmark III was a pool lift designed to solve the downsizing problem of Benchmarks I and II, which are commercial pool lifts. For this, the size of the actuation system arms connected to the spindle were reduced, thus reducing the lever arm and its mechanical advantage.

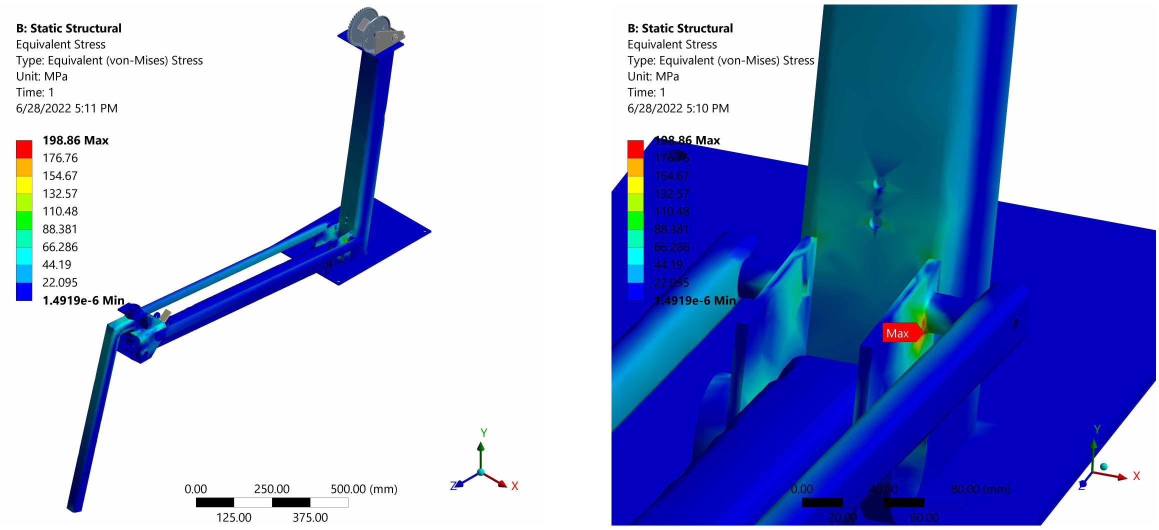
4.1.3 Failure Analysis

Numerical simulations were performed in the computational package ANSYS Workbench. The Rigid Body Dynamic Analysis found potentially dangerous positions in the movement of the pool lift. It provided the graph of the reaction force in the bears' joints, so it is possible to retract the maximum required load for the bearing specification, taking into account the safity margin provided by the manufacturer. Secondly, the Static Analysis, in the position of greatest risk, i.e., where the structure undergoes maximum stress, provided the deformation and stresses of the metallic frame and components of the pool lift.

Figure 28a shows the equivalent von-Mises stress graph suffered by the structure under the imposed conditions. The maximum stress occurs in the spacer bush that supports the shaft that receives the control arm, more specifically in the weld region, which is a sharp re-entrant corner, as shown in Fig (28b). Re-entrant sharp corners should be avoided, as they are points of strain energy concentration, which feed mechanisms of crack propagation or localized buckling.

Analyzing the results, the maximum value for equivalent von-Mises stress converged to 198 MPa, which is below the yield strength of AISI 1045 steel. Therefore, the proposed metallic structure is expected to retain its structural integrity for the load case considered. A more straightforward solution to this problem is to increase the spacer bushing thickness.

Figure 28 – ANSYS Static Structural Analysis.



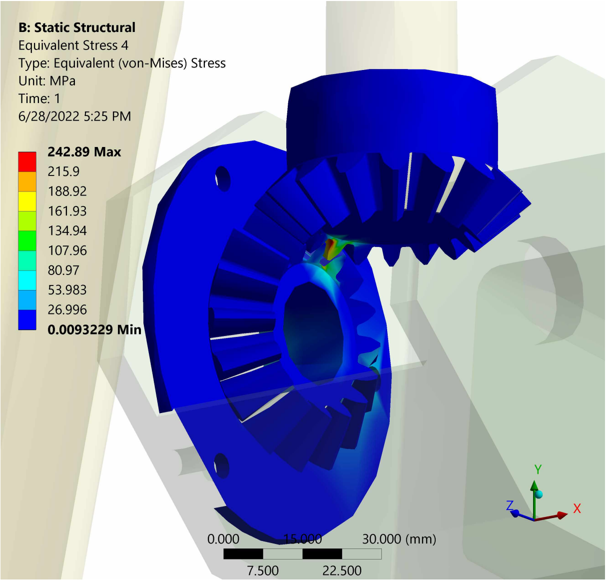
(a) Equivalent (von-Mises) Stress (b) Detail of the maximum stress location

Source: Elaborated by the author.

In this analysis, it was also noted that the contact region between the gears did not result in high stress, for the loading conditions. Thus, it was performed a gradual increase of the 140 kg point of mass until the localized stress reached an unsafe value. For a load of 400 kg, the equivalent von-Mises stress values on the bevel gears is shown in Figure 29. It is worth noting that this load value is exceptionally high and unexpected to occur as other parts would fail before this increment. Therefore, the proposed bevel gear module 2 is safe to operate in the conditions considered.

The explanation for the maximum stress not occurring in the gears is that they do not receive the load of the weight, which is all deposited in the thrust bearings and transferred to the connecting link. The connecting link is in force balance with the lifting arm and the control arm. Thus, the effective force acting on the gears is to rotate the inertia of the user's mass supported on the seat arm.

Figure 29 – ANSYS Static Structural Analysis of the bevel gears.



Source: Elaborated by the author.

