Development of Swimming Pool Lift for physically challenged

A Project Report

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THESIS CERTIFICATE

This is to certify that the thesis titled **Development of Swimming Pool Lift for physically challenged**, submitted by **Swostik Sourav Dash (ME08B088)**, to the Indian Institute of Technology Madras, Chennai for the award of the degree of **Bachelor of Technology and Master of Technology**, is a bona fide record of the research work done by him under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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- Swostik Sourav Dash

ABSTRACT

KEYWORDS: Swimming Pool Lift, Aquatic Lift, Lift, Assistive Device, Accessibility Equipment, Physically Challenged

For physically challenged persons, primarily wheel chair users, swimming provides multiple health benefits, physically and mentally. It is one of the few means where they can achieve free movement or a full body exercise. Also, being in the pool instills a sense of independence, thereby making them happy. But most pools are equipped only with stairs for entry or exit and all physically challenged may not be capable of using them. In such cases, additional assistance like a swimming pool lift is required. This device lowers and raises the user into or out of the pool. The scope of the project is detailed design, analysis and initial prototyping of a pool lift.

The development of the pool lift was conducted sequentially, starting with study of previous work in form of market survey and patent study. This helped develop an insight into various designs and technologies already being used and what may be improved. Design requirements were listed and kinematic designs were explored to meet the requirements. A four-bar parallelogram mechanism was selected and its kinematic design was gradually improved through iterations. 3D model was developed for the finalized kinematics. Forces acting on various joints were determined and used to design all parts for suitable strength. A full scale prototype was developed and tested with partial loading conditions to demonstrate the design.

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ABBREVIATIONS

CAD	Computer Aided Drawing
ID	Inner diameter
IITM	Indian Institute of Technology Madras
OD	Outer diameter
OEM	Original Equipment Manufacturer

NOTATIONS

G	Acceleration due to gravitational force on earth
M	Mass on a swimming pool lift acting as the load

Chapter 1

Introduction

1.1. Need for a swimming pool lift

For physically challenged persons, primarily wheel chair users, swimming provides multiple health benefits, physically and mentally. It is one of the few means where they can achieve free movement or a full body exercise. Also, being in the pool instills a sense of independence, thereby making them happy.

Most pools, to provide an entry and exit from the pool, are equipped with stairs having rails on sides for support. Stairs pose a problem for physically challenged persons, as most of them may not be capable of using them.

In such cases, additional assistance is required to hold and help lower physically challenged into the pool. And more importantly, assistance is required to remove them out of the pool. Providing lifts at swimming pool is one solution for the problem.

Figure 1-1: A swimming pool lift

(Image Courtesy: Dolphin Lifts [1])

1.2. Pool lifts in the west

Pool lifts have become extremely popular in the west. This can be demonstrated by the ADA 2010 [2] (Americans with Disabilities Act) by the US Department of Justice. The act requires all public and private swimming facilities to be facilitated for access to persons with disability. The compliance date for the same was January 31, 2013. The table shows the type of accessibility device that needs to be provided for a given type of water body, as per ADA 2010.

Type of Pool	Slope	Lift	Others
Swimming Pools with less than 300 Lineal Feet of Pool Wall	√	√	-
Swimming Pools - 300 or more Lineal Feet of Pool Wall (2 means of entry)	√	√	√
Wave Action, Leisure River, Other Pools where User Entry is Limited to 1 Area	√	√	√
Wading Pools	√	-	-
Spas	-	√	√

Table 1-1: ADA 2010, recommended accessibility device for a given water body

1.3. Pool lifts in India

In India, pool lifts aren't very popular yet. A few manufacturers have ventured into this like Callidai Motor Works, Chennai. But the cost of available equipment is very high (INR 160,000/-). Reason may be attributed to specific design of the available lifts and low market competition.

1.4. Pool lift study through market survey

A detailed study of products existing in the market was done through online resources. It was attempted to identify the following engineering parameters and concepts while studying them.

Engineering parameters of interest:

- Lifting Capacity (kg)
- Horizontal Arm Travel (m)
- Vertical Arm Travel (m)
- Planar Rotation (deg.)
- Down-lifting time (s)
- Up-lifting time (s)
- Total Weight (kg)
- Actuator
- Power-pack
- Fixture
- Price

Engineering concepts of interest:

- Kinematics
- Actuator and Power pack
- Fixture

1.4.1. BlueOne Portable Pool Lift [3]

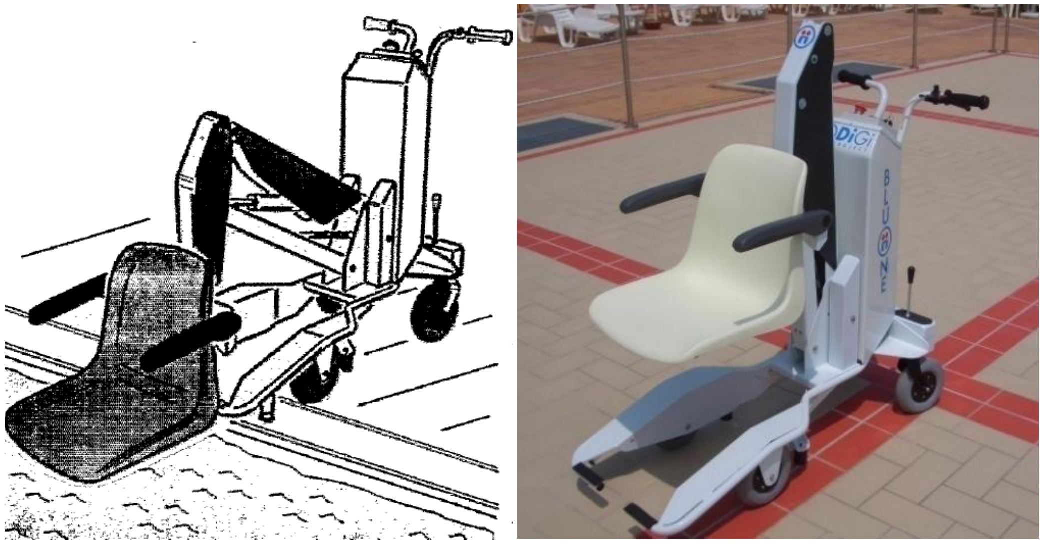


Figure 1-2: BlueOne Portable Pool Lift

This device acts both as a wheel chair and a pool lift. A person needs to be transferred to the chair of the device away from the pool-edge for safe transfer. This can happen at the dressing room or any other location. Following the transfer, the device is rolled to the edge of the pool and its wheels are locked. The seat, which is the coupler of a four-bar parallelogram mechanism, is then lowered into the pool.

- Lifting Capacity (kg): 110
- Horizontal Arm Travel (m): Max 1.15
- Down-lifting time (s): 23
- Up-lifting time (s): 17
- Total Weight (kg): 120
- Actuator: hydraulic piston
- Power-pack: 24 V Battery
- Fixture: portable, a wheel-chair in itself
- Price: GBP 5695
- An emergency manual pump is present to be used in case of power failure
- Rubber stoppers between front and rear wheels to prevent the lift to be pushed into the water

1.4.2. BluOne F100 Swimming Pool Lift [4]

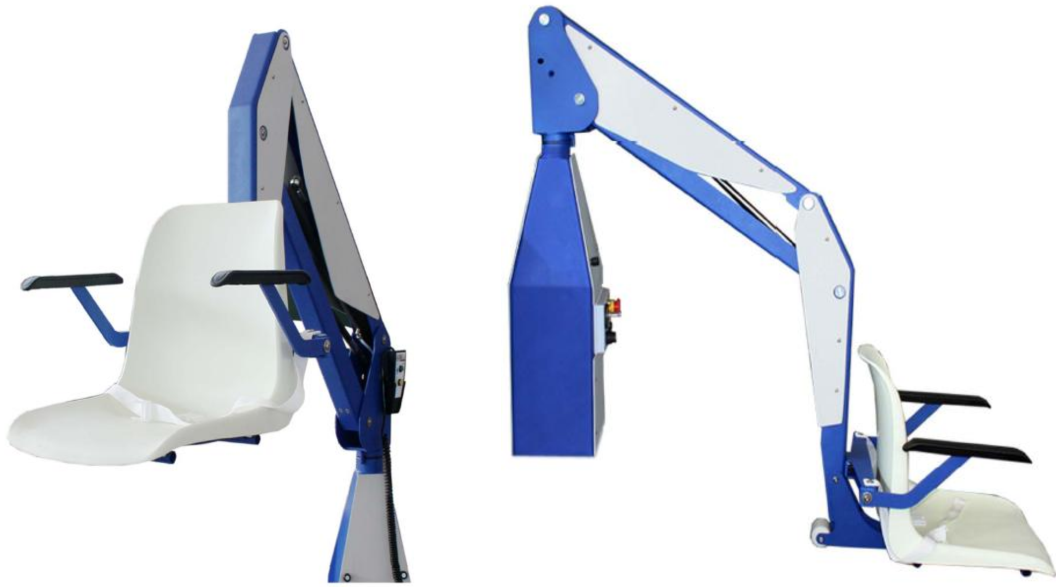


Figure 1-3: BluOne F100 Swimming Pool Lift

This device is a fixed in nature where the base is mounted on the pool-deck. There are two degrees of freedom: rotation of the parallelogram mechanism about a vertical axis (over the central mast) and rotation of the parallelogram arms. A person on a wheel-chair comes next to the seat and transfers himself/herself to the seat. The parallelogram arms are then rotated till they reach over the pool. Next the seat is lowered to a desired depth into the pool.

- Lifting Capacity (kg): 140
- Horizontal Arm Travel (m): Max 1.15
- Planar Rotation (deg.): 340
- Down-lifting time (s): 23
- Up-lifting time (s): 17
- Total Weight (kg): 45
- Actuator: hydraulic piston
- Power-pack: 24 V Battery
- Fixture: Floor plate mounting (20cm x 20 cm), fixed with screws to concrete
- Price: GBP 5440

1.4.3. BluOne F145 Swimming Pool Lift [5]

Figure 1-4: BluOne F145 Swimming Pool Lift

This device consists of a central mast fixed to the pool deck. A top arm is connected to the central mast through a hinge joint. The seat is freely suspended on the top arm. Unlike the first two devices, this does not involve any parallelogram arms. The seat is lowered or raised from the pool using a linear actuator.

- Lifting Capacity (kg): 140
- Horizontal Arm Travel (m): From -0.6 to 1.45
- Planar Rotation (deg.): 360
- Down-lifting time (s): 23
- Up-lifting time (s): 17
- Total Weight (kg): 40
- Actuator: hydraulic piston
- Power-pack: 24 V Battery
- Fixture: Floor plate mounting (40cm x 40 cm), fixed with screws to concrete
- Price: GBP 4600

1.4.4. BluOne F130 Portable Lift [6]

Figure 1-5: BluOne F130 Portable Lift

This device consists of a wall mounted plate which supports the entire lift. A top arm is connected to the wall mount through a hinge joint. The seat is freely suspended on the top arm. The device will be useful only in those cases where the pool has a raised wall, or an arrangement similar to a bathtub.

- Lifting Capacity (kg): 140
- Horizontal Arm Travel (m): From -0.25 to 1.15
- Planar Rotation (deg.): 180
- Down-lifting time (s): 23
- Up-lifting time (s): 17
- Total Weight (kg): 45
- Actuator: hydraulic piston
- Power-pack: 24 V Battery
- Fixture: Wall plate mounting (90cm x 20 cm)
- Price: GBP 4390

1.4.5 PAL Portable Pool Lift [7]

Figure 1-6: PAL Portable Pool Lift

As the name suggests, the device is portable in nature and can be stationed anywhere on the pool deck. This device operates through two degrees of freedom: swiveling of the central mast and rotation of the parallelogram arms. A person on wheelchair can come close to the seat of the device and transfer himself/herself to the seat. Swiveling of the mast brings the seat over the pool which is subsequently lowered into the pool. To avoid toppling into the water, heavy counter weights are used in the base of the device.

- Lifting Capacity (kg): 136
- Planar Rotation (deg.): 240
- Maximum actuator traverse speed (mm/s): 15
- Total Weight (kg): 385
- Actuator: Ball screw type linear actuator
- Power-pack: 24 V Battery
- Fixture: Portable
- Price: GBP 6722

1.4.6. Aqua Creek Patriot Portable Pool Lift [8]

Figure 1-7: Aqua Creek Patriot Portable Pool Lift

Patriot Pool Lift has only one degree of freedom, i.e. rotation of parallelogram arms. These arms are L-shaped which allow for the seat to be located away from the pool edge for safety. A ballast tank filled with sand is used as counter-weight to avoid toppling.

- Lifting capacity (kg): 204 kg
- Weight with ballast tank filled (kg): 397
- Cost: USD 4,837

1.4.7. Aqua Creek Pro Pool Lift [9]

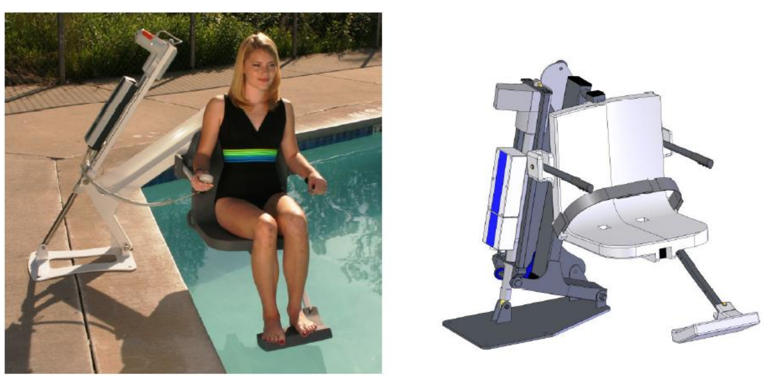


Figure 1-8: Aqua Creek Pro Pool Lift

Pro Pool Lift is exactly the same as Patriot Pool Lift with a fixed base to pool deck instead of ballast tank. This makes the overall dimension of lift smaller but with loss of portability.

1.4.8. Handimove Mobile Pool Lift [10]

Figure 1-9: Handimove Mobile Pool Lift

Handimove Lift is mobile in nature but needs a prepared pool-deck. A coupling (hole with lock) needs to installed on the pool-deck where the entire lift-base can be inserted for usage. The lift has a planar rotation capability of 360 deg. and weighs 44 kg.

1.4.9. Rail arrangement [11]

Figure 1-10: Railing arrangement lift

This lifting device consists of a seat which slides on rails. The rails are horizontal on the pool deck and later convert into a slope to provide entry into pool. A cable connected to a motor-shaft over a pulley moves the seat over the rails.

1.5. Patent search

1.5.1. Swimming Pool Lift by Richards [12]

The device consists of a platform positioned in a swimming pool which is supported on hydraulic rams located at corners of the pool. These rams raise or lower the platform. Each ram has a barrel attached to the platform and a piston rod which is supported on the bottom of the pool. There is a hydraulic motor for each ram. The hydraulic fluid is water. The pistons of the motor cylinders are actuated in unison by a single main cylinder.

