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KINETIC ANALYSIS OF NON-ROTATIONAL CANTILEVERED POOL TRANSFER DEVICES FOR DISABLED PEOPLE

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Abstract. *Sport, physical activity and leisure are extremely important to promote physical and mental health, promoting social inclusion for people with physical disabilities and reduced mobility. The Federal law 5296/04, in accordance with the standards of the ABNT (NBR 9050/2004), guarantees to all the accessibility rights. Disabled people that use wheelchairs who practice swimming or hydrotherapy generally need to transfer to the pool. In this there are risks to the safety of these people or even difficulties for the person who assists in the transfer. A mechanism designed to aid the transfer of people with limited mobility or physical disability to a pool is commonly called a "pool lift". This equipment usually includes an electronic transmission system with articulated movement, a base attached in the edge of the pool and a seat for the user. The proposal of this work is to develop a kinematic and kinetic model for a non-rotational cantilevered pool lift to evaluate its mechanical performance. The analytical model will be validated through numerical simulations with finite elements method. The work showed that the analytical model developed has a good approximation with the numerical model and can be used as a reference for the kinematic design of new transfer systems for pools.*

Keywords: *Pool transfer device, Kinematic analysis, Disabled people, Paralympic sport, Accessibility, Paralympic swimming.*

1. INTRODUCTION

According to Instituto Brasileiro de Geografia a e Estatística (2010), neurological, neuromuscular, orthopedic and other congenital or acquired formations are the main responsible for defining a Brazilian reality with about 45.6 million people with disabilities. In addition, a large part of this population lives in a society that, in general, is not adapted to provide accessible conditions to meet their needs (Siqueira *et al.*, 2009; Frontera, 2012).

The practice of sports and physical activities for people with disabilities and/or with reduced mobility is of fundamental importance for the improvement of physical conditioning, as well as for health and assistance in habilitation and rehabilitation. These practices improve the motor and psychological conditions and, indirectly, increase the social inclusion of this population (Bellomo *et al.*, 2015).

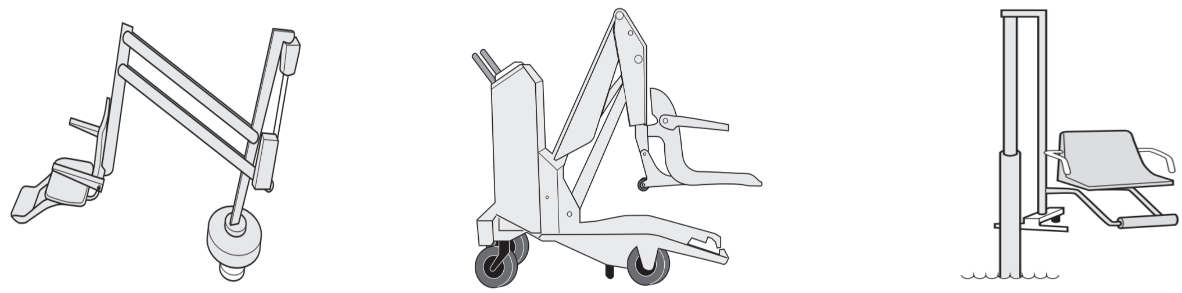
Currently, there are different modalities of adapted sports that cover the different types of disability (Instituto Brasileiro dos Direitos da Pessoa com Deficiência, 2008; Guimarães, 2003; Palla and de Mauerberg-de castro, 2004; de Mauerberg-de castro, 2005). Aware of the importance of sports practice and the growth of adapted sports, the Brazilian Paralympic Committee has been developing strategies to encourage sport ranging from the dissemination and organization of competitions to the exchange of athletes with other associations abroad (Costa and dos Santos, 2002; Costa, 2009). In this respect, since 1960, the year of the first Paralympic Games in Rome, until the participation of Brazil as the host of the Olympics and Paralympics in (2016), Brazil is a highlight and has medalists in the various Paralympic modalities (Ministério da Saúde *et al.*, 2010; Marques *et al.*, 2013; Parsons and Winckler, 2012).