Therefore, with the completion of the finite element analysis, it is possible to conclude that the pool lift design is well dimensioned for use at the stated conditions.

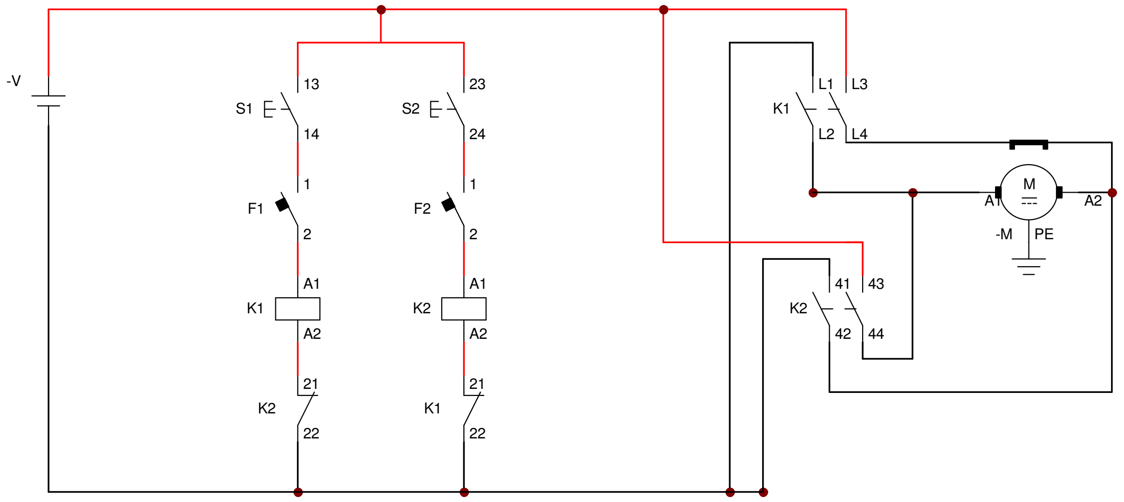
4.2 Control

This section gives details about the pool lift's control components, such as the electrical control, battery, and motor. These components were designed with user safety in mind. Another aspect considered during the design was cost reduction, so we opted for simple systems that met the minimum requirements of specifications and standards.

4.2.1 Electrical Command

A simplified electrical command was developed to control the actuation of the swimming pool lift. All electrical components are contained in a control box. The system is powered by a battery and powers a 24V DC motor. The user uses a wired controller with two buttons, one for going up and one for going down. The button must be held down for the electric motor to run. The command has two limit switches, which interrupt the circuit when open. The control operates with two contactors, which are interlocked. The interlocking system ensures that only one contactor can be on while another one will be in off condition even if we try to manually on it. Figure 30 shows the Electric scheme of the command panel, where M is the electric motor, V is the battery, S1 and S2 are the push button, F1 and F2 are the limit switches, and K1 and K2 are the contactors. The remote control can be submerged in water because its case is sealed; that is, electrical components do not come into contact with water. In addition to this safety aspect, it is worth noting, as discussed, that the system operates at an extra-low voltage, 24 V.

Figure 30 – Electric scheme of command panel.



Source: Elaborated by the author.

4.2.2 Electric Motor

The electric winch assembly is formed by combining a geared motor with approximately 9,070 N heavy duty strap winch, where the strap has the capacity to lift up to approximately 20,000 N.

For the selection of the electric motor, the operating time of a descent or ascent cycle of the pool lift was taken into account among the design specifications. Having a time of 30 s to 60 s as ideal, that is, neither too fast, nor too slow. It can be extracted from the model drawing a value of 1215 mm of tape length, so that the arm travels through the angular displacement of the cycle. That is, it has a tangential winding speed of the spool strap $v = \frac{\Delta s}{t}$ of 20.25 mm/s to 40.5 mm/s . Therefore, considering that the diameter of the tape winding is approximately 80 mm, it has a required rotational speed $n = \frac{60v}{2\pi r}$ of 4.8 RPM to 9.7 RPM. Furthermore, through the result of the kinematic analysis, it appears that the maximum linear force required is approximately 2800 N. Therefore, the required torque $T_r = Fr$ is 112 Nm.

In order to achieve the design specifications, a 1:80 gearbox was selected, which, together with the reduction of $\frac{44}{10} = 4.4$ teeth/teeth of the winch, has a total reduction of 352 is obtained. Therefore, it has a required motor speed of 1690 RPM to 3415 RPM and a required torque of 0.32 Nm. Figure 37, in the annex A, and Table 6 show the specifications of the selected electric motor, which is commercially easy to find in the Brazilian market.

This assembly gives a rotational speed on the spool of 8.5 RPM, or approximately 35 mm/s tangential strap speed. According to the manufacturer, the worm gear reducer has an efficiency of 60 %, so it has an output torque of approximately 170 Nm.

Table 6 – Motor specifications.

Parameter	Value
Voltage	24 V
Power	250 W
Rotation	3000 RPM
Current (rated)	12 A
Current (maximum)	21 A
Torque (nominal)	0.8 N-m
Torque (maximum)	1.6 N-m
Direction of rotation	CW/CCW
Protection degree	IP 34
Weight	2.0 Kg

Source: (LANDELL TECNOLOGIA, 2022)

4.2.3 Battery

The selected DC motor is rated to operate at 24V, which defines the battery voltage requirement. The motor draws 12 A rated current. The power used by this motor at rated current and voltage is 250 W during the lifting and lowering process. For a lift time of 1215 mm/35 mm/s = 35 s, the total energy required $E = IVt$ is 10kJ per lift cycle.