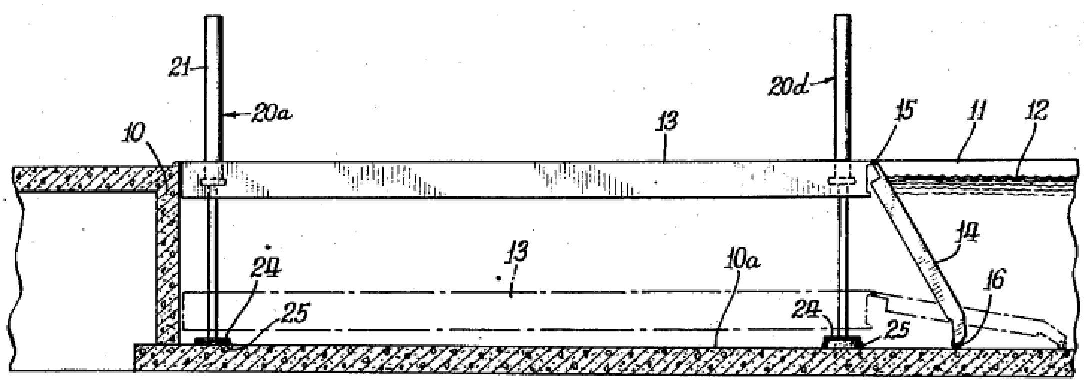


Figure 1-11: Swimming Pool Lift by Richards (US3955797)

1.5.2. Swimming Pool Lift for Handicapped by Grimes et al. [13]

The apparatus supports a chair at the side of the pool in a position to receive physically challenged. Chair is rotated out over the water and then lowered into the water where the occupant glides or pushes off the seat for a swimming. The chair is adapted to receive the person after the session and then is raised out of the water and rotated back to the poolside position so that the person can leave the chair. In the particular description all actuations are achieved through hydraulic means.

1.5.3. Swimming Pool Chair Lift by Nolan [14]

The device transfers people vertically and in a helical pattern into and out of the pool of water. The seat or carrier is supported on a piston of a hydraulic cylinder. There is an external guide-way or groove present on the housing cylinder which ensures that the seat moves along a helical path as it is moved up or down.

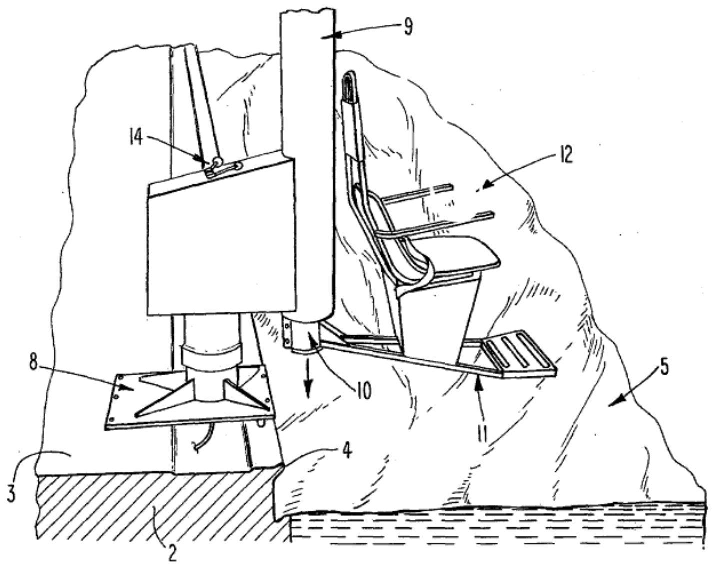


Figure 1-12: Swimming Pool Lift for Handicapped by Grimes et al. (US4183106)

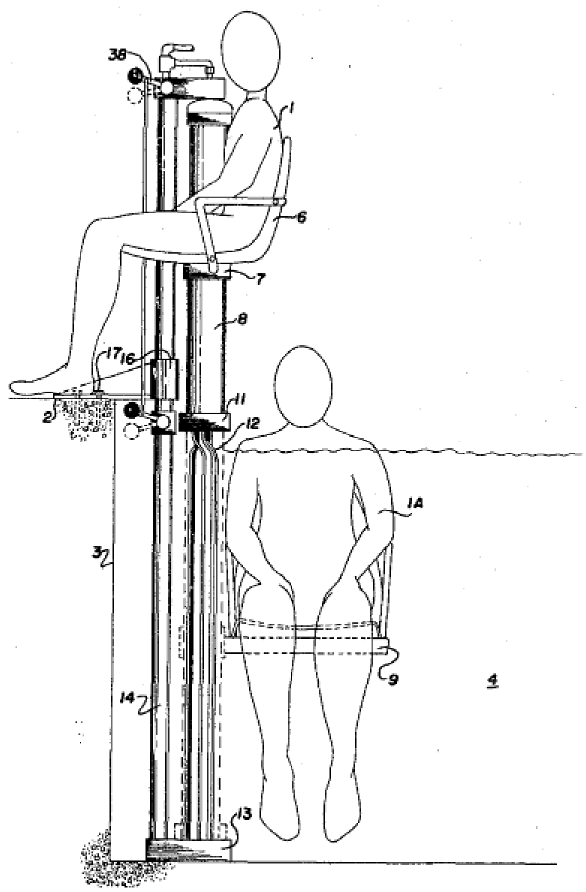


Figure 1-13: Swimming Pool Chair Lift by Nolan (US4221008)

1.5.4. Process for immersing in a swimming pool disabled persons using a wheel-chair by Krumbeck [15]

This swimming pool lift installation for the physically challenged employs a platform for carrying a wheel chair that is lowered and elevated with the platform. The person can sit on his chair and be lowered into the pool for swimming away from the chair and can leave the pool by swimming back into the wheelchair. The chair is reasonably secured to the platform so that there is no danger of it being rendered unstable by its buoyancy in water and so that it can be wheeled on and off the platform. A water hydraulic system operates the lift to avoid any contamination of the pool.

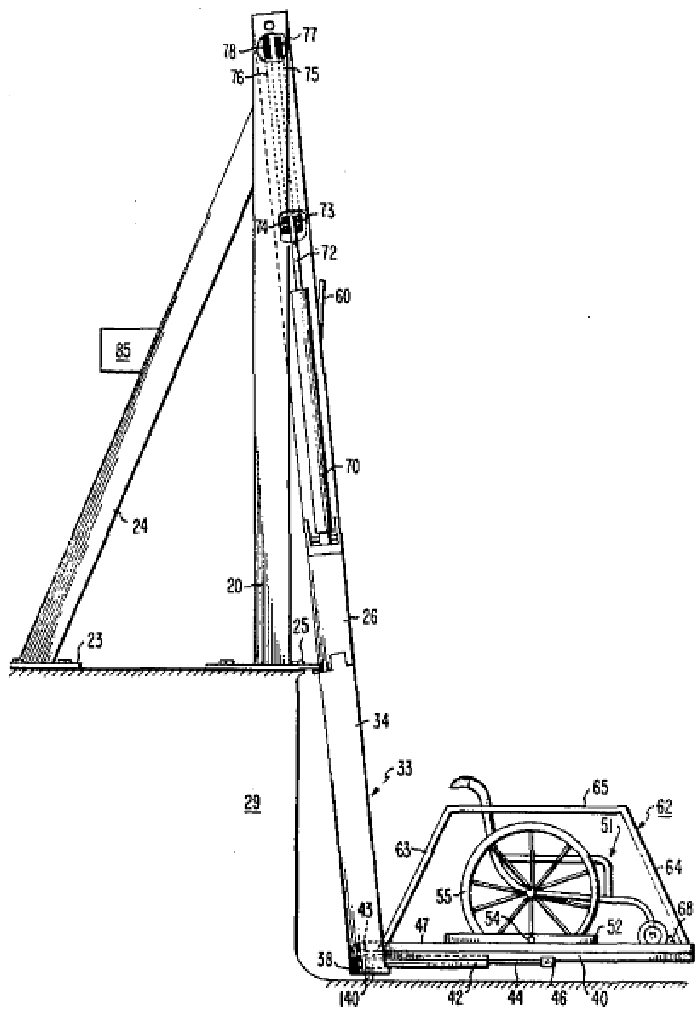


Figure 1-14: Process for immersing in a swimming pool disabled persons using a wheel-chair by Krumbeck (US4283803)

1.5.5. Aquatic lifting device by Caden et al. [16]

The lift includes a base with a mast segment coupled to and extending upwardly from the base. A pair of spaced parallelogram arms is pivotally coupled to the mast segment. As the arms are rotated, the seat attached to one end of the arms, also move up and down. Castors are provided at the base of the device to position it anywhere on the pool deck. A counterweight assembly is provided on the base to secure the base and avoid unwanted movements.

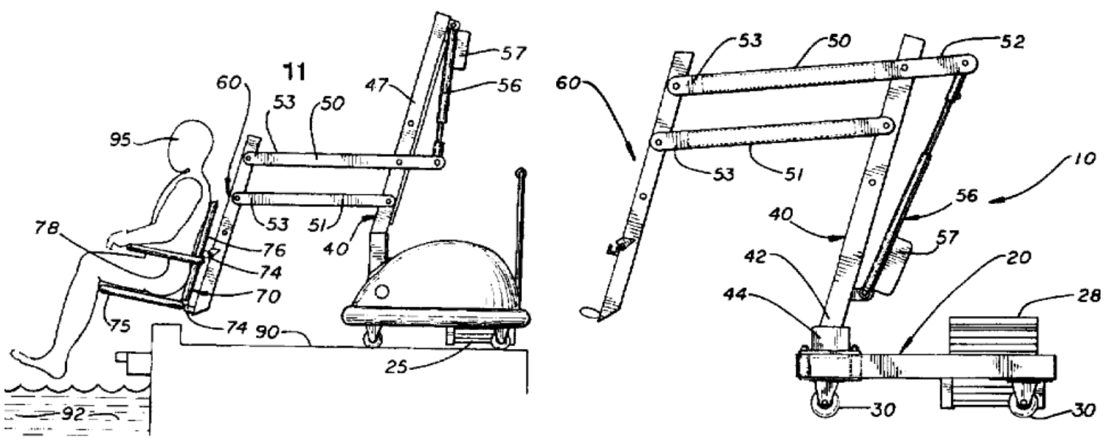


Figure 1-15: Aquatic lifting device by Caden et al. (US5790995)

1.5.6. Swimming pool lift by Krumbeck [17]

In this patent a hydraulic pool lift is disclosed. The lift has enhanced stability due to its adjustable support assembly and areinforced piston rod. A load carrying component is rotated 180 deg. from a deck position to the pool position. A curved track on hydraulic driven piston guides the displacement of load carrying component.

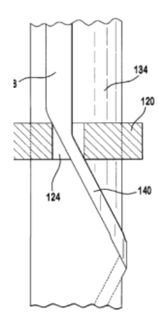


Figure 1-16: Swimming pool lift by Krumbeck (US6170612), curved track

1.5.7. Portable pool lift for disabled persons by Terzo [18]

This pool lift has a base, release-ably position-able on a pool deck placed adjacent to pool edge. The base pivotally mounts an elongate arcuate lift frame about an axis parallel to the pool edge. A hydraulic cylinder extends in pivotal interconnection between the base and medial portion of the arcuate lift frame. This pivotally moves a chair carried by the lift frame and oriented in a direction parallel to the adjacent pool edge. An orienting cable maintains the chair in horizontal seating orientation during its course of motion.

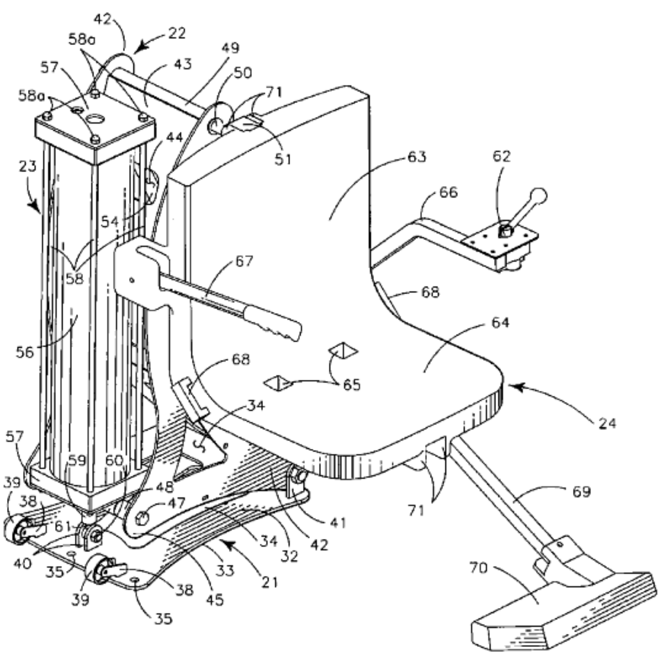


Figure 1-17: Portable pool lift for disabled persons by Terzo (US7249386)

1.5.8. Swimming pool lift by Gallan [19]

The lift is a portable apparatus for lowering and lifting a user into and out of the pool. It includes a frame with vertical, longitudinally adjustable legs, horizontal support arms extending rearwardly from upper end of legs and feet extending forward from the lower end of the legs. The support arms are adapted to rest on the pool deck and feet are adapted to rest on the pool bottom, with the apparatus being held on position only by friction forces of arms and feet. A hydraulic cylinder moves a chair into and ot of the pool. The chair can be rotated when in raised position to permit ingress and egress.

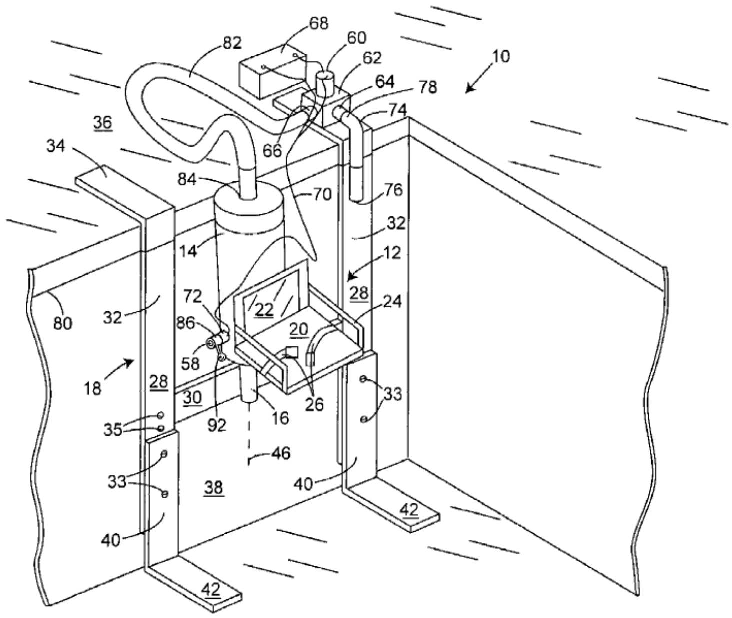


Figure 1-18: Swimming pool lift by Gallan (US7275272)

1.5.9. Swimming pool lift and transfer bar by Maguire et al. [20]

The device facilitates access to swimming pools and spas. The lift includes a base and a mast extending there-from. An arm pivotally connects to the mast. A seat assembly connects to the arm. An overhead support is positioned over the seat assembly. A first actuator moves the arm about the mast, thereby moving the seat assembly out of and into the pool. A second actuator rotates the seat assembly relative to the base to position the seat assembly over the pool deck. In use, the lift attaches to the pool deck.