The modalities of adapted sport require the assistance of assistive technologies so that sports practice can be performed efficiently, for example in improving physical fitness (Frontera, 2012). One of these assistive technologies related to the sports practice in swimming pools aims to assist in the transfer of people with disabilities to the pool. This procedure should be performed safely, avoiding overloads for these people and also for the coach during transference, especially in the initial stages of training (Busto, 2013; International Olympic Committee, 2016; Comitê Paralímpico Brasileiro, 2010). Cerqueira *et al.* (2010) emphasize that there are shortages of equipment that assist in the transfer of patients to the pool for the development of the sport or even therapeutic use. In this case, the high cost of importation has led to physio-therapeutic clinics to restrict the offer of services of this nature, reducing the treatment options of patients with these needs.

The objective of this work is to develop an analytical, kinematic and kinetic model of non-rotational cantilevered pool transfer mechanisms for disabled people. For validation, the models were compared with a finite element analysis. The objective was to understand the influence of the devices, parameterize their dimensions and evaluate their influence on the performance of the system. The validation of this model allows its use in future designs of new lifts for the transfer of disabled people to pools.

2. POOL TRANSFER DEVICE

According to S.R.Smith LLC (2012), pool transfer equipment can be classified into three categories. The first is the rotational cantilevered lift type, shown in Fig. 1a, and has the ability to raise and rotate the seat position on the deck and extend out from the anchor point. Because they are more complex, they have a relatively higher cost. The second category is the non-rotational cantilevered lift type, shown in Fig. 1b, which has a limited movement, having only seat extension directly from the loading point toward the pool, and is, therefore, simpler, and consequently, has a lower cost. Finally, there is the non-cantilevered category, shown in Fig. 1c, where the seat is attached to and rotates around the anchor point and is most often supplied by water, and its operation is smooth and relatively slow and may cause difficulties in times of emergency.



(a) Rotational cantilevered lift. (b) Non-rotational cantilevered lift. (c) Non-Cantilevered lift.

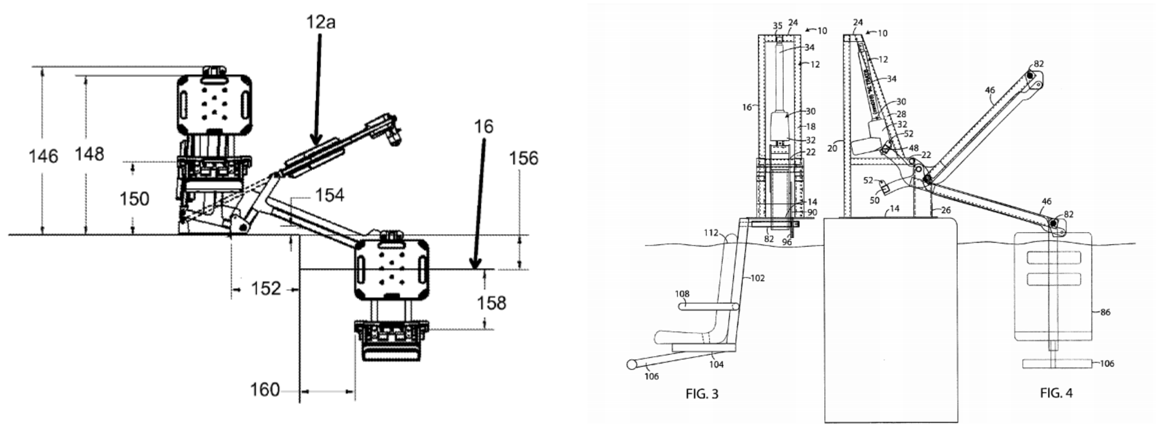
Figure 1: Examples of pool lift devices. Source: (S.R.Smith LLC, 2012)

Among the transfer lifts, the non-rotational cantilevered lifts have a lower cost and can be used safely and quickly. Therefore, it is important to develop optimized mechanisms for this category of device, especially considering a stationary system near the edge of the pool. The most recent patents of this type of pool lift feature six-bar articulated mechanisms actuated by linear electromechanical actuator, and are shown in Fig. 2.

Regarding the operation of these devices, basically a wheelchair user approaches the pool lift, placing his wheelchair next to the seat. He transfers himself onto the seat, fasten the seat belt and uses a remote control to drive the pool lift, which will perform an articulated movement transporting him into the pool. When he is submerged, he must loosen the belt. When he has completed his activity inside the pool, he comes back and sits on the seat, fasten the seat belt and uses a remote control to drive the pool lift, which will perform the reverse articulated movement transporting him out of the pool. When it is at the top of the deck, he loosen his belt and transfer himself to his wheelchair.