Several batteries with these specifications are commercially available. An illustrative but non-limiting example is the 6-DZM-15 batteries are used for wheelchairs specially designed for frequent and deep cycle discharges. In this project, two 12V batteries connected in series were used.

The potential energy of a battery ΔPE_{elec} is given by multiplying the potential difference ΔV by its total charge Q. So the battery with the capacity of 30 Ah has $q = 30Ah = 30C/s.3600s = 108kC$. Therefore, its total energy is $\Delta PE_{elec} = 108kC.24V = 2,592kJ$. So this battery is enough for 2,592/10 kJ/kJ ≈ 259 cycles, however this assumes a full discharge which reduces the battery life.

4.3 Prototype Evaluation

Before carrying out the evaluation at SESI, a pre-test was carried out in the workshop, where the pool lift was set up on an experimental bench. Weights were placed gradually until one of the following conditions was reached: motor stall, a mechanical failure, or until it exceeded 20 % of the capacity required by the ADA Standard. The pool lift was successfully tested with a load of 160 kg, as shown in Fig. (31a). Then, an experimental test was carried out with two subjects, both wheelchair users, at the Faculty of Physical Education and Physiotherapy - FAEFI/UFU, which validated the prototype as a Technology Readiness Level (TRL) 7. Figure 31b show one of the subjects using the pool lift.

Figure 31 – Prototype pre-test and demonstration.

(a) Pre-test at the workshop

(b) Demonstration in operational environment

Source: Elaborated by the author.

During the discussion portion of the focus group, subjects were asked to provide any comments about this pool lift. Several insights were gained through the feedback. One subject said that there was no need for standing support, while the other, with fewer mobility skills, said he found it necessary. This leads to consider that the foot support, although it must be provided, must be easy to remove and optional for the specific user.

Another pertinent comment was in relation to the wobble that the seat had in the initial position, i.e., when the user transferred to the seat. This problem was found not only in the proposed pool lift but as in others of the rotational type available on the market. This occurs because the rotation of the bevel gears creates the rotational movent of the seat arm. Therefore, the solution was placing a jamb at the end of the seat arm travel when the person is sitting, reducing the gear backlash responsible for this unwanted movement.

One last important comment was regarding the final position of the seat inside the pool. Initially, it was hypothesized that it would be more comfortable for the user to get out of the seat closer to the edge, but the subjects opted that it would be better for the seat to stop further into the pool. In this way, the transmission ratio of the gears was changed from 1:2 to 1:1 so that the seat performed a 90° turn instead of 180°.

4.4 Focus Group Testing

In order to evaluate a pool lift's functionality, human testing was conducted in accordance with CEP - the Brazillian Research Ethics Committee. Three subjects (Mass 79±23kg, Height 132±48cm), described in Table 7, were recruited from a pool of SESI's Paralympics students and athletes having some kind of disability. During the experimental session, each subject used the device to enter and exit the pool. After the subject completed the usability test operation cycle, a questionnaire was provided to assess the user's overall satisfaction with the usability of the system.

Table 7 – Descriptive measurements of the recruited subjects.

	Age [yr]	Mass [kg]	Height [cm]
S1	24	76	161
S2	22	104	173
S3	28	57	64

Source: Elaborated by the author.

Figure 32 – Real-world testing at SESI's pool.

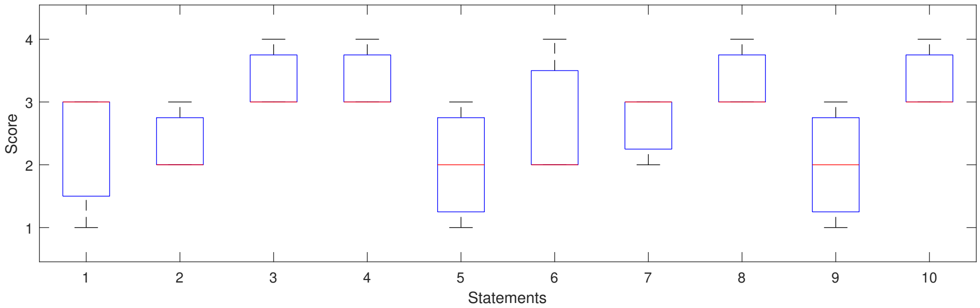
Source: Elaborated by the author.

SUS consists of ten statements, to which respondents must respond on a five-point Likert scale, with 1 being "strongly disagree"and 5 being "strongly agree". The sum of the score contributions from each item is used to get the SUS score. The scoring contribution for each item varies from 0 to 4. The score contribution for the positively phrased statements Q1, Q2, Q3, Q5, Q6, Q7, and Q9 is equal to the scale position (from 1 to 5) minus 1. The contribution for the negatively stated phrases Q4, Q8, and Q10 is 5 minus the scale position. Then, a system usability score ranging from 0 to 100 is created by multiplying the total of the scores by 2.5.

The Box-and-Whisker diagram of the scores of the 10 SUS assertions is depicted in Figure 33. It displays the ten SUS statements' scores' medians and distributions. As can be seen, the medians range between 2 and 3, which is a very acceptable result given that the maximum score is 4. Regarding the responses for the 10 SUS statements, it is noticed that Q3, Q4, Q8, and Q10 have the greatest average scores. This suggests that the pool lift's users thought its operation was easy. They also thought that using the system did not need much technical knowledge or learning new skills.

The items with the lowest scores, however, are Q2, Q6, and Q9. This suggests that users were not entirely confident in their ability to utilize the system and believed that most users might not pick it up quickly.

Figure 33 – Box and Whisker plot of the scores of the ten SUS statements.



Source: Elaborated by the author.