1.5.10. Disabled person swimming pool usage system by Hill [21]

The device helps a physically challenged person more fully utilize a swimming pool by transporting the person over the pool water and lowering the person into the water. The device uses a base that has a lift platform that is capable of being raised and lowered as well as rotated. The base is at least partially submerged within the pool and has a stairway. Three separate platforms extend outwards and rest on the pool deck. Each platform has a rail system that is traversable by a chair that rides on the rail systems. Transition between out rail and another is accompanied at the lift platform which operates similar to a roundhouse turntable.

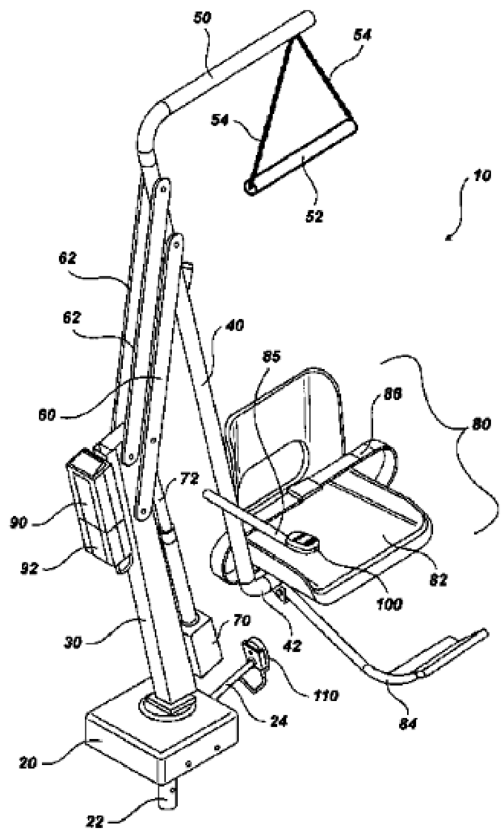


Figure 1-19: Swimming pool lift and transfer bar by Maguire et al. (US7310833)

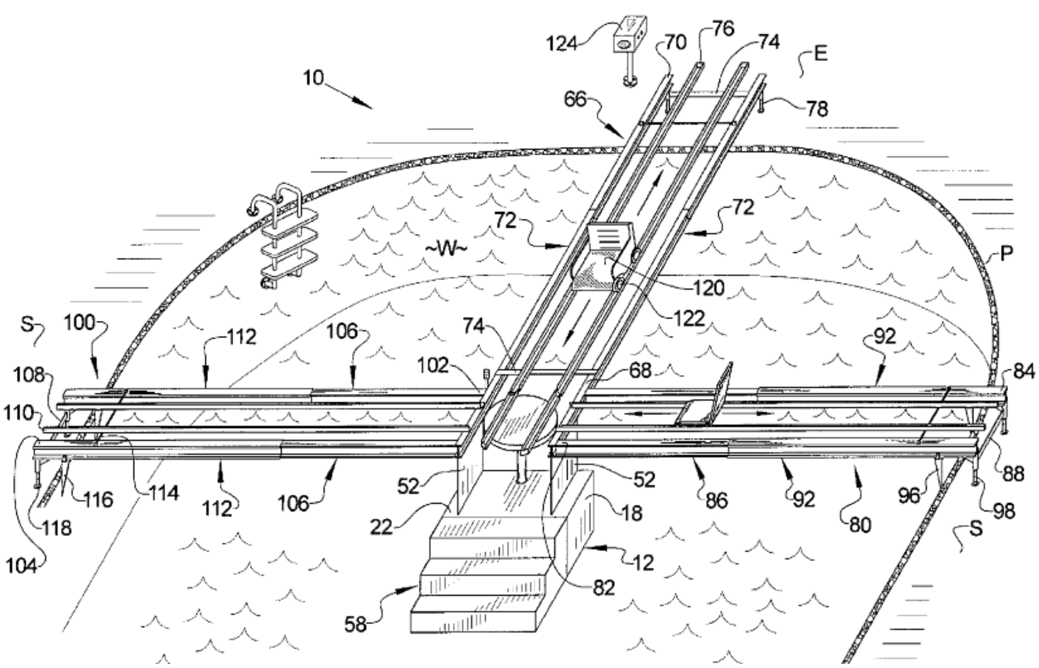


Figure 1-20: Disabled person swimming pool usage system by Hill (US7617546)

1.5.11. Mobile equipment for transport and positioning of disabled people by Mariani et al. [22]

The device is mobile equipment comprising a frame positioned on wheels, a support structure secured to frame and parallelogram arms that engage with seat, a control panel assigned to move a linear actuator which makes the parallelogram arms perform a rotation of 90 deg.

The equipment comprises of a locking system to prevent any movement at wheels. The safety feature has been designed such that the arms cannot be rotated till the wheel locking system has been activated. A manual emergency pump is also present to raise the seat in case of power failure.

The equipment is conceived to operate from a closed position in which an operator moves the equipment by means of push with the person sitting on the seat to a descent position in which the seat support structure rotates making the seat shift and descend, without the sitting surface rotating.

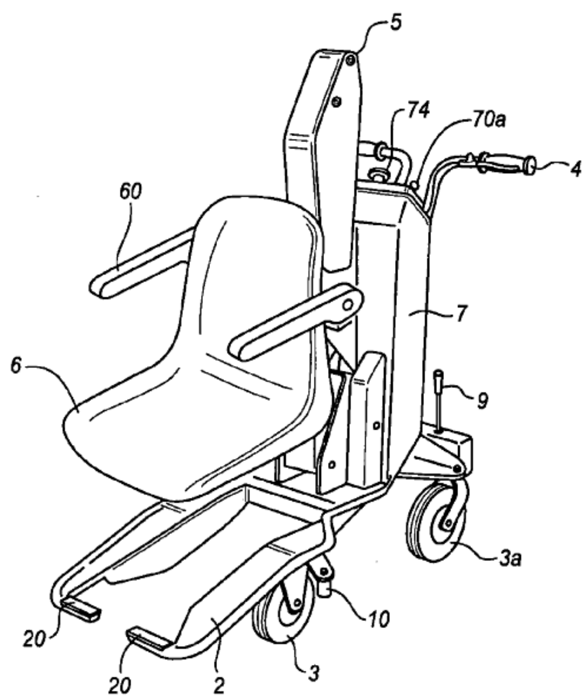


Figure 1-21: Mobile equipment for transport and positioning of disabled people by Mariani et al. (US20080042404)

1.6. Summary of existing designs

Pool lift is not a new concept and numerous designs have been developed over time. Multiple variants of pool-lifts are possible and any particular design addresses a combination of the following options:

- **Fixture**
  - Portable
  - Removable
  - Fixed
- **Location of lift**
  - Pool edge
  - Pool corner
  - Pool base
  - Wall or ceiling mount (indoor pools)
- **Location of transfer of individual to the lift**
  - **Away from pool:** Person is transferred to the device away from the pool and the device is moved to the pool
  - **At the pool:** The device is already located at the pool and person is transferred at the pool
- **Dependency**
  - Independent usage (no assistant required)
  - Dependent usage (assistant required)
  - Combined (can be used with or without assistant)
- **Pool gutter configuration**

  The arm-lengths and actuator requirements vary depending on the gutter configuration of a pool
- **Actuator type**
  - Hydraulic cylinder-piston
  - Linear actuator
  - Motor and tension cable
  - Others

1.7. Objective and scope of the project

A pool lift is initially at the pool deck and allows for a physically challenged person to transfer himself or herself from a wheel-chair to the lift. The lift is subsequently lowered inside the pool; the depth of lowering can be controlled by the user. After the person has used the pool, the lift raises the person back to the pool deck.

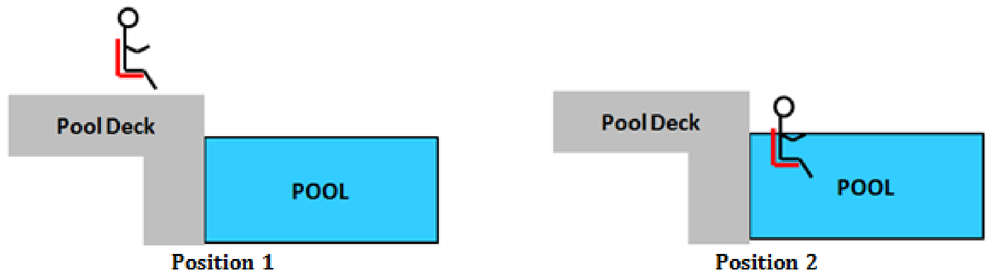


Figure 1-22: Objective of pool lift - achieve these two extreme positions with a horizontal seat at all times

The project aims to design and manufacture a swimming pool lift for physically challenged persons to be used in the IITM swimming pool. Once the deployment is successful locally in a cost effective manner, it is hoped that other pools may also be able to provide the facility. The scope of the project is detailed design, analysis and initial prototyping of pool lift.

1.8. Organization of thesis

The thesis has been organized closely following a product development cycle. Chapter 1 introduces the problem and provides an insight into existing products and technologies in the field of pool lifts through market survey and patent study. Chapter 2 covers customer survey and lays down the design requirements. Multiple kinematic designs are explored and a particular design is selected to be developed further. In Chapter 3, the selected design is modeled using CAD and individual parts of the conceived solid model are described. Chapter 4 analyses forces experienced by various parts of the solid model. These forces are used to design cross-section of individual members for suitable strength in chapter 5. Chapter 6 explains the development of a full scale metal prototype. Key achievements, learning and future work have been concluded in chapter 6.

Chapter 2

Design Development

In this chapter various design criteria and constraints are laid out and subsequently designs are developed in stages which progressively meet the criteria. Finally, a design is selected, based on suitable parameters, which is further developed in the following chapters.

2.1. Customer Survey

In an interaction, a group of physically challenged people were asked to comment on products already existing. No one had used a pool lift earlier and source of information for them was videos of pool lifts available on websites. Two primary needs were mentioned:

1. User should feel safe at all times:
    a. Slow moving device
    b. No jerky movements
    c. Handle to hold on to and/or seat-belt
2. Transfer should be easy at all instances
    a. From wheel-chair to pool-lift & vice-versa
    b. From pool-lift to water & vice-versa

Figure 2-1: Interaction with potential users at Velachery Aquatic Complex, Chennai

2.2. Design Requirements

ADA 2010 (American with Disability Act) [2] provides standards for safe and ergonomic design of pool lifts, key parameters being:

2.2.1. Lift location: Pool lifts shall be located where the water level does not exceed 48 inches (1220 mm). Where the entire pool depth is greater than 48 inches (1220 mm), compliance shall not be required.

2.2.2. Seat Location: In the raised position, the centerline of the seat shall be located over the deck and 16 inches (405 mm) minimum from the edge of the pool.

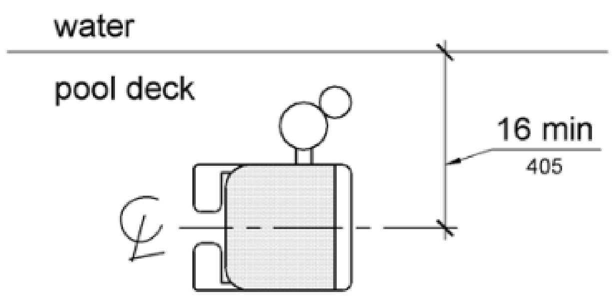


Figure 2-2: Seat location on pool deck, ADA 2010 [2]

2.2.3. 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 36 inches (915 mm) wide minimum and shall extend forward 48 inches (1220 mm) minimum from a line located 12 inches (305 mm) behind the rear edge of the seat.

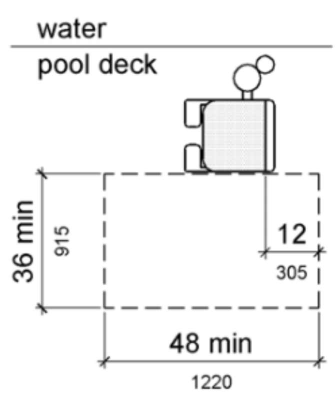


Figure 2-3: Clear deck space, ADA 2010 [2]

2.2.4. Seat height: The height of the lift seat shall be designed to allow a stop at 16 inches (405 mm) minimum to 19 inches (485 mm) maximum measured from the deck to the top of the seat surface when in the raised (load) position.

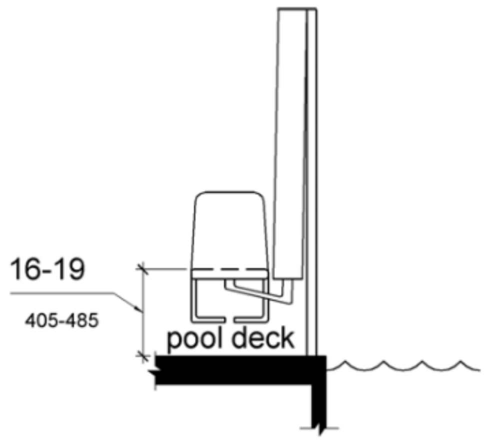


Figure 2-4: Seat height, ADA 2010 [2]

2.2.5. Seat Width: The seat shall be 16 inches (405 mm) wide minimum.

2.2.6 Foot-rests and arm-rests: 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.

2.2.7. Submerged depth: The lift shall be designed so that the seat will submerge to a water depth of 18 inches (455 mm) minimum below the stationary water level.

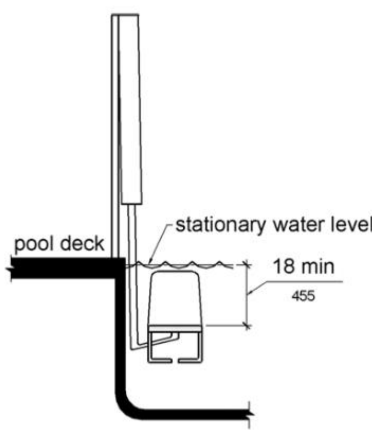


Figure 2-5: Submerged depth, ADA 2010 [2]

2.2.8. Lifting capacity: Single person pool lifts shall have a weight capacity of 300 pound (136 kg) minimum and be capable of sustaining a static load of at least one and a half times the rated load.

Apart from the guidelines as specified by ADA 2010, a few other goals that were envisaged are as follows:

2.2.9. Ready to use: A lift which can be used once developed and does not require any alterations to be made on the pool deck.

2.2.10. Cost-effectiveness: A few means of achieving the same would be:

1. Low forces to be generated by actuator resulting in a smaller actuator
2. Low material usage

2.2.11. Low counter-weight or down-force: To balance the lift from toppling into water, a very low value of counter-weight or down-force (in case of fixed base lift) should be required.

2.2.12. Compact structure: the active or moving components of the lift should be as small as possible.

2.3. Possible kinematic configurations

Three kinematic configurations were considered for the lift design and each of them have been presented in the table below.