Figure 2a shows the front view of the pool lift in a retracted and in an extended position, taken from the US patent 2014/0101839 A1. This pool lift has the base positioned adjacent to the edge of the pool. An elongate arched lifting structure functions as a ternary link, where its central joint, fulcrum, is pivoted to the base and rotates about an axis parallel to the pool edge. An electromechanical linear actuator is also pivoted to the base and extends at one the end pivotal joint of the ternary link, driving its angular movement. A seat is supported by the other end joint of the ternary link, and travels a circular trajectory from the deck to the pool cavity.

Figure 2b shows the front view of the pool lift in a median and final position, taken from the US patent 8,646,119 B1. This pool lift includes a stationary metal frame adjacent to the pool edge. The lift arm is a ternary link, where its central joint is pivoted to the metal frame, functioning as support point, fulcrum. One of the end links of the ternary link is connected to an electromechanical linear actuator, which in turn is connected to the metal frame. The other end joint is attached to the chair. There is a protective cover around the metal frame to provide protection from environmental damage. When the linear actuator extends, the ternary link rotates carrying the seat from the pool deck to the pool cavity in a circular trajectory.



(a) Source: (S.R.Smith LLC, 2014)

(b) Source: (Sheridan, 2014)

Figure 2: Front and side view of the pool lifts in a retracted and in an extended position.

3. PROPOSED ANALYTICAL MODEL - KINEMATIC ANALYSIS

The kinematic model of the lifting arm considers the dimensions and geometric configuration of the positions and dimensions of the mechanisms shown in Fig. 2. Figure 3 shows a schematic modeled configuration for this type of mechanism where r is the length of the spindle to the nut, represented by D.

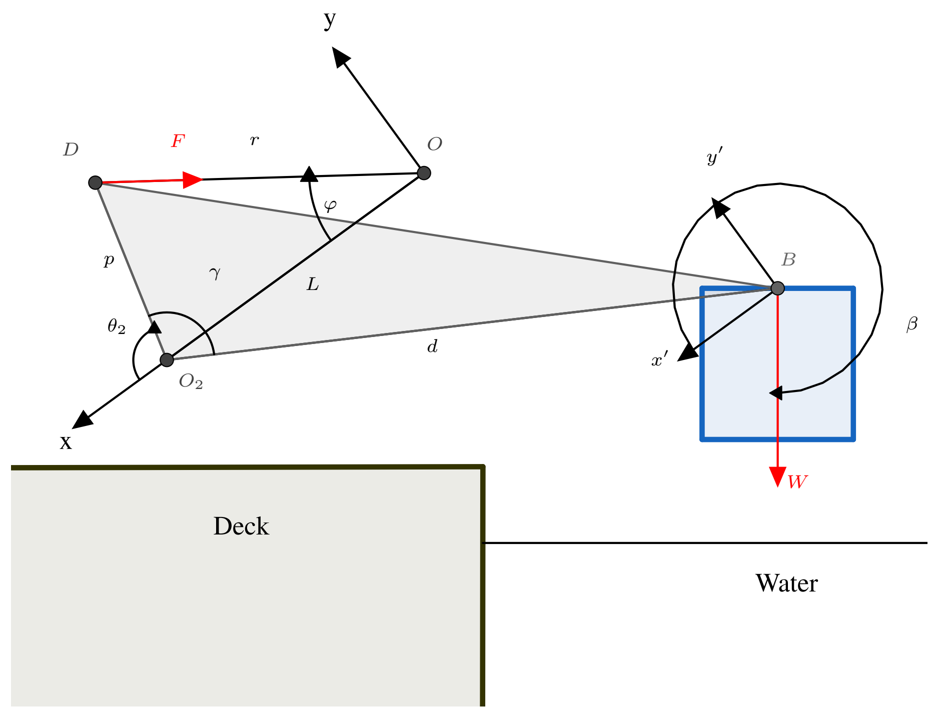


Figure 3: Kinematic layout of the proposed pool lift.