In general terms, it was found that the equipment was considered satisfactory by users, reaching a result of 68 points, which is a considerable result, but not good. It is worth noting that the number of subjects was small to have a statistically relevant result. There were difficulties in attracting participants due to the low participation in pool activities during the winter during this research period. In addition, one subject gave answers that were close to being an outlier because, according to him, he would not need to use the equipment. Taking into account all these factors, new tests should be carried out in the future with a larger group of participants.

In addition to answering the questionnaires, the subjects were able to express their opinions in writing, as in each item of the questionnaire there was a "comments"field for the subject to complement his answer. And with that, it was possible to generate a list of frequent complaints that can be used as demand items for future corrections and system improvements. Thus, the point that presented the highest number of complaints was the lack of arm support. Despite the seat having side portions to hold on to, the lack of a larger frame probably caused a feeling of insecurity in the respective subjects.

Comments were also collected from two trainers, who followed the tests and were able to observe the operation without getting involved in the procedures. Their remarks are essential as they may eventually operate the pool lift to help users transfer to the pool. Both trainers reported that the equipment would help them in their activities and praised the resourcefulness of the device. A relevant comment was related to rust spots on the footrest. This and other comments will be considered in future works.

4.5 Discussion of Contributions

The pool lift project serves the majority of the population, in terms of weight, as it considers the values for selected percentiles of weight measurements for an adult male Brazilian subject according to sample data and population estimates of the median height and weight of the population (IBGE, 2010a). For this average person, the average weight corresponds to 72.7 kg, but, as a safety measure, all calculations were made for a weight of 140 kg.

Regarding the Benchmark I, following the completion of its prototype, it was determined that, despite being competitive in the national market, the final pricing is not adequately affordable to low-income people. Electronic equipment, which is imported, is thought to be the most influential aspect of the lift's final price. As a result of this insight, Benchmark III and the proposed pool lift were designed and envisioned to utilize equipment available on the Brazilian market. This is advantageous because, in addition to having the potential to be cheap, such equipment is easily interchangeable in the event of failure, eliminating the need for international imports and eliminating the risk of currency fluctuations. Therefore, the production cost of the proposed pool lift is lower than that of benchmarks I and II, due to the cost of electronic equipment such as the controller, battery, remote control, and the replacement of the linear actuator with a power screw assembly.

Furthermore, the maintenance problem of the Benchmark I design is solved by providing a stationary protective physical cover for the electronics and motion drive system, just like the Benchmark II design. However, the physical coverage of the Benchmark II is large as it has to accommodate a linear actuator and this is a setback according to the need survey. Benchmark III solved the large volume problem by replacing the linear actuator with a power screw and nut assembly.

Hence, with the work presented, the author sought to contribute to the popularization of Assistive Technology for the low-income population. Consequently, helping to reduce the gap caused by the inequality of opportunities existing in Brazilian society. On the other hand, this work sought to advance in the field of Lift Engineering, helping to lead to a better understanding of the mechanisms, through the application of kinematics and dynamics knowledge to the case of swimming pool lifts and their validation by numerical methods.

5 CONCLUSION

The proposed pool lift met the performance and design specifications, including the Brazilian and ADA standards. This work followed the design methodology tools presented by Norton (2010), enabling the structuring of the problem, elaborating concepts, understanding of users' needs, organization of research, the proposal of solutions, analysis, selection, manufacturing, and finally, evaluation.

The computational tools of CAD and CAE were fundamental in the design process, structural analysis of the models, and prototype manufacture. The FEA showed that the designed pool lift is safe to operate in the conditions considered. Kinematic and kinetic analysis validated some results of FEA simulations and demonstrated the reduction of the linear force of the actuator compared to the benchmarks.

The prototype was successfully manufactured and tested, using components easily found in the Brazilian market at a low cost. The evaluation in an operational environment demonstrated its maturity at TRL 7 level. The experimental test validated the operation of key components developed: the bevel gear transmission of the seat support arm's automatic rotation, the lift arm's four-bar mechanism, and the jamb efficacy to lower the bevel gear backlash.

Finally, the focus group evaluation validated the prototype's usability, resulting in a 68 SUS score, which is an acceptable usability score. The practical assessment also provided valuable feedback from subjects, which will be invaluable for future improvements.

5.1 Future Work

Considering research on transfer pool lifts for swimming pools is uncommon, there is still a lot of work to be done. In general, it is suggested for future efforts as a continuation of this work:

i. Carrying out a more robust clinical study with people with disabilities to assess the acceptance of the product;

ii. Realization of a more elaborated FEA settings regarding the bearings and welding;

iii. Carrying out an experimental analysis of the functioning of the electric motor, measuring amperage and torque; and

iv. Analysis of feedback from users of the prototype installed in a relevant environment, to collect insights for future implementation in the design.

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Appendix

APPENDIX A – MATLAB SCRIPTS

Código A.1 – Solving Symbolic Equations

```
clear all;
clc;
close all;

%% Solving the Angular Positions

syms r L p theta2 phi beta

eqn1 = r*cos(phi) - p*cos(theta2) - L == 0;
eqn2 = r*sin(phi) - p*sin(theta2) == 0;

sol = solve([eqn1, eqn2], [phi, theta2]);
phiSol = sol.phi;
theta2Sol = sol.theta2;

phiSol % Angular Position at O (phi)

theta2Sol % Angular Position at O_2 (teta2)

%% Solving the Velocity Equations

syms rp theta2p phip

eqn3 = rp*cos(phi) - r*phip*sin(phi) + p*theta2p*sin(theta2) == 0;
eqn4 = rp*sin(phi) + r*phip*cos(phi) - p*theta2p*cos(theta2) == 0;

sol = solve([eqn3, eqn4], [phip, theta2p]);
phipSol = sol.phip;
theta2pSol = sol.theta2p;

phipSol  % Angular Velocity at O

theta2pSol  % Angular Velocity at O_2