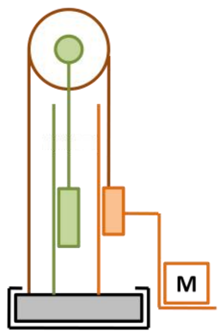
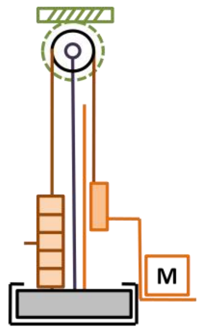
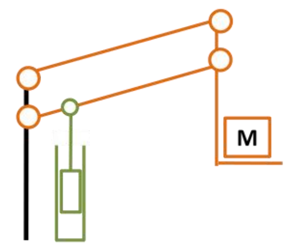
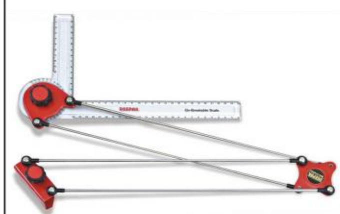
	Kinematic 1	Kinematic 2	Kinematic 3
Kinematic Configuration			
Inspired by			

Table 2-1: Candidate kinematic configurations

In each of the kinematics:

- M represents the load to be lifted (person) placed on chair
- Green color represents the actuator
- Orange colour represents the moving arms/links/guides
- Brown colour represents tension-cable and pulley arrangement
- Grey colour represents swivel joint

2.3.1. Kinematic Design 1: Similar to a forklift, it consists of a central actuator with a pulley on top. A cable runs over the pulley fixed to base at one end and fixed to the load M at other end. As the central actuator moves up and down, the load M also moves along with it, thereby allowing a person to be lowered into or raised out of the pool. The entire structure is supported on a swivel base. This allows for the person to sit on the chair at pool-deck, following which the chair is rotated over the pool (water) for lowering.

2.3.2. Kinematic Design 2: Inspired from gym-pull-down equipment, the device consists of a tension cable running over a pulley, connected to load M on one end and equivalent counter-weight on other end. This ensures that the load is approximately balanced at all instances and needs very less actuator force for movement. The pulley is coupled to a worm-gear arrangement. As the worm is rotated, the load M is raised or lowered into the pool. The entire structure is supported on a swivel base. This allows for the person to sit on the chair at pool-deck, following which the chair is rotated over the pool (water) for lowering.

2.3.3. Kinematic Design 3: Inspired from a drafter and other developed pool lifts, this device consists of parallelogram four bar mechanism. One link is fixed (black colour) and the two links attached to the fixed link act as double rocker, only one of them being actuated using a linear actuator. The seat is attached to the coupler and stays horizontal at all instances. It follows a circular path and hence can be moved from the pool deck to pool water without any additional swiveling

2.3.4. Selection of kinematic

Kinematic-3 (4-bar parallelogram mechanism) was selected for further development because of the following reasons:

- Kinematic-3 involves only one actuator i.e. the linear actuator and there is no requirement of any additional swiveling. In case swiveling is required, it may be restricted to the seat only and the entire structure need not be rotated.
- Kinematic-3 does not require any alterations to be made in the pool deck for installation of the swiveling base.
- Kinematic-3 will generate a compact structure (shorter arm lengths) for achieving the same pool-depth when compared to the other two kinematic designs.
- Kenematic-3 provides options for using different types of actuators: linear actuator, hydraulic actuators or motor and tensions cable.

2.4. Design 1

Consider a design where the seat is mounted on the coupler arm of the parallelogram and the seat faces the pool at all instances. At the raised position, a person needs to get onto the seat which will then be subsequently lowered to water.

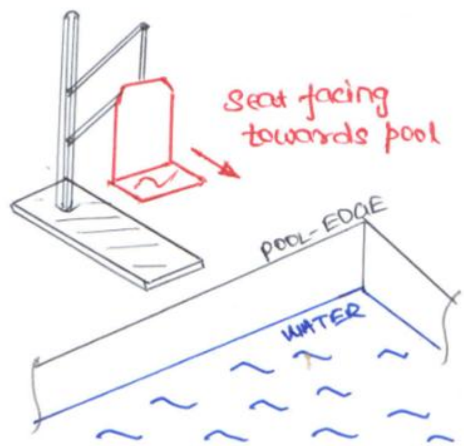


Figure 2-6: Design 1, Parallelogram arms with seat facing towards water

2.4.1. Variables

Figure below shows side view of the design. For determining individual arm-lengths and other lift dimensions, variables have been marked in the. Note that the seat has been represented using red colour and base using checkered black lines.

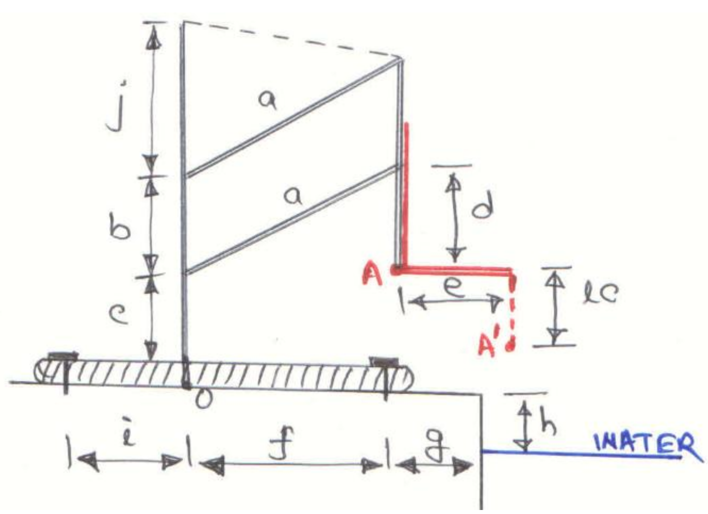


Figure 2-7: Design 1, Side View 1 with notations

Figure below shows the side view as the seat-corner (point A) just clears the pool edge. Note that geometrically, *point-A* on seat is rotating about *point-O'* which is located at a distance *u* below *point-O*.

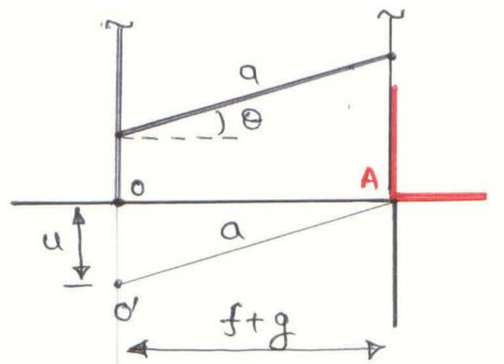


Figure 2-8: Design 1, Side View 2 with notations

2.4.2. Objective function: Minimize (a) [Refer section 2.2 Design Requirements]

2.4.3. Constraints for Design 1 (C1): [Refer section 2.2 Design Requirements]

C1.1. Seat location $(at\ \theta = 90°)$: $f + g - e/2 \geq 405\ mm$

C1.2. Pythagoras theorem (consider $\Delta OO'A$): $u^2 + (f+g)^2 = a^2$

C1.3. Seat height $(at\ \theta = 90°)$: $O'A - u = a - u = 450\ mm$

C1.4. Seat height $(at\ \theta = 90°)$: $c + a - d = 450\ mm$

C1.5. Submerged depth $(at\ \theta = \theta_{min})$: $[-(c + a.\sin\theta_{min} - d) - h] \geq 455\ mm$

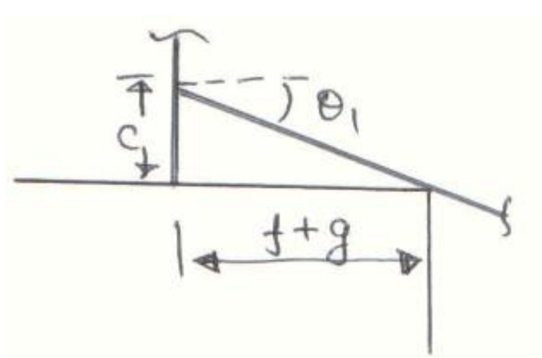


Figure 2-9: Design 1, Minimum rotation angle

$\theta_{\min}$ occurs when the parallelogram arm hits the pool edge

$$\theta_{\min} = \theta_1 = -tan^{-1}\left(\frac{c}{f+g}\right)$$

2.4.4. Assumptions for Design 1 (A1):

A1.1. Seat length: $e = 400\ mm$

A1.2. Base length: $i + f = 1000\ mm$

A1.3. Gutter length: $g = 200\ mm$

A1.4. Deck clearance: $c = 300\ mm$

A1.5. Water level: $h = 100\ mm$

A1.6. Fixed arm or coupler length: $b = a/5$

A1.7. Support arm length: $j = a$

2.4.5. Solution:

Substituting A1.1 in C1.1

$$f + g \geq 605\ mm$$

Substituting C1.3 in C1.1,

$$u^2 + (f+g)^2 = (450 + u)^2$$

$$Or, \qquad u = \frac{(f+g)^2 - 450^2}{2 \times 450}$$

$$u \geq 181.69\ mm$$

Using C1.3, $a \geq 631\ mm$. Objective function is min (a), hence we select $a = 631\ mm$.

Using C1.4, $d = 481\ mm$

For these developed dimensions, C1.5 is not satisfied as submerged depth $= 362\ mm$

Hence, either **c** needs to be increased to increase θ_{min} to increase submerged depth or **a** needs to be increased. Both possibilities have been represented in Table 4-2.

For fixed c = 300 mm		For fixed a = 631mm	
a (mm)	Submerged Depth (mm)	c (mm)	Submerged Depth (mm)
660	403	300	360
680	432	350	395
700	461	400	427
720	490	450	456
740	519	500	481

Table 2-2: Design 1, Varying submerged depth through variation of dimensions **a** & **c**

A combined improvement is selected where $a = 700\ mm$ and $c = 350\ mm$ result in submerged depth of $500\ mm$, thereby satisfying all constraints.

2.4.6. Dimension Summary:

All the dimensions have been summarized in the table.

Parameter	**Dimension or Value**	**Parameter**	**Dimension or Value**
All dimensions are in mm unless specified			
a	700	g	200
b	140	h	100
c	350	i	595
d	600	j	700
e	400	θ_{min}	-30^{o}
f	405	Submerged depth	500

Table 2-3: Design 1, dimension summary

A MATLAB code was written to visualize the movement of the lift. The complete code is present in Appendix-A1.

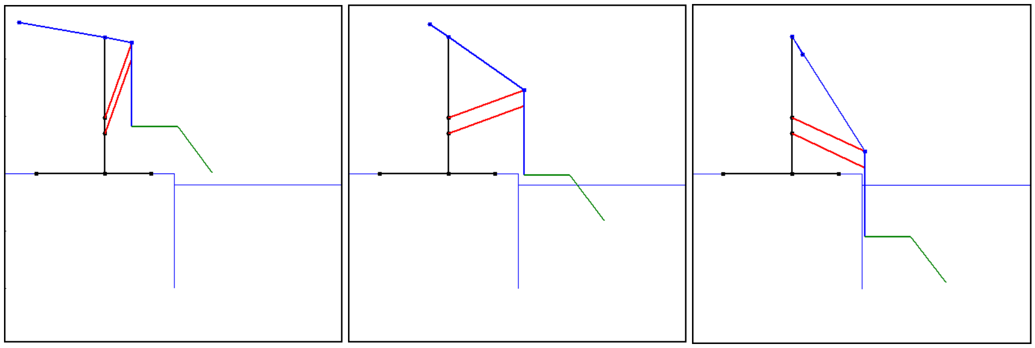


Figure 2-10: Design 1, MATLAB screenshots of kinematic simulation

2.4.7. Base force calculation:

Forces acting on the base of the lift will be calculated to provide an insight into counter-weight (portable lift) or down-force (fixed-base lift) requirements.

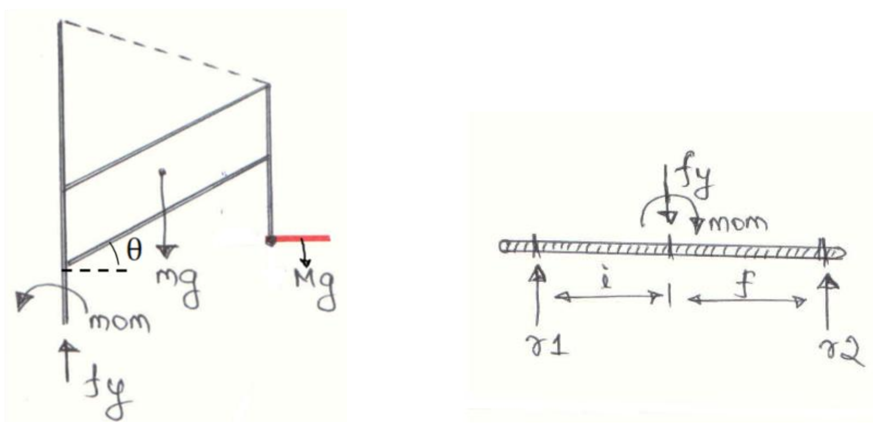


Figure 2-11: Design 1, free body diagram of lift

Applying moment balance and force balance in y-direction on the 2 FBDs, following four equations can be written.

$$mom = 2.\gamma.(a+b).G.\frac{a}{2}.\cos(\theta) + \gamma.d.G.a.\cos(\theta) + M.G.\left(a.cos(\theta) + \frac{e}{2}\right)$$

$$f_y = M.G + (2.(a+b) + c + d + j).\gamma.G$$

$$r1 = \frac{f_y \times f - mom}{i + f}$$

$$r2 = f_y - r1$$

γ is mass per unit-length and has been assumed to be 5 kg/m for initial calculations. Using lift dimension details and $M = 204\ kg$, the forces and moment are computed for all θ and represented in the figure below.

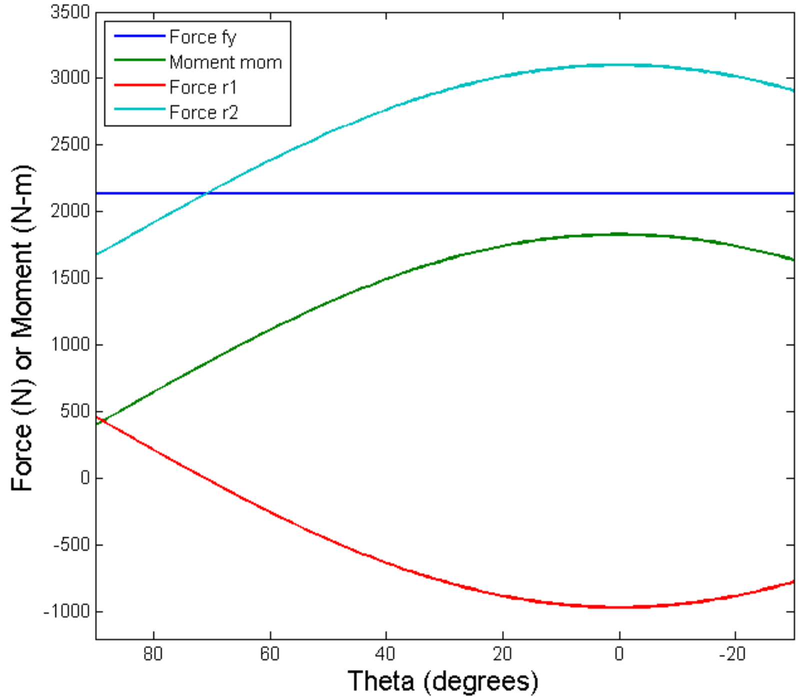


Figure 2-12: Design 1, Variation of forces and moment with rotation of parallelogram arm

Maximum value of force will be encountered when $\theta = 0°$ and these values are shown in the table. Note that r1 is negative. A down-force of at least 973 N will be required to avoid toppling of lift into water.

Parameter	Unit	Value
fy	N	2164
mom	N-m	1850
r1	N	-973
r2	N	3138

Table 2-4: Design 1, base force and moment summary

2.5. Customer feedback for Design-1

The operation of lift Design-1 was explained to the customers using a scaled-down wooden prototype.