This set is controlled by a motor coupled at point O. In the model, $\mathbf{L}$ represents the distance between points 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 point, with $\mathbf{p}$ being the length of the arm which sustains the driving force $\mathbf{F}$ and d the length of the lever arm of the resistive force $\mathbf{W}$. The coordinate system is positioned with the origin coincident at point O and with the x-axis parallel to $\mathbf{L}$. The angle φ represents the angle formed from $\mathbf{L}$ to $\mathbf{r}$. The angle θ_2 is the angle formed from $\mathbf{x}$ to $\mathbf{p}$. We can describe this mechanism completely by means of the position vector $\mathbf{q} \equiv (\mathbf{r}, \varphi, \theta_2)$. The independent variable is $\mathbf{r}$, so it is necessary to determine the angles φ and θ_2 for the solution of the kinematic motion of the system.

The angular amplitudes of movement of the lifting arm were estimated considering the reference dimensions and the degrees of freedom of the mechanism, besides the relative positions of the non-rotational cantilevered system.

Considering the operation of the mechanism in a plane, it was used the Kutzbach criterion (Angeles and Truesdell, 1989) to determine the number of degrees of freedom, as shown in Eq. (1):

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

where N is the number of DOFs; B is the total number of bodies (including the ground); n_{j1} is the number of lower pairs; and n_{j2} is the number of higher pairs.

The closed-loop vector equation is given by,

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

It's possible to express these vectors in polar and Cartesian coordinates, that is,

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

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

Similarly, 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 position vector and are therefore represented in the polar system, that is,

$$(\dot{r} + ir\dot{\varphi})e^{i\varphi} - (\dot{p} + ip\dot{\theta}_2)e^{i\theta_2} - (\dot{L} + iL\dot{0})e^{i0} = 0 \tag{5}$$

$$(\ddot{r} + i2\dot{r}\dot{\varphi} + ir\ddot{\varphi} - r\dot{\varphi}^2)e^{i\varphi} - (\ddot{p} + i2\dot{p}\dot{\theta_2} + ip\ddot{\theta_2} - p\dot{\theta_2}^2)e^{i\theta_2} - (\ddot{L} + i2\dot{L}\dot{0} + iL\ddot{0} - L\dot{0}^2)e^{i0} = 0 \tag{6}$$

By performing the same procedure used to find φ and θ_2 from the position vector, one can find $\dot{\varphi}$, $\dot{\theta}_2$, $\ddot{\varphi}$ and $\ddot{\theta_2}$. The angular acceleration at the point O_2 will be used in the dynamic analysis and its expression is calculated as:

$$\ddot{\theta_2} = -\frac{r\ddot{\varphi}^2 - 2\ddot{r} - 2p\dot{\theta_2}^2 cos(\varphi - \theta_2) + r\dot{\varphi}^2 cos(2\varphi) + r\dot{\varphi}^2 sen(2\varphi)}{2psen(\varphi - \theta_2)} \tag{7}$$

3.1 Dynamic analysis

It is assumed 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

$$A_x + F_x = m_b a_x \tag{8}$$

$$A_y + F_y - W = m_b a_y \tag{9}$$

$$M_F + M_W = I\ddot{\theta_2} \tag{10}$$

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

$$M_F = Fcos(\varphi + \pi)psen(\theta_2) + Fsen(\varphi + \pi)pcos(\theta_2) \tag{11}$$

$$M_W = Wsen(\beta)dcos(\theta_2 + \gamma) + Wcos(\beta)dsen(\theta_2 + \gamma) \tag{12}$$

Substituting I and Eqs. (11), (12), and (7) into Eq. (10) we obtain the load force **F** acting on the power screw, that is,