```

```
%% Solving the Acceleration Equations

syms rpp theta2pp phipp

eqn5 = rpp*cos(phi) - 2*rp*phip*sin(phi) - r*phipp*sin(phi) -
    r*phip^2*cos(phi) - r*phip^2*sin(phi) + p*theta2pp*sin(theta2) +
    p*theta2p^2*cos(theta2) == 0;
eqn6 = rpp*sin(phi) + 2*rp*phip*cos(phi) + r*phipp*cos(phi) -
    p*theta2pp*cos(theta2) + p*theta2p^2*sin(theta2) == 0;

sol = solve([eqn5, eqn6], [phipp, theta2pp]);
phippSol = sol.phipp;
theta2ppSol = sol.theta2pp;

phippSol % Angular Acceleration at O

theta2ppSol % Angular Acceleration at O_2
```

Código A.2 – Solving Force Equation

```
clear all
clc
close all

%% Equilibrium Equation

syms Mf F p phi theta2
Mf = F*cos(phi+pi)*p*sin(theta2) + F*sin(phi+pi)*p*cos(theta2);

syms Mw W gamma d beta
Mw = W*cos(beta)*d*sin(theta2+gamma) + W*sin(beta)*d*cos(theta2+gamma);

syms I m
I = m*d^2;

syms theta2pp theta2p r rp rpp phip phipp
theta2pp = -(rpp*cos(phi)^2 + rpp*sin(phi)^2 - phip^2*r*cos(phi)^2 +
    p*theta2p^2*cos(phi)*cos(theta2) - phip^2*r*cos(phi)*sin(phi) +
    p*theta2p^2*sin(phi)*sin(theta2))/(p*(cos(phi)*sin(theta2) -
    cos(theta2)*sin(phi)));
```

```

%% Solving the Force Equation

%Mf - Mw = I*theta2pp
sol = solve( -(F*cos(phi+pi)*p*sin(theta2) -
    F*sin(phi+pi)*p*cos(theta2)) + (-W*cos(beta)*d*sin(theta2+gamma) +
    W*sin(beta)*d*cos(theta2+gamma)) == m*d^2*(-(rpp*cos(phi)^2 +
    rpp*sin(phi)^2 - phip^2*r*cos(phi)^2 +
    p*theta2p^2*cos(phi)*cos(theta2) - phip^2*r*cos(phi)*sin(phi) +
    p*theta2p^2*sin(phi)*sin(theta2))/(p*(cos(phi)*sin(theta2) -
    cos(theta2)*sin(phi)))) ,F);
```

Código A.3 – Main

```
clear all
clc
close all
format short g


%% Data Input

p = 0.76913; % [mm]
L = 0.85809; % [mm]
r = 0.12689; % [mm]
d = 0.90000; % [mm]

rp = 0.03; % [mm/s] (constant velocity)
rpp = 0; % zero acceleration

gamma = 0.06510; % [rad]
beta = 0.18343; % [rad]

W = 1500; %1000 N
m = 140; %100 kg
P = 200; % 200 N ou 20 kg aprox peso da estrutura metalica



%% Calculations
```

```
for t = 0:1:35

    %Angulo
    phi = -2*atan(((p*(L + p + r)^2*(((L + p - r)*(p - L + r))/((L + p +
       r)^3*(L - p + r)))^(1/2))/(p - L + r) - (L*(L + p + r)^2*(((L + p
       - r)*(p - L + r))/((L + p + r)^3*(L - p + r)))^(1/2))/(p - L + r)
       + (r*(L + p + r)^2*(((L + p - r)*(p - L + r))/((L + p + r)^3*(L -
       p + r)))^(1/2))/(p - L + r))/(L + p + r));
    theta2 = -2*atan(((L + p + r)^2*(((L + p - r)*(p - L + r))/((L + p +
       r)^3*(L - p + r)))^(1/2))/(p - L + r));

    %Velocidade angular
    phip = (-(rp*(cos(phi)*cos(theta2) +
       sin(phi)*sin(theta2)))/(r*(cos(phi)*sin(theta2) -
       cos(theta2)*sin(phi))));
    theta2p = (-(rp*(cos(phi)^2 + sin(phi)^2))/(p*(cos(phi)*sin(theta2) -
       cos(theta2)*sin(phi))));

    %Aceleracao angular
    phipp = (-(rpp*cos(phi)*cos(theta2) + rpp*sin(phi)*sin(theta2) +
       p*theta2p^2*cos(theta2)^2 + p*theta2p^2*sin(theta2)^2 -
       phip^2*r*cos(phi)*cos(theta2) - phip^2*r*cos(theta2)*sin(phi) +
       2*phip*rp*cos(phi)*sin(theta2) -
       2*phip*rp*cos(theta2)*sin(phi))/(r*(cos(phi)*sin(theta2) -
       cos(theta2)*sin(phi))));
    theta2pp = (-(rpp*cos(phi)^2 + rpp*sin(phi)^2 - phip^2*r*cos(phi)^2 +
       p*theta2p^2*cos(phi)*cos(theta2) - phip^2*r*cos(phi)*sin(phi) +
       p*theta2p^2*sin(phi)*sin(theta2))/(p*(cos(phi)*sin(theta2) -
       cos(theta2)*sin(phi))));

    % Forca
    F = -(W*d*cos(gamma + theta2)*sin(beta) - W*d*sin(gamma +
       theta2)*cos(beta) + (d^2*m*(rpp*cos(phi)^2 + rpp*sin(phi)^2 -
       phip^2*r*cos(phi)^2 + p*theta2p^2*cos(phi)*cos(theta2) -
       phip^2*r*cos(phi)*sin(phi) +
       p*theta2p^2*sin(phi)*sin(theta2)))/(p*(cos(phi)*sin(theta2) -
       cos(theta2)*sin(phi))))/(p*cos(phi)*sin(theta2) -
       p*cos(theta2)*sin(phi));
    F1(t+1)= abs(-(W*d*cos(gamma + theta2)*sin(beta) - W*d*sin(gamma +
```

```
       theta2)*cos(beta) + (d^2*m*(rpp*cos(phi)^2 + rpp*sin(phi)^2 -
       phip^2*r*cos(phi)^2 + p*theta2p^2*cos(phi)*cos(theta2) -
       phip^2*r*cos(phi)*sin(phi) +
       p*theta2p^2*sin(phi)*sin(theta2)))/(p*(cos(phi)*sin(theta2) -
       cos(theta2)*sin(phi))))/(p*cos(phi)*sin(theta2) -
       p*cos(theta2)*sin(phi)));


r = r + rp;
end


%% [ANSYS vs Analytic] Plot


time1 = linspace(0,t,length(F1));

load ansys_bench4.csv
time = ansys_bench4(:,1);
data = ansys_bench4(:,2);

figure
plot(time1,abs(F1),'o')
hold on
plot(time,data, 'r')
legend({'Analytic', 'ANSYS'})
xlabel('Time [s]')
ylabel('Force [N]')
```