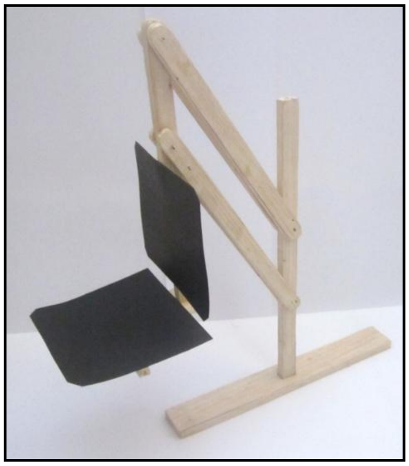


Figure 2-13: Design-1, scaled down wooden prototype

After explaining the operation, a dummy transfer exercise of a person was conducted from a wheel-chair to a regular chair (assumed to be the chair of lift). To ensure that the wheel-chair is not taken very close to the pool edge and the user feels comfortable, following *seat clearance* (refer figure below) needs to be maintained:

1. At least 1 m in case of side-transfer
2. At least 1.2 m in case of corner-transfer

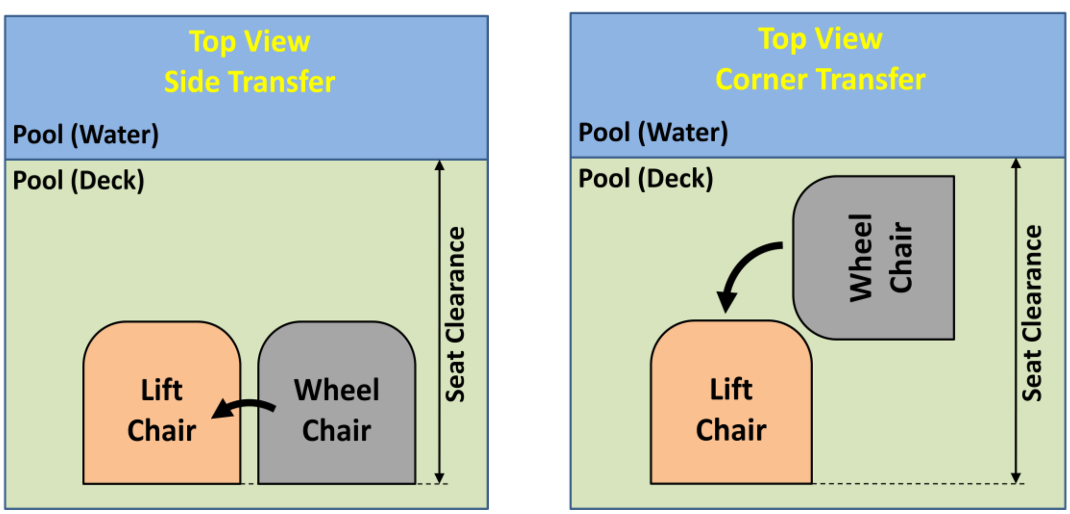


Figure 2-14: Design 1, transfer methods

2.6. Revisit Design-1

The seat-clearance dimension (in previous section) requires that the constraint C1.1 is modified to $f + g = 1200\ mm$. With only this modification, Design-1 dimensions, forces and moments are re-evaluated.

Parameter	Dimension or Value	Parameter	Dimension or Value
All dimensions are in mm unless specified			
a	1830	g	200
b	370	h	100
c	300	i	0
d	1680	j	1830
e	400	θ_{min}	-14^{o}
f	1000	Submerged depth	1720

Table 2-5: Design 1 (Re) dimension summary

Parameter	Unit	Value
fy	N	2402
mom	N-m	4398
r1	N	-1996
r2	N	4398

Table 2-6: Design 1 (Re) base forces and moment summary

It can be observed that the arm-length **a** has increased, resulting in increase of base down-force r1. A 200 kg mass will be required as counter-weight to balance the lift. Hence, it is desired that an alternate design be developed.

2.7. Design 2

Consider a design where the seat is mounted on the coupler arm of the parallelogram and the seat faces sideways i.e. towards the pool-edge at all instances. At the raised position, a person needs to get onto the seat which will then be subsequently lowered to water

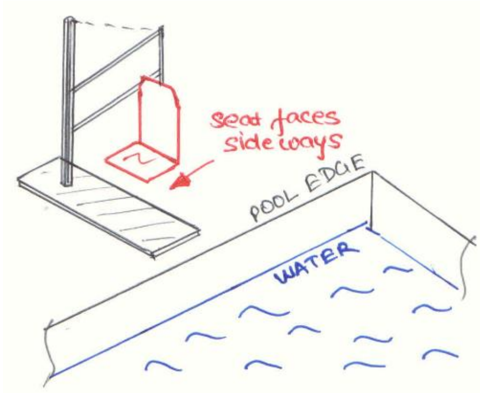


Figure 2-15: Design 2, Parallelogram arms with seat facing sideways

This design has the advantage that the lift-chair acts as a barrier between the pool water and the wheel-chair in side transfer (figure 2-16). Therefore there is no requirement for the wheel-chair to be far from the pool edge, an improvement over Design-1. Also the Design-Requirement 2.2.2 can be exactly satisfied in its stated form where the seat centre is 405 mm away from the pool edge. In case of corner-transfer, the wheel chair is in a configuration similar to figure 2-14 *Side Transfer* and the equivalent seat clearance criteria can be satisfied.

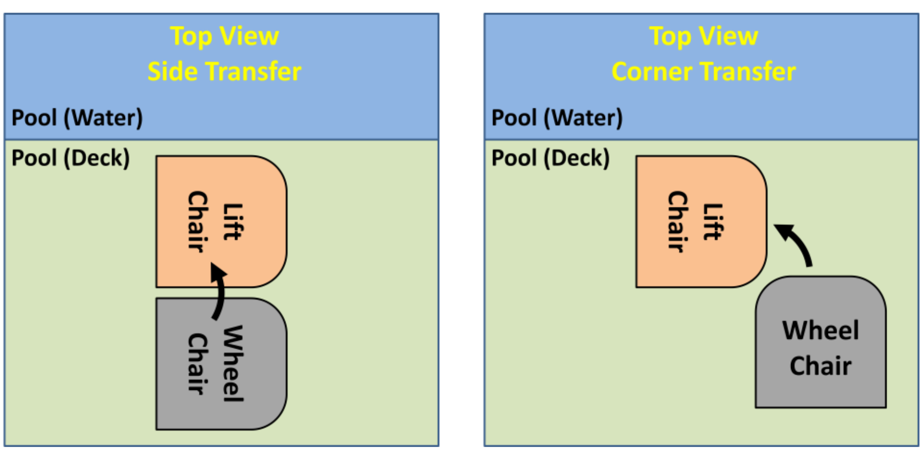


Figure 2-16: Design 2, transfer methods

2.7.1. Variables

Figure below shows side view of the design. For determining individual arm-lengths and other lift dimensions, variables have been marked. Note that the seat has been represented using red colour and base using checkered black lines. *Point-A* is a location on a hypothetical box which encloses the legs.

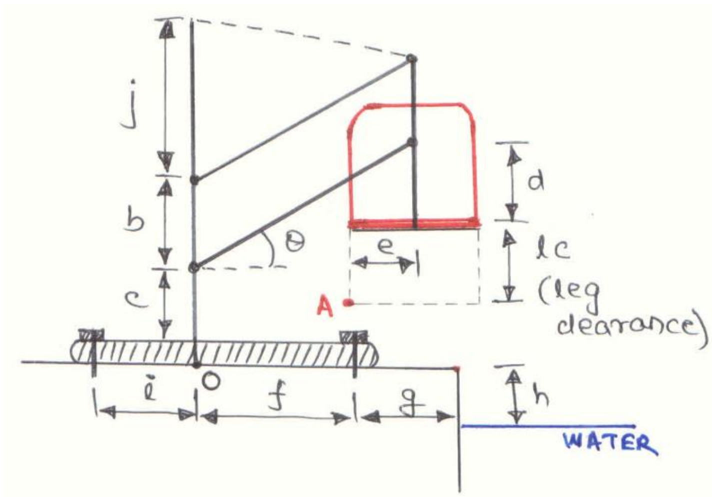


Figure 2-17: Design 2, Side View 1 with notations

Figure below shows the side view as the hypothetical box enclosing the legs just clears the pool edge. Note that geometrically, *point-A* on the hypothetical box is rotating about *point-O''* which is located at a distance *u* below *point-O* and distance *e* to the left of *point-O'*.

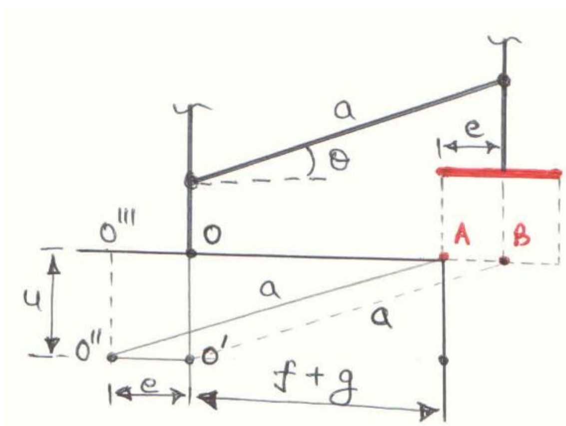


Figure 2-18: Design 2, Side View 2 with notations

2.7.2. Objective function: Minimize (a)   [Refer section 2.2 Design Requirements]

2.7.3. Constraints for Design 2 (C2): [Refer section 2.2 Design Requirements]

C2.1. Seat location $(at\ \theta = 90°)$: $f + g \geq 405\ mm$

C2.2. Pythagoras theorem (consider $\Delta O''O'''A$): $u^2 + (e + f + g)^2 = a^2$

C2.3. Seat height $(at\ \theta = 90°)$: $a - u + lc = 450\ mm$

C2.4. Seat height $(at\ \theta = 90°)$: $c + a - d = 450\ mm$

C2.5. Submerged depth $(at\ \theta = \theta_{min})$: $[-(c + a.\sin\theta_{min} - d) - h] \geq 455\ mm$

θ_{min} occurs in either of the two cases below

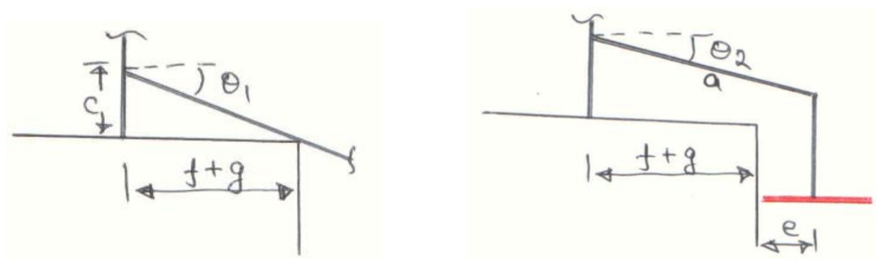


Figure 2-19: Design 2, minimum rotation angle

$$\theta_1 = -tan^{-1}\left(\frac{c}{f+g}\right);\ \theta_2 = -cos^{-1}\left(\frac{e+f+g}{a}\right);\ \theta_{min} = \max\ (\theta_1, \theta_2)$$

2.7.4. Assumptions for Design 1 (A2):

A2.1. Seat length: $e = 205\ mm$

A2.2. Base length: $i + f = 1000\ mm$

A2.3. Gutter length: $g = 200\ mm$

A2.4. Deck clearance: $c = 300\ mm$

A2.5. Water level: $h = 100\ mm$

A2.6. Fixed arm or coupler length: $b = a/5$

A2.7. Support arm length: $j = a$

A2.8. Leg clearance: $lc = 300\ mm$

2.7.5. Dimension Summary:

Using the constraints and assumptions, the variables were solved for.

Parameter	Dimension or Value	Parameter	Dimension or Value
All dimensions are in mm unless specified			
a	1320	g	200
b	260	h	100
c	300	i	795
d	1170	j	1320
e	205	θ_{min}	-36.5°
f	205	Submerged depth	1550

Table 2-7: Design 2, dimension summary

A MATLAB code was written to visualize the movement of the lift. The complete code is present in Appendix-A2.

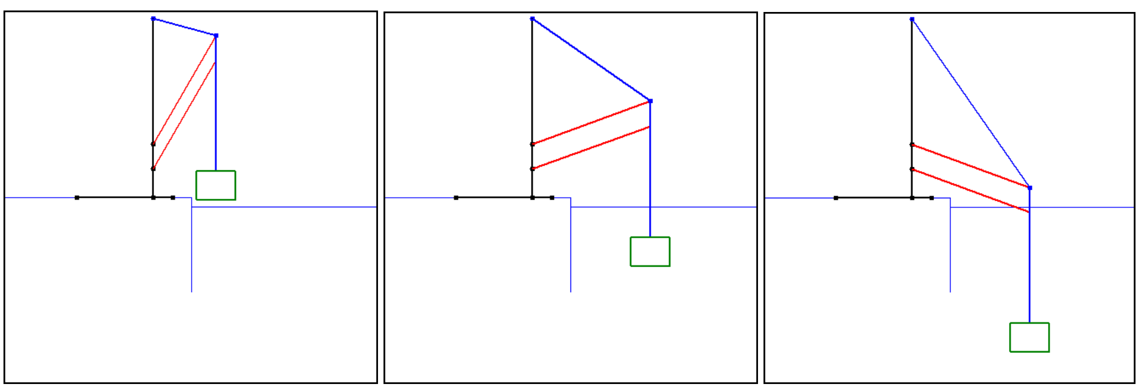


Figure 2-20: Design 2, MATLAB screenshots of kinematic simulation

2.7.6. Base force calculation:

Forces acting on the base of the lift will be calculated to provide an insight into down-force requirements. Applying moment balance and force balance in y-direction on the 2 FBDs, the four equations can be written. All equations are same as that in Design-1 except moment equation.

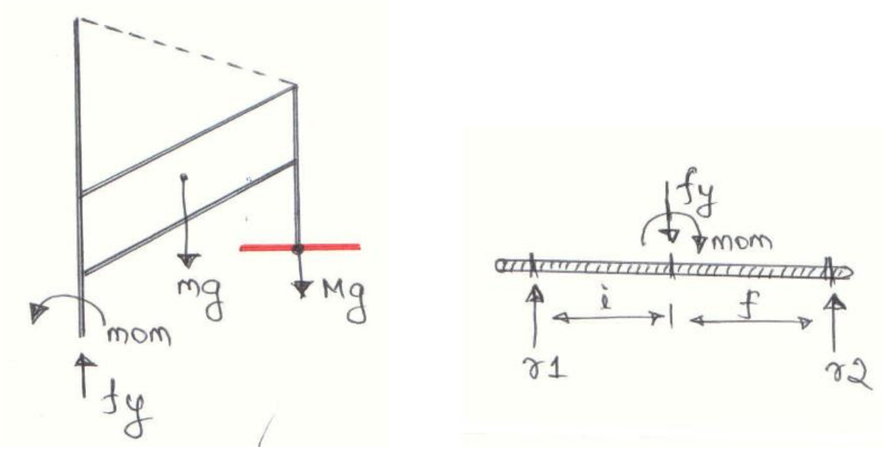


Figure 2-21: Design 2, free body diagram of lift

$$mom = 2.\gamma.(a+b).G.\frac{a}{2}.\cos(\theta) + \gamma.d.G.a.\cos(\theta) + M.G.a.cos(\theta)$$

$$f_y = M.G + (2.(a+b) + c + d + j).\gamma.G$$

$$r1 = \frac{f_y \times f - mom}{i+f} \; and \; r2 = f_y - r1$$

γ is mass per unit-length and has been assumed to be 5 kg/m for initial calculations. Using lift dimension details and $M = 204\,kg$, the forces and moment are computed for all θ and represented in the figure below.