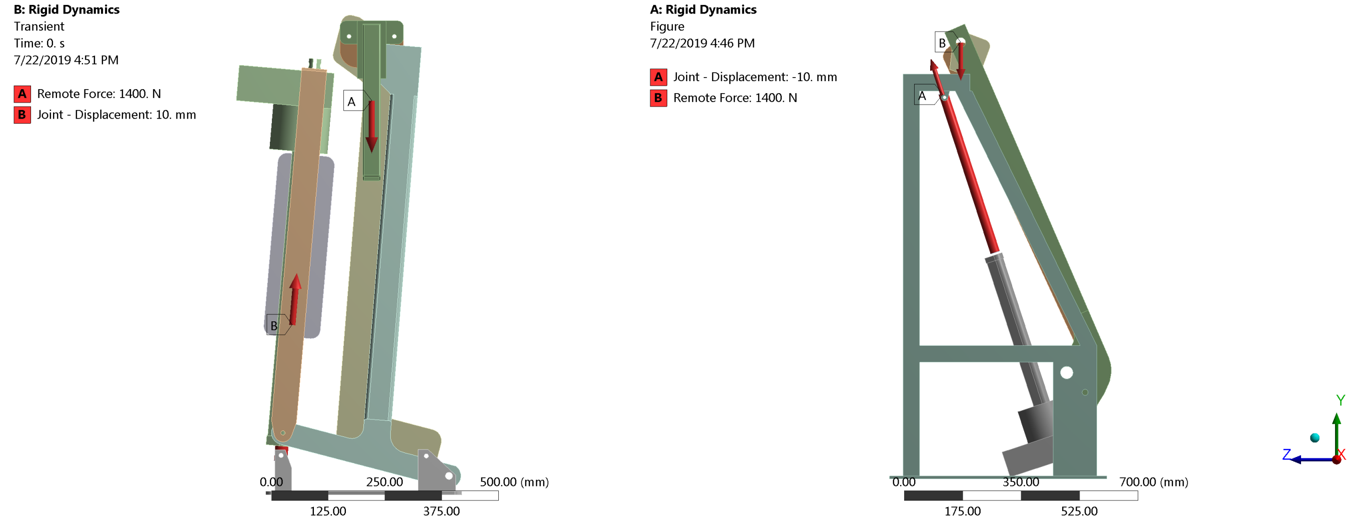
$$F = \frac{\begin{aligned}&-(d(Wpcos(\gamma - \beta + \varphi) - Wpcos(\beta - \gamma + \varphi - 2\theta_2) - 2dm\ddot{r} \\ &+ dm\dot{\varphi}^2 r - 2dmp\dot{\theta_2}^2 cos(\varphi - \theta_2) + dm\dot{\varphi}^2 rcos(2\varphi) + dm\dot{\varphi}^2 rsin(2\varphi))\end{aligned}}{p^2(cos(2\varphi - 2\theta_2) - 1)} \tag{13}$$

3.2 Simulation

For the two elevator models evaluated in this work, three-dimensional geometric models were developed to be evaluated in the SolidWorks and ANSYS® Workbench software.

The simulation was implemented representing the lowering movement of the seat, i.e. from the pool deck to the pool cavity. The starting position is when the lift arm is on the deck, allowing the user to transport onto the seat. Operating the linear actuator, the articulated mechanism makes an angular movement to the final position, when the seat is 40 cm submerged in the water.

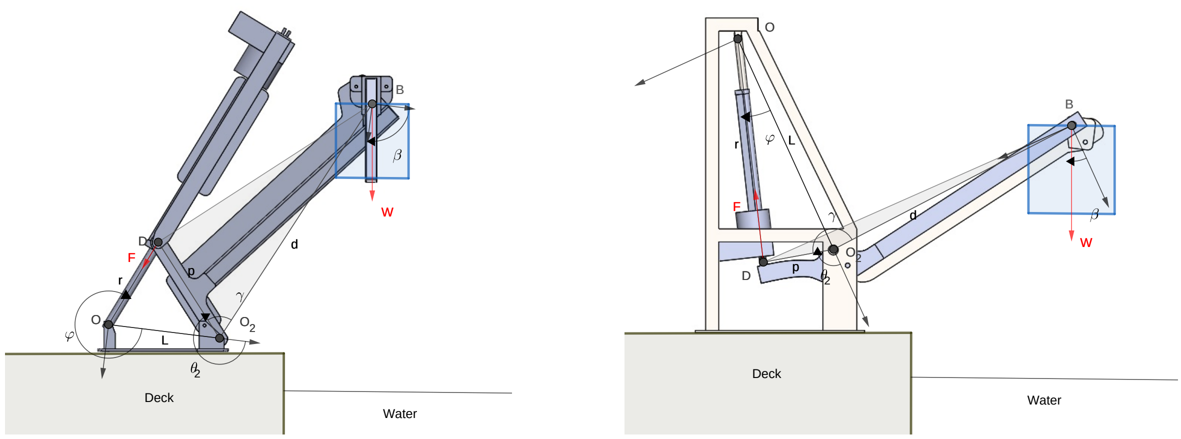
Figure 4 shows the boundary conditions of the simulation in ANSYS. Both pool lifts were set up in its initial position, i.e. when the the chair is above the pool deck, enabling the user entrance. A joint displacement of 10 mm per second is axially applied to the the piston rod, representing its velocity, according to manufacturer specifications (S.R.Smith LLC, 2016). A remote force of 1400 N is applied to the surface area of the link that supports the seat, according to the 2010 ADA Standards for Accessible Design (Dept. of Justice, 2010) that stipulates a minimum lifting capacity of 300 lb/ 136 kg.