APPENDIX B – BILL OF MATERIALS

Table 8 – Simplified estimate of the manufacturing cost of the presented prototype.

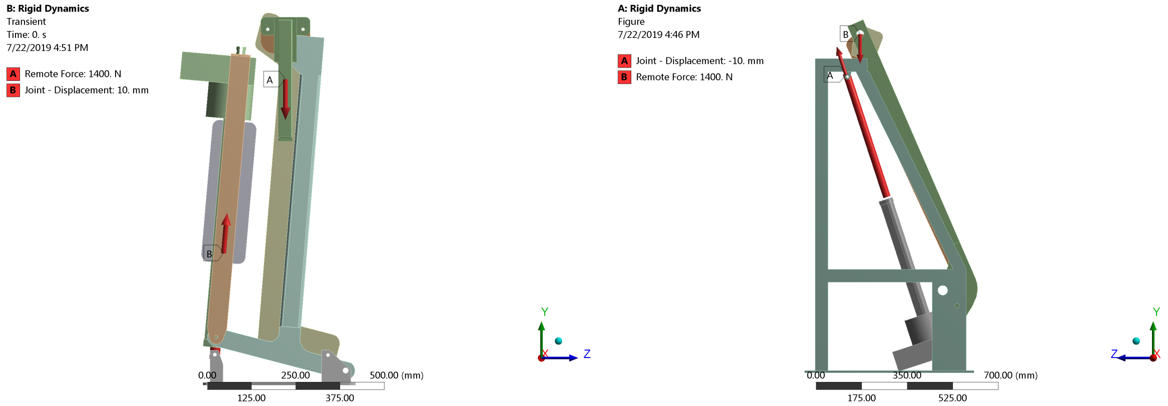
Description	Value (BRL)
Electric motor	380.00
Reducer gearbox	680.00
Commercial seat	334.00
Motor	500.00
Battery	583.00
Battery charger	314.20
Strap winch	259.00
Electrical panel	780.00
Bevel Gears	327.80
Bearings	200.00
Fasteners	150.00
Blasting and painting	400.00
Metal frame	3,000.00
3D printing	400.00
Workmanship	2,000.00
Total	**10,308.00**

Source: Elaborated by the author.

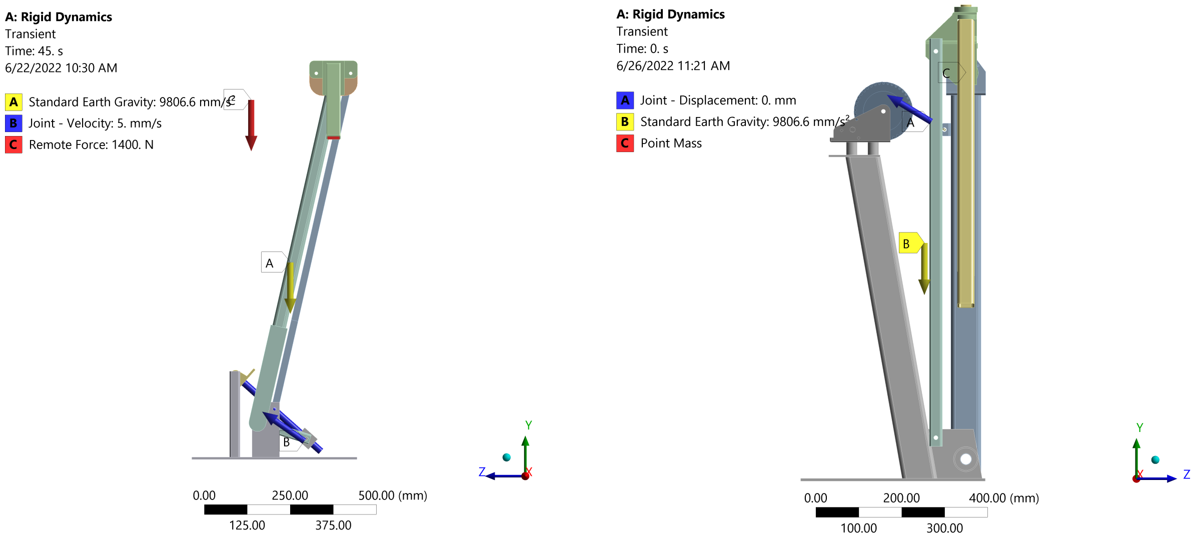
APPENDIX C – FEA

C.1 Rigid Body Dynamic Analysis

Figure 34 – Boundary conditions on the 3D models in ANSYS software.