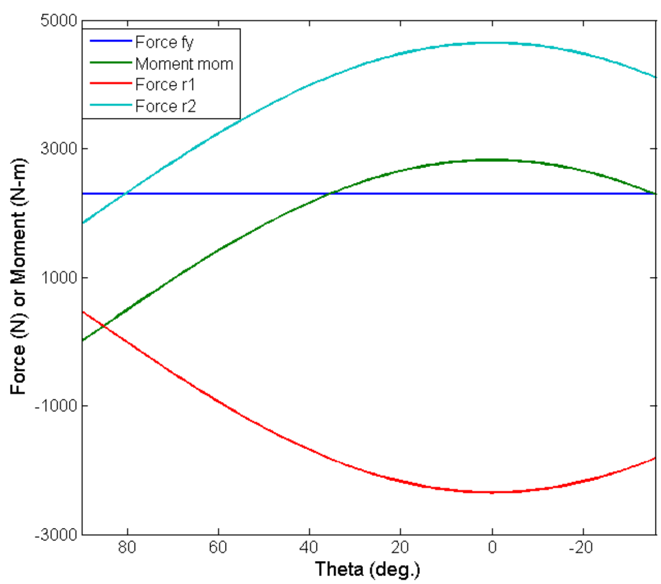


Figure 2-22: Design 1, Variation of forces and moment with rotation of parallelogram arm

Maximum value of force will be encountered when $\theta = 0°$ and these values have been tabulated. Note that r1 is negative. A down-force of at least 2339 N will be required to avoid toppling of lift into water. It is desired that another design is attempted which may require lesser down-force.

Parameter	Unit	Value
fy	N	2292
mom	N-m	2809
r1	N	-2339
r2	N	4631

Table 2-8: Design 2, base force and moment summary

2.8. Design 3

Consider a design where the seat is mounted on the coupler arm of the parallelogram through a **swivel joint**. At raised position, the seat faces sideways. Once a person is seated, the seat is swiveled to face towards the pool. Subsequently, it is lowered into water.

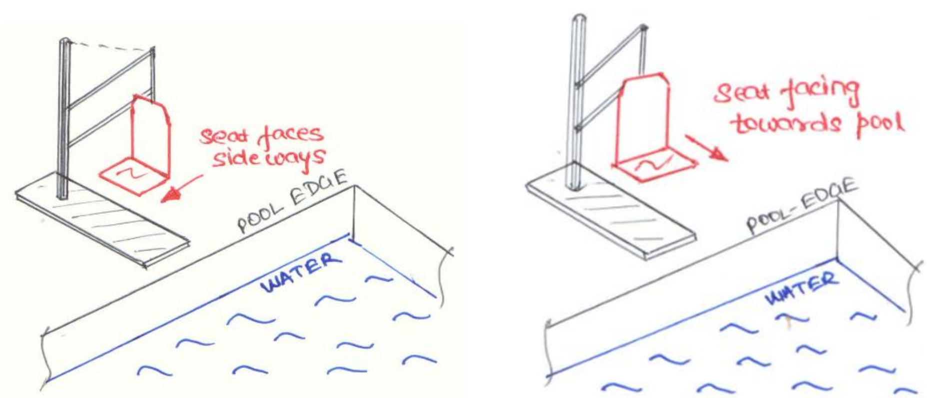


Figure 2-23: Design 3, parallelogram arms with swivel seat seat

The variables and dimension of the lift will be same as developed in section 2.4. Swivel arrangement will allow the dimensions in table 2-3 to be used resulting in a compact pool lift. Note that these dimensions were rejected for Design-1 as the safety criteria were not being satisfied (section *Customer Feedback for Design-1*).

2.8.1. Dimension Summary:

Parameter	Dimension or Value	Parameter	Dimension or Value
All dimensions are in mm unless specified			
a	700	g	200
b	140	h	100
c	350	i	595
d	600	j	700
e	400	θ_{min}	-30^{o}
f	405	Submerged depth	500

Table 2-9: Design 3, dimension summary

2.8.2. Base force calculation:

The forces and moment had also been computed before while developing Design-1.

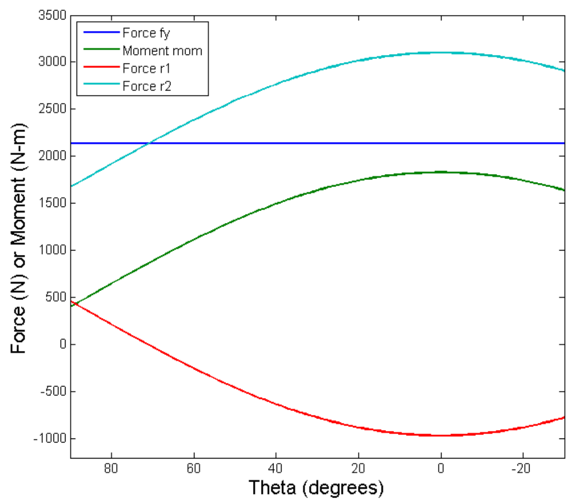


Figure 2-24: Design 3, Variation of forces and moment with rotation of parallelogram arm

Parameter	Unit	Value
fy	N	2164
mom	N-m	1850
r1	N	-973
r2	N	3138

Table 2-10: Design 3, base force and moment summary

2.9. Design 4

Consider a design where the base has two separated legs and is located at corner of the pool. This base design allows for base-arms to be extended which will result in lowered down-force requirement. The seat is mounted on a swivel arrangement on parallelogram. In raised position, the seat faces perpendicular to the parallelogram arm plane. Once a person has seated, the seat is swiveled to face the water and is lowered into the pool.

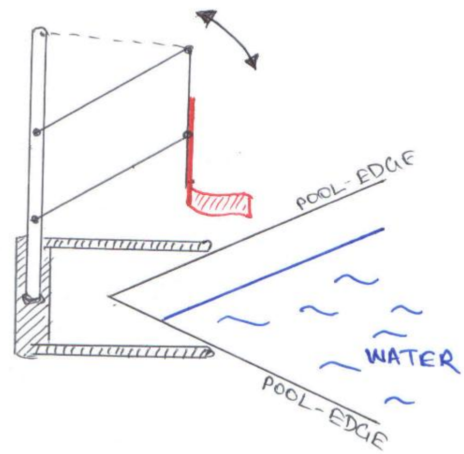


Figure 2-25: Design 4, parallelogram arms with split base and swivel arm

2.9.1. Variables

Figure 2-26 and Figure 2-27 show all variables that need to be determined.

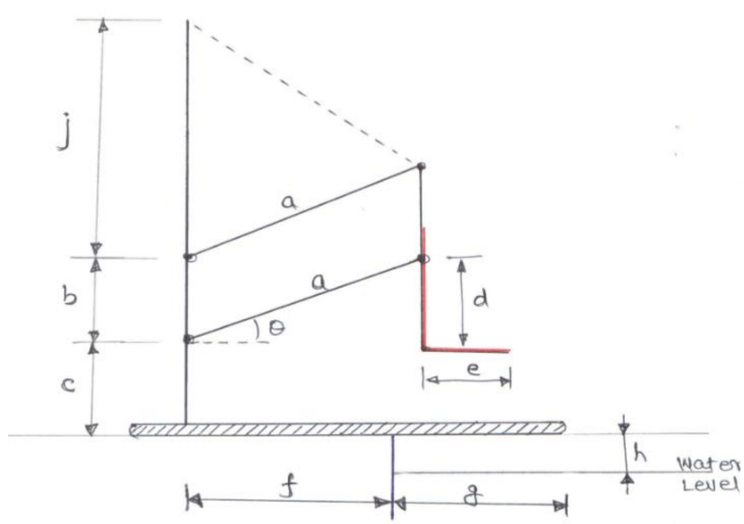


Figure 2-26: Design 4, side view with notations

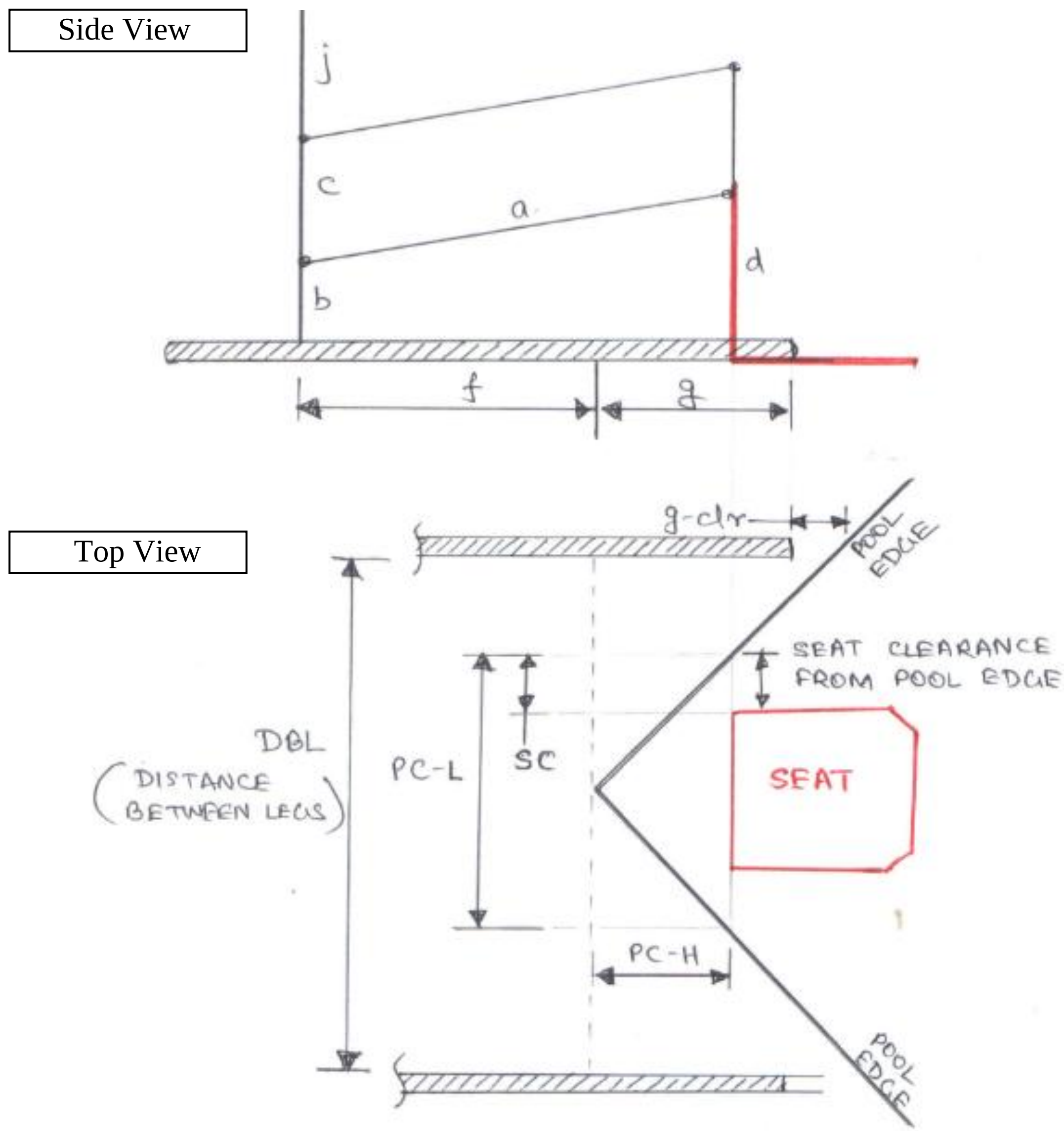


Figure 2-27: Design 4, pool corner clearance configuration

In the top view in figure 2-27, the two separated legs of the base have been shown using checkered lines. Distance between the two legs has been denoted by DBL. The base is positioned at corner of pool. The legs maintain a clearance *g-clr* from the pool edge. The figure shows the lift when the seat is about to cross the plane of the pool-deck. In this configuration, the seat requires sufficient clearance from the pool edges and this is being denoted by SC. For a given SC, PC-H and PC-L can be determined.

Figure 2-28 below provides a representation and few more notations to be used for determining all dimensions. In this figure, point-A on seat just clears PC-H.

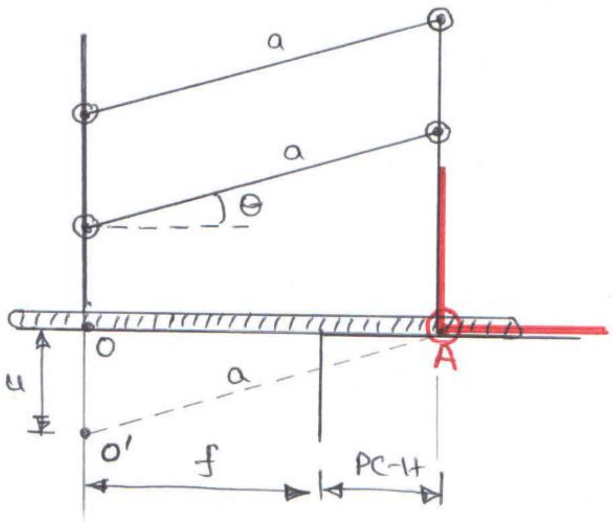


Figure 2-28: Design 4, Side view 2 with notations

2.9.2. Objective function: Minimize (a)

2.9.3. Constraints for Design 4 (C4):

C4.1. Seat location ($at\ \theta = 90°$): $f \geq 405\ mm$

C4.2. Pythagoras theorem (consider $\Delta OO'A$): $u^2 + (f + PCH)^2 = a^2$

C4.3. Seat height ($at\ \theta = 90°$): $a - u = 450\ mm$

C4.4. Seat height ($at\ \theta = 90°$): $c + a - d = 450\ mm$

C4.5. Submerged depth ($at\ \theta = \theta_{min}$): $[-(c + a.\sin\theta_{min} - d) - h] \geq 455\ mm$

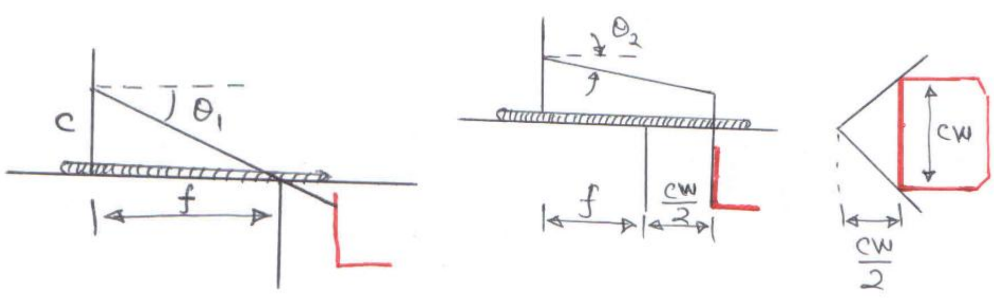


Figure 2-29: Design 4, minimum rotation angle

$$\theta_1 = -tan^{-1}\left(\frac{c}{f}\right);\ \ \theta_2 = -cos^{-1}\left(\frac{f + CW/2}{a}\right);\ \ \theta_{min} = \max\ (\theta_1, \theta_2)$$

C4.6. Geometry: $PCL = CW + 2 \times SC$

C4.7. Geometry: $PCH = PCL/2$

C4.8. Geometry: $g = DBL/2 - gclr$

2.9.4. Assumptions for Design 4 (A4):

A4.1. Seat clearance: $SC = 150\ mm$

A4.2. Distance between legs: $DBL = 1200\ mm$

A4.3. Chair width: $CW = 450\ mm$

A4.4. Base leg clearance from pool edge: $gclr = 100\ mm$

A4.5. Seat length: $e = 400\ mm$

A4.6. Deck clearance: $c = 300\ mm$

A4.7. Water level: $h = 100\ mm$

A4.8. Fixed arm or coupler length: $b = a/4$

A4.9. Support arm length: $j = a$

2.9.5. Dimension Summary:

The constraints and assumptions are used to solve the objective function and derive other lift dimensions which are summarized in the table below.