(a) S.R. Smith LLC's 3D model. (b) Sheridan's 3D model.

Figure 4: Boundary conditions on the 3D models of the studied patents in ANSYS software. Source: Authors.

The kinematic model was superimposed on these three-dimensional models, as shown in Fig. 5. By configuring the elevator in its initial position it is possible to collect the dimensions used to perform the analytical calculations, listed in Tab. 1.



(a) S.R. Smith LLC's 3D model. (b) Sheridan's 3D model.

Figure 5: Kinematic layout superimposed on the 3D models of the studied patents. Source: Authors.

Table 1: Parameters used in the calculations and simulation.

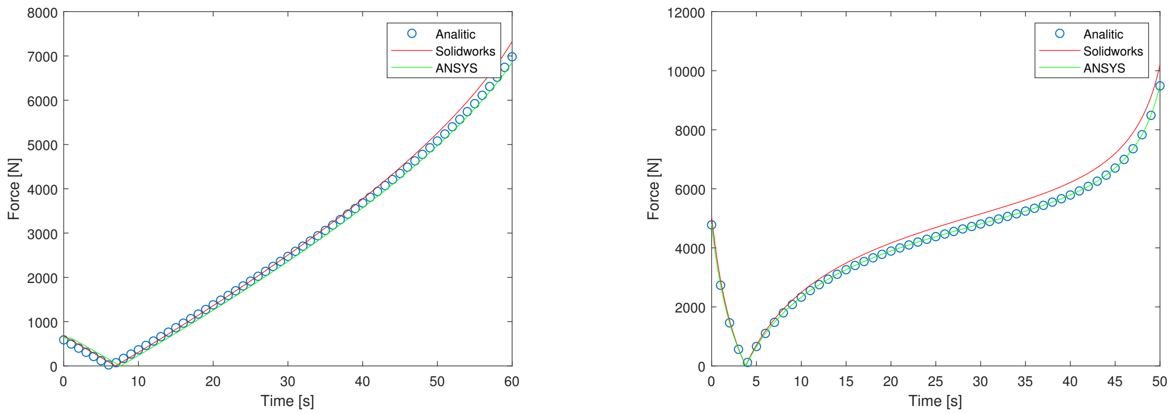
Parameter	Value of S.R. Smith's model	Value of Sheridan's model
W (N)	1400	1400
m_w (Kg)	140	140
L (N)	0.37263	0.89935
p (m)	0.37767	0.27374
r (m)	0.05536	1.15236
$\dot{r}$ (m/s)	0.01	0.01
$\ddot{r}$ (m/s^2)	0	0
d (m)	0.93791	1.03539
γ (rad)	1.1353	2.8023
β (rad)	1.4502	0.4185

4. RESULTS

The kinematic and kinetic analytical model was validated using the numerical simulations comparing the axial force values in the power screw, shown in Fig. 6.

The results show a growth of the force in proportion to the increase of the moment due to the force W, as the lever arm that supports this force increases according to the angular movement of the lifting arm.

At the same time, at the other end of this arm, there is a counterbalance made by the moment due to force F, forming a class 1 lever system (Davidovits, 2008). Therefore, the shape of the curve observed in the kinematic analysis has a direct relation with the lever arms, which, in turn, is conditioned both by the spatial arrangement of the links in the mechanism and its dimensions.



(a) S.R. Smith LLC's model.

(b) Sheridan's model.

Figure 6: Confrontation of the power screw axial force of the studied patents' models between the analytical calculation and simulations. Source: Authors.

5. CONCLUSION

The kinematic and kinetic analytical model developed for non-rotational cantilevered pool transfer devices was validated by finite element numerical simulations. Through this model it is possible to understand the kinematic and structural behavior in transfer operations of the lifts and can be used for the development and analysis of new types of lifts that have a similar articulated mechanism, facilitating the search for optimal dimensions through the iterations of their geometric parameters.

6. ACKNOWLEDGEMENTS

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