(a) Benchmark I (b) Benchmark II

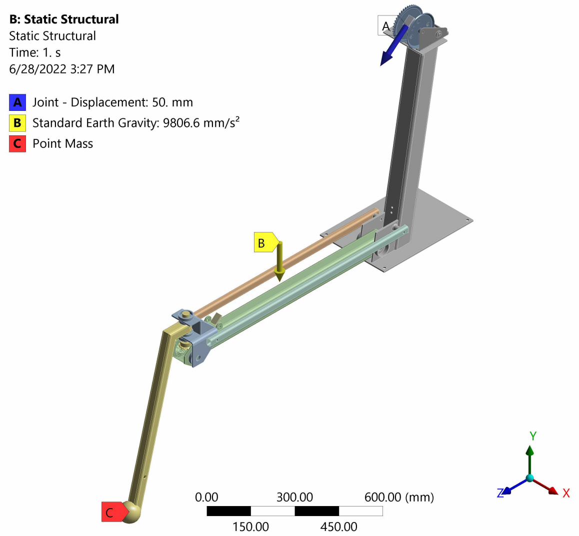


(c) Benchmark III (d) Ours

Source: Elaborated by the author

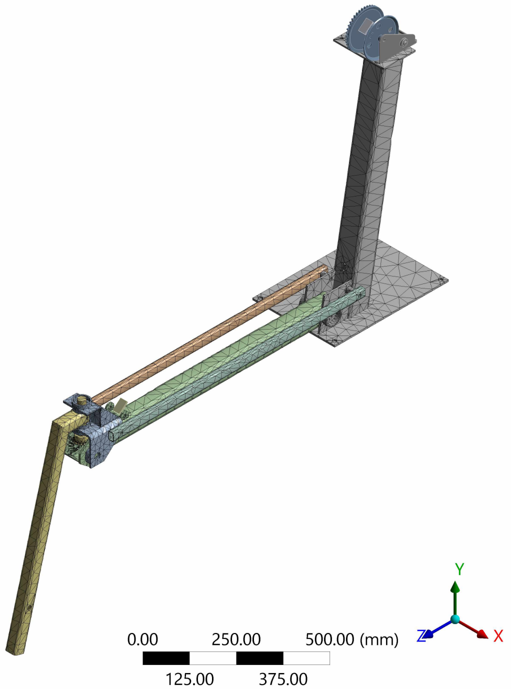
C.2 Static Analysis

Figure 35 – Boundary conditions.



Source: Elaborated by the author.

Figure 36 – Final mesh.



Source: Elaborated by the author.

APPENDIX D – QUESTIONNAIRES

The following questionnaires were proposed for this research and submitted to the Research Ethics Committee (*Comitê de Ética em Pesquisa - CEP*).

Sociodemographic Questionnaire

Name: ____

Gender: ☐ Male ☐ Female

Age: ___________

What is your disability? ____

Marital Status: ____

Occupation: ____

What is your level of education?

- ☐ No education
- ☐ Elementary School
- ☐ Middle School
- ☐ High School
- ☐ College
- ☐ Grad School

How long have you been using a wheelchair? _________________________________

How often do you use swimming pools?

____

Did the pools you used have access for persons with disabilities? Which one?

____

Which method of access to the pool do you prefer?

- ☐ By yourself
- ☐ Carried by people
- ☐ Transfer walls
- ☐ Pool ramps or stairs
- ☐ Pool lifts

Participant ID: _____ Date:____/___/___

System Usability Scale

Instructions: For each of the following statements, mark one box that best describes your reactions to this pool lift *today*.

		Strongly Disagree				Strongly Agree
1.	I think that I would like to use this pool lift frequently.	☐	☐	☐	☐	☐
2.	I felt safe to transfer to the pool lift.	☐	☐	☐	☐	☐
3.	I thought this pool lift was easy to use.	☐	☐	☐	☐	☐
4.	I think that I would need assistance to be able to use this pool lift.	☐	☐	☐	☐	☐
5.	I found the various functions in this pool lift were well integrated.	☐	☐	☐	☐	☐
6.	I found the transfer movement to the pool smooth and safe.	☐	☐	☐	☐	☐
7.	I would imagine that most people would learn to use this pool lift very quickly.	☐	☐	☐	☐	☐
8.	I found this pool lift very cumbersome/awkward to use.	☐	☐	☐	☐	☐
9.	I felt very confident using this pool lift.	☐	☐	☐	☐	☐
10.	I needed to learn a lot of things before I could get going with this pool lift.	☐	☐	☐	☐	☐