Parameter	Dimension or Value	Parameter	Dimension or Value
All dimensions are in mm unless specified			
a	900	f	405
b	230	g	500
c	300	j	900
d	750	θ_{min}	-30^{o}
e	400	Submerged depth	800

Table 2-11: Design 4, dimension summary

2.9.6. Base force calculation:

Forces acting on the base of the lift will be calculated to provide an insight into down-force requirements. Applying moment balance and force balance in y-direction on the 2 FBDs, four equations can be written.

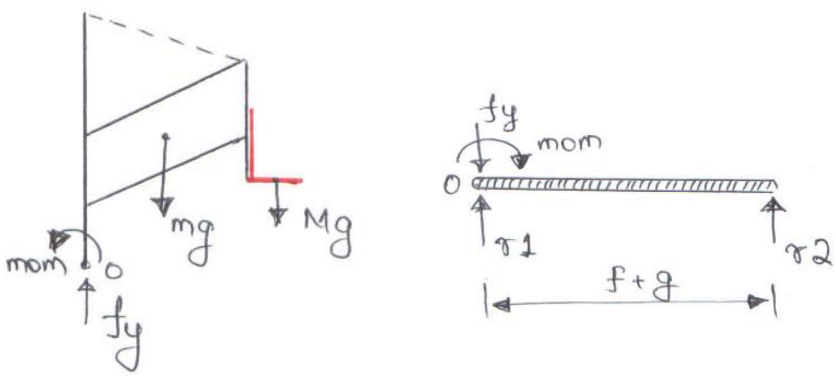


Figure 2-30: Design 4, free body diagram of base

$$mom = 2.\gamma.(a+b).G.\frac{a}{2}.\cos(\theta) + \gamma.d.G.a.\cos(\theta) + M.G.\left(a.cos(\theta) + \frac{e}{2}\right)$$

$$f_y = M.G + (2.(a+b) + c + d + j).\gamma.G$$

$$r1 = f_y - r2$$

$$r2 = \frac{mom}{f+g}$$

Maximum value of force will be encountered when $\theta = 0°$ and these values have been tabulated. A down-force of at least 319 N will be required to avoid toppling of lift.

Parameter	Unit	Value
fy	N	2207
mom	N-m	2286
r1	N	-319
r2	N	2526

Table 2-12: Design 4, base force and moment summary

2.10. Design 5

Consider the lift design of Aquacreek Pro Pool Lift [9], as shown in the wooden prototype. The lift is similar to Design-2 but its parallel arms are L-shaped thereby allowing greater submerged depth with same effective arm length ***'a'*** as in Design-2.

Figure 2-31: Design 5, wooden prototype

2.10.1. Variables

Figure 2-32 and figure 2-33 show side view of design along with variables/notations.

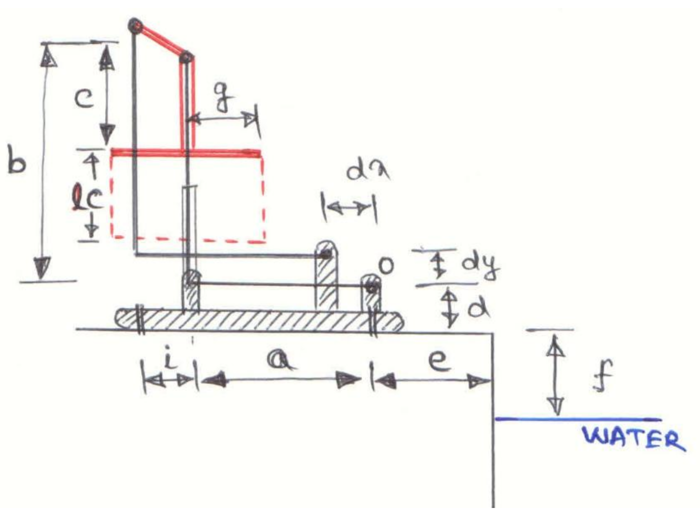


Figure 2-32: Design 5, Side View 1 with notations

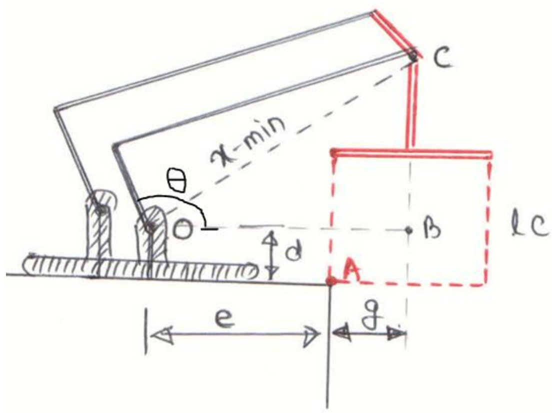


Figure 2-33: Design 5, Side View 2 with notations

2.10.2. Objective function: Minimize (x_min)

2.10.3. Constraints for Design 4 (C5):

C5.1. Seat location $(at\ \theta = 180°)$: $a + e \geq 405\ mm$

C5.2. Pythagoras theorem (consider ΔOBC): $(e + g)^2 + (c + lc - d)^2 = x\_min^2$

C5.3. Geometry: $a^2 + b^2 = x\_min^2$

C5.4. Seat height $(at\ \theta = 180°)$: $d + b - c \in [405\ mm, 485\ mm]$

2.10.4. Assumptions for Design 1 (A5):

A5.1. Leg clearance: $LC = 350\ mm$

A5.2. Deck clearance: $d = 100\ mm$

A5.3. Gutter clearance: $e = 320\ mm$

A5.4. Water level: $f = 100\ mm$

A5.5. Seat length: $g = 210\ mm$

2.10.5. Dimension Summary:

For the constraints and assumptions, it is required to determine the values of a and c. This is done iteratively using MS Excel. The table summarizes all the developed dimensions.

Parameter	Dimension or Value	Parameter	Dimension or Value
All dimensions are in mm unless specified			
a	230	g	210
b	770	i	370
c	350	LC	350
d	100	x-min	894
e	320	θ_{min}	44^{o}
f	200	Submerged depth	540

Table 2-13: Design 5, dimension summary

A MATLAB code was written to visualize the movement of the lift. The complete code is present in Appendix-A3.

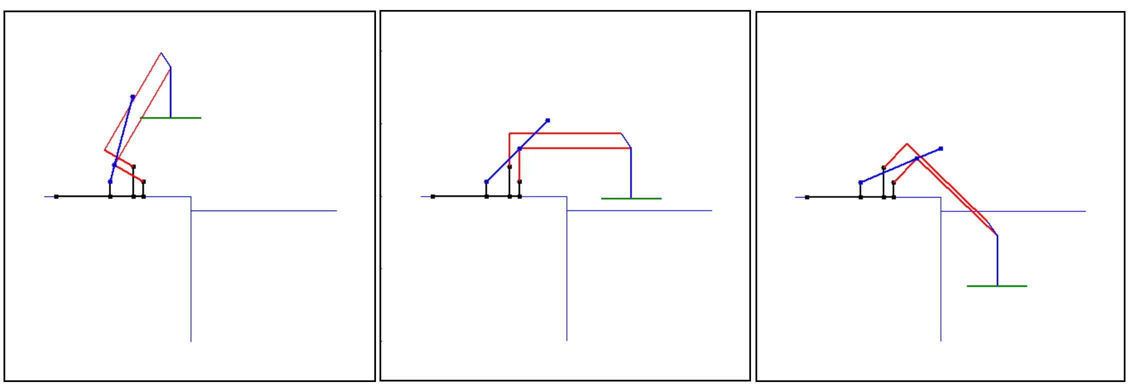


Figure 2-34: 1, MATLAB screenshots of kinematic simulation

2.10.6. Base force calculation:

Forces acting on the base of the lift will be calculated to provide an insight into down-force requirements. Applying moment balance and force balance on the 2 FBDs and using M=204 kg and γ=5 kg/m the forces are calculated for all angles of parallelogram arm rotation.

$$f_y = M.G + (a + b + c).y.G + f_l.sin(\beta)$$

$$f_x = f_l.cos(\beta)$$

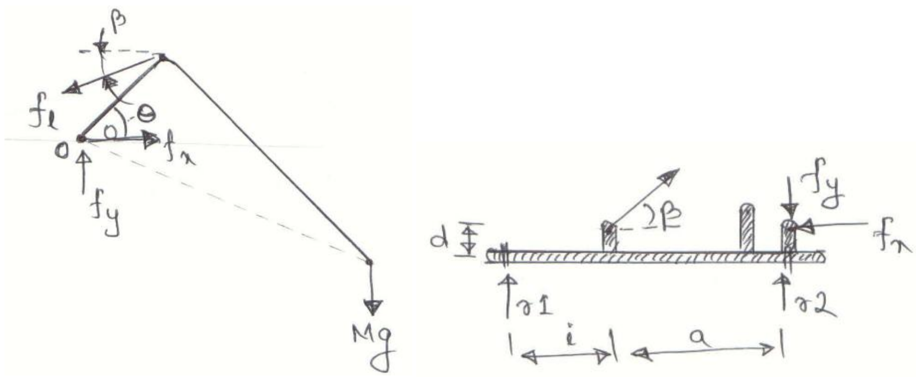


Figure 2-35: Design 5, free body diagram

$$r_1 = \frac{f_x . d - f_l . \sin(\beta) . a - f_l . \cos(\beta) . d}{a + i}$$

$$and\ r_2 = f_y - f_l . \sin(\beta) - r_1$$

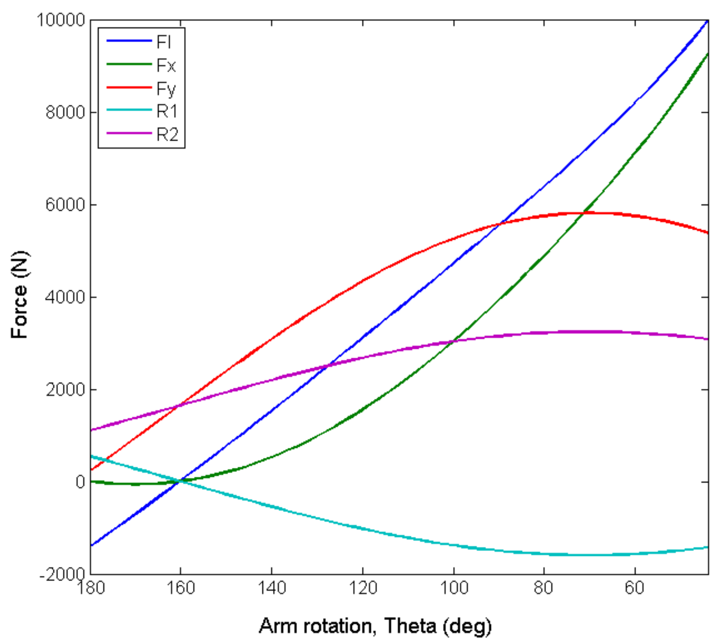


Figure 2-36: Design 5, Variation of forces and moment with rotation of parallelogram arm

Parameter	Unit	Value
Min r1	N	-1596
Max r2	N	3239

Table 2-14: Design 5, base force summary

2.11. Selection of Design

As stated in the section 2.2 Design Requirements, it is desired to have a lift which satisfies all the ADA 2010 guidelines, needs low down-force, is compact in nature and preferably does not need a fixture. The developed designs are evaluated against these criteria.

Design No	**ADA 2010 Compliant**	**Down force (N)**	**Effective parallelogram arm length (mm)**
Design 1	Yes	1996	1830
Design 2	Yes	2339	1320
Design 3	Yes	973	700
Design 4	Yes	319	900
Design 5	Yes	1596	894

Table 2-15: Design summary

The down-force in table is the indicator of equivalent counter-weight that will be required to balance the lift. Effective parallelogram arm is indicator of the compactness of lift. It can be observed that Design-4 requires very low down force for a reasonable compactness. Hence **Design-4** is selected for further development.

The following chapters discuss the detailed design of the selected kinematic model like solid modeling, force analysis, stress analysis and prototyping.

Chapter 3

3D Modeling

This chapter covers development of a 3D Model of the conceived design. The nomenclatures of all parts and sub-assemblies have been described followed by operation of the lift. Note that the model described here has been developed after multiple iterations, considering dimensions of readily available parts or stock dimensions.