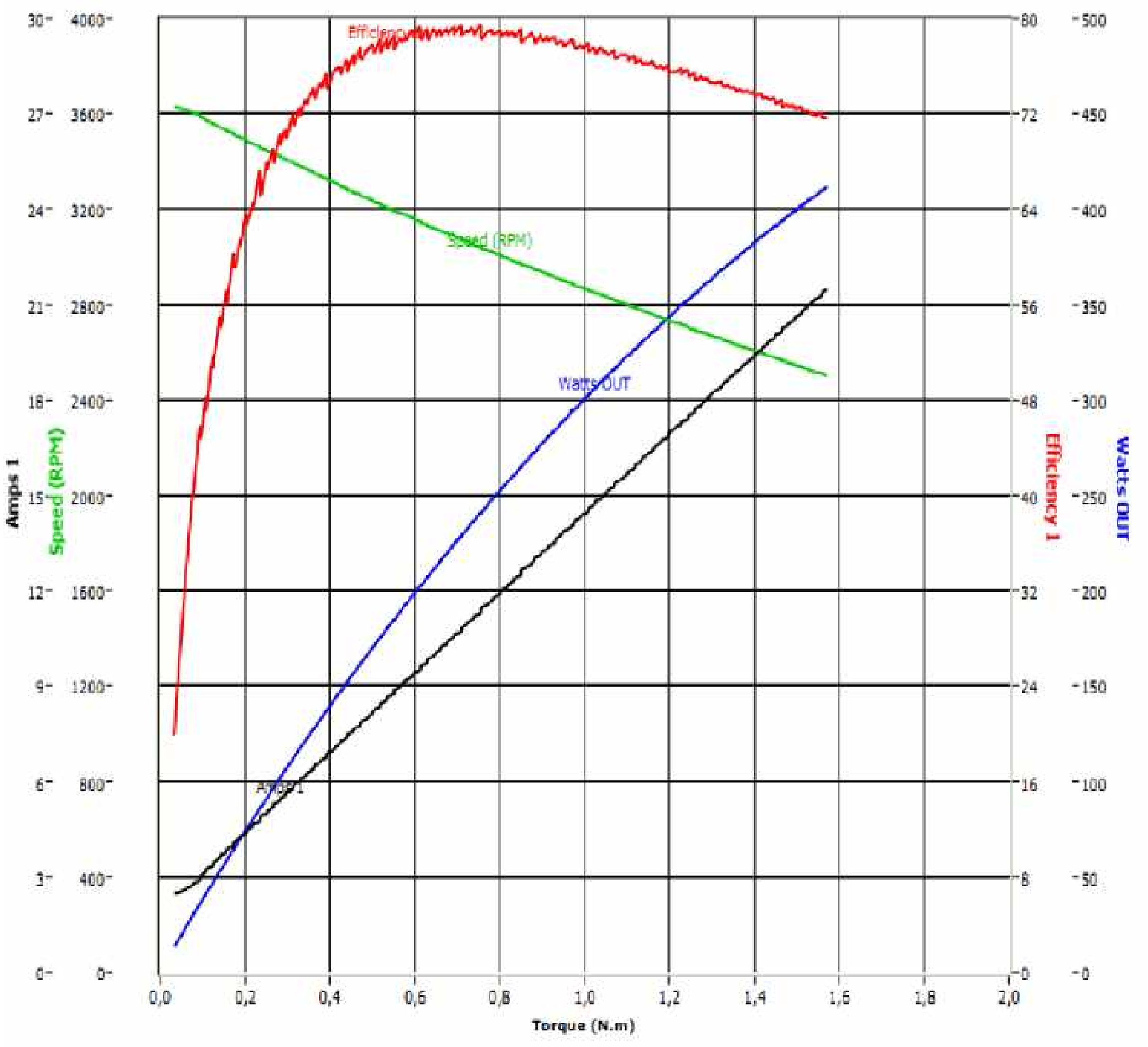
Please provide any comments about this pool lift:

This questionnaire is based on the System Usability Scale (SUS), which was developed by John Brooke while working at Digital Equipment Corporation.

Annex

ANNEX A – ELECTRIC MOTOR DATA-SHEET

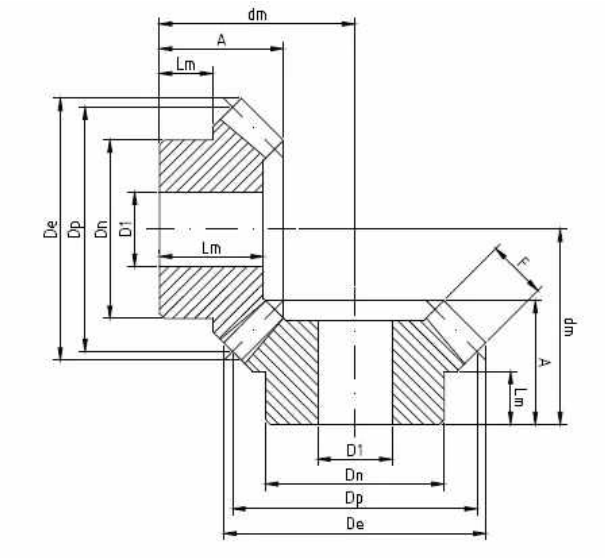
Figure 37 – Selected electric motor performance curve.



Source: (LANDELL TECNOLOGIA, 2022)

ANNEX B – BEVEL GEAR DATA-SHEET

Figure 38 – Bevel gear dimensions indication.



Source: (AZANELLI LLC, 2022)

Table 9 – Bevel Gear specifications.

Parameter	Value [mm]
Z	16
De	52.2
Dp	48.0
A	30.0
F	12.0
Dn	40.0
D1	15.0
dm	44.2
L	IP 26.0
Lm	16.2

Source: (AZANELLI LLC, 2022)

Dados do Pedido

Natureza Patente: 10 - Patente de Invenção (PI)

Título da Invenção ou Modelo de Utilidade (54): GUINCHO DE TRANSFERÊNCIA PARA PISCINA

Resumo: A presente invenção refere-se a um dispositivo para realizar a transferência de pessoas com mobilidade reduzida entre uma piscina e seu deck. O guincho de transferência (10) de piscina compreende uma estrutura de suporte (20), um conjunto de elevação (40), um elo de ligação (60) e uma montagem de assento (80). Um gabinete protetor (90) cobre a estrutura de suporte (20) fornecendo proteção como uma barreira de segurança contra a interação humana durante seu movimento mecânico.

Figura a publicar: 1