3.1. Lift part description

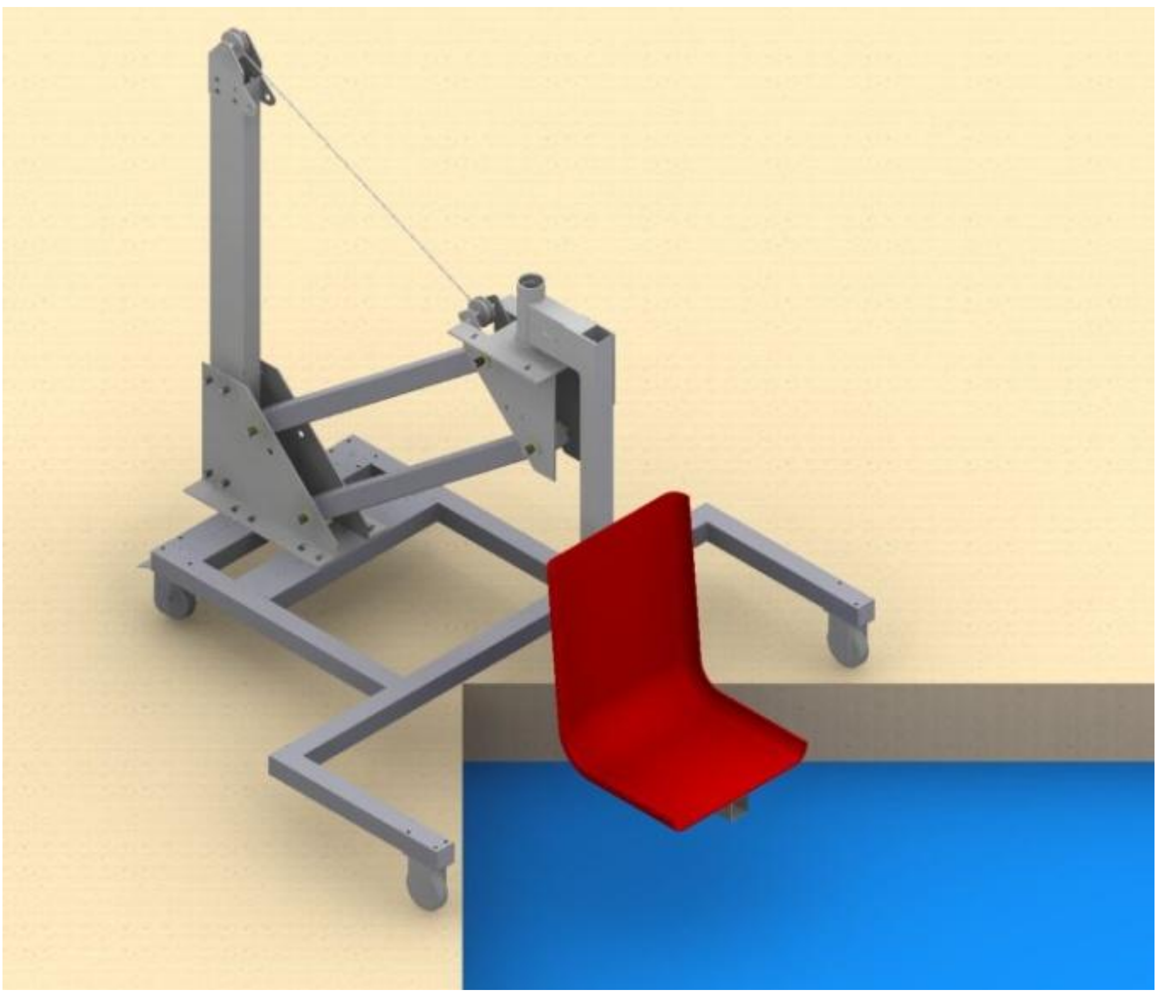


Figure 3-1: Pool lift placed a corner of pool at half lowered configuration

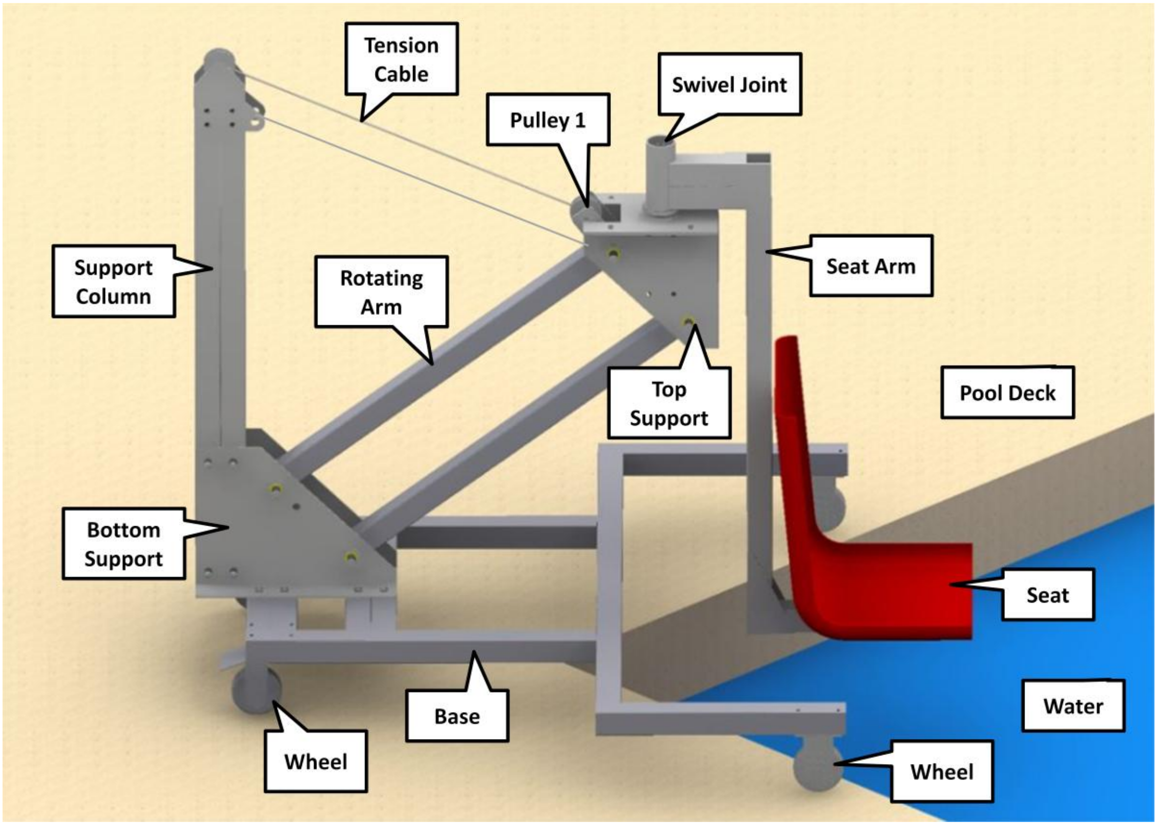


Figure 3-2: Lift part description

The figure labels all parts of the lift. The device consists of a Y-shaped **Base** which is mounted on four wheels, two front-wheels and two back-wheels. The back-wheels have push-brake which will stop it from rotating.

Bottom-Support, a set of two symmetric plates, is fixed on top of the **Base**. Two **Rotating-Arms** of equal length, which are parallel to each other, are attached to the **Bottom-Support** using pin-joints. This allows for these arms to be rotated. On the other end of the **Rotating-Arms** there is a **Top-Support**, connected again using pin-joints.

A **Seat-Arm** is connected to the **Top-Support** using a **Swivel-Joint**. This allows for the **Seat-Arm** to the rotated/swiveled about the **Top-Support** in horizontal plane. A **Seat** is fixed to the **Seat-Arm** for allowing a person to sit on it.

A **Support-Column** is fixed to the **Bottom-Support**. A **Tension-Cable** connected to **Support-Column** runs over **Pulley-1** (connected to **Top-Support**) and back to **Support-Column** where it is connected to a motor.

3.2. Operation of lift

The table below shows the sequence of lowering a person from pool-deck to inside water. The reverse operation raises the person from water to pool deck.

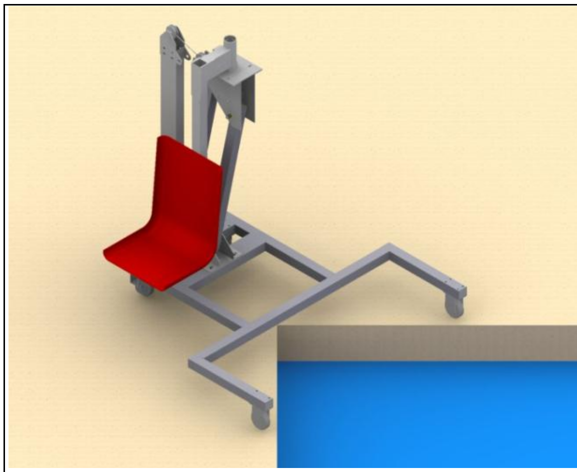
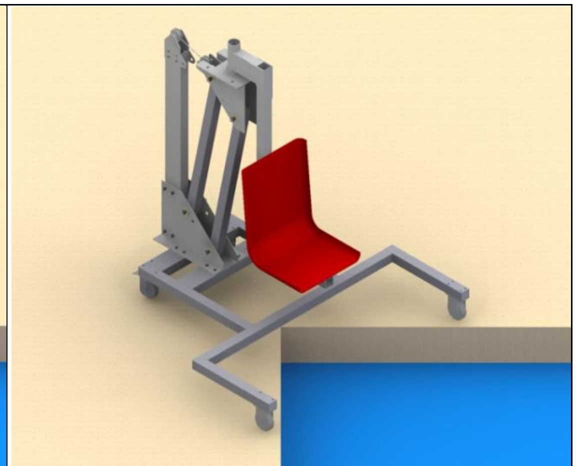
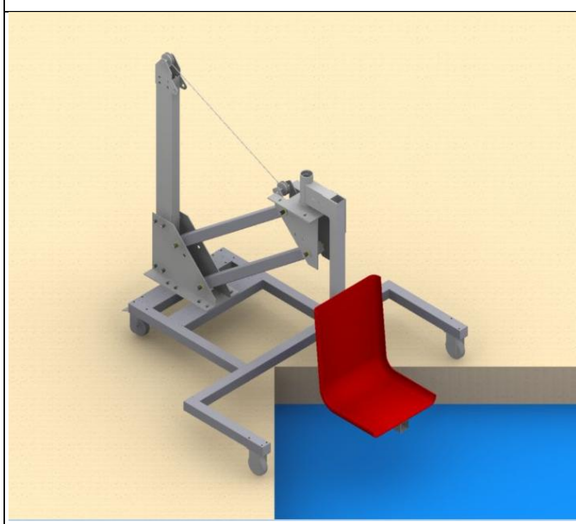
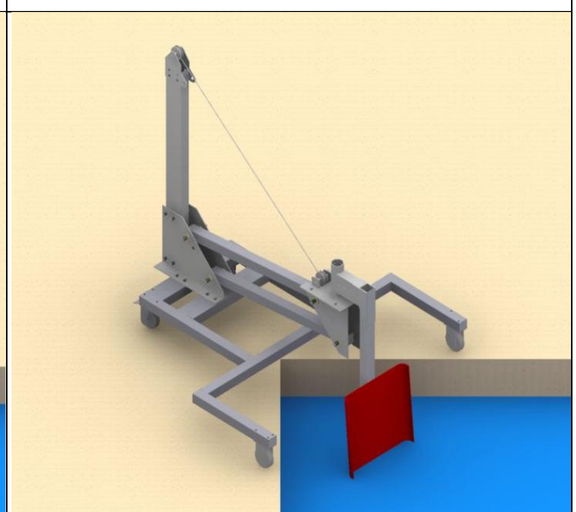
 STEP-1 Person on wheel-chair comes from the side and transfers oneself to the Seat of the lift	 STEP-2 The Seat Arm is swiveled and locked
 STEP-3 The Rotating-Arm is lowered using a Tension-Cable powered using a Motor	 STEP-4 Once the Seat is completely lowered, the Motor is turned off.

Table 3-1: Sequence of lowering operation of pool-lift

In this chapter, a physical form was imparted to the line diagram of selected kinematic model. Entire lift was constructed using smaller parts and each of these parts was described. Steps in the overall functioning of the lift were also presented.

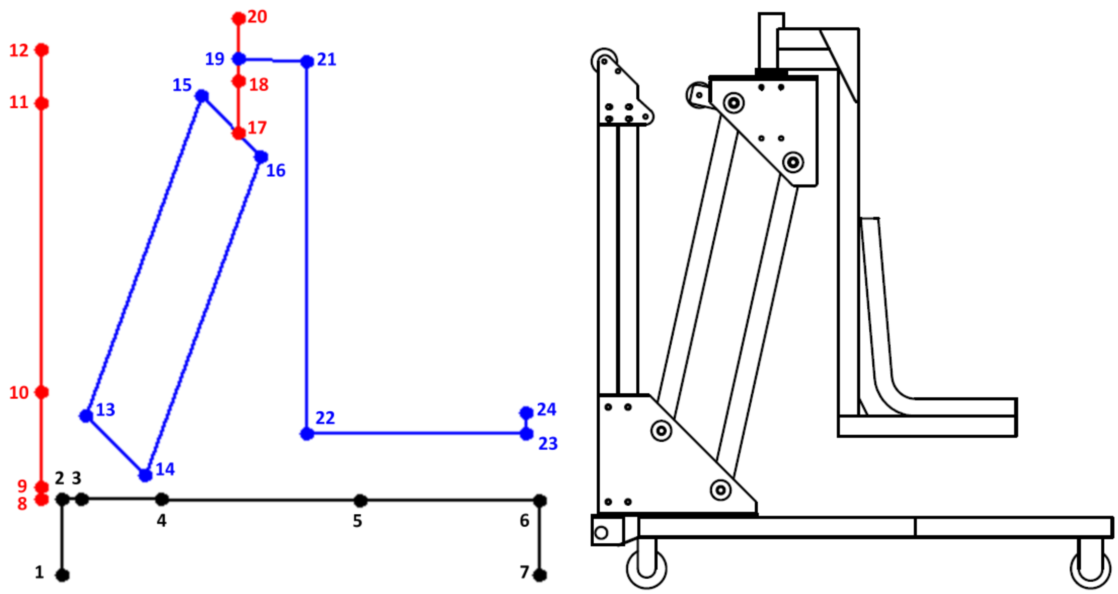
In the following chapter, forces acting on each of the parts will be evaluated so that they can be designed for appropriate strength.

Chapter 4

Force Analysis

4.1. Skeletal model

A skeletal model (fig. 4-1a), of the actual 3D model (fig. 4-2b) is created using few key-points. The forces acting on the key-points will be determined which will be used for designing individual members or part for strength.



(a) (b)

Figure 4-1: Skeletal model of design

Table below shows the relation between each key-point-sequence and the actual part of the device. Refer to the previous chapter for viewing part-names.

Key-Points	Part Name	Key-Points	Part Name
1-2-3-4-5-6-7	Base	14-16	Rotating Arm 2
13-14	Bottom Support	17-18-19-20	Seat Arm Support
15-16	Top Support	19-21-22-23-24	Seat Arm
13-15	Rotating Arm 1	8-9-10-11-12	Support Column

Table 4-1: Key-points and part-name relation

4.2. Free body diagram

Free-body diagrams of all parts were drawn using the key-points. Force and moment balance equations were written.

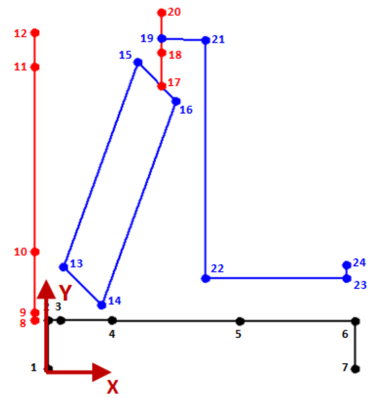


Figure 4-2: Skeletal model, global coordinate system

Note that x_{23} and y_{23} represent x-coordinate and y-coordinate respectively of point-23 with respect to global coordinate system X-Y (figure 4-2). All moment balance equations have been written with respect to origin of the local-coordinate system (present in individual part's FBD).

6.2.1 Seat Arm

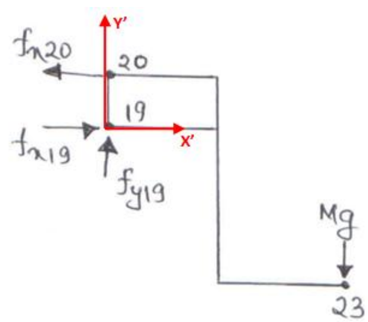


Figure 4-3: Seat arm FBD

$$f_{x20}.(y_{20} - y_{19}) - M.G.(x_{23} - x_{19}) = 0$$

$$f_{x19} - f_{x20} = 0$$

$$f_{y19} - M.G = 0$$

6.2.2 Seat Arm Support

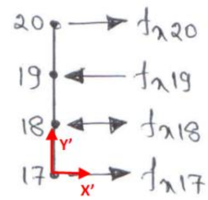


Figure 4-4: Seat Arm Support FBD

$$f_{x18}.(y_{18} - y_{17}) + f_{x19}.(y_{19} - y_{17}) - f_{x20}.(y_{20} - y_{17}) = 0$$

$$f_{x17} + f_{x20} - f_{x18} - f_{x19} = 0$$

6.2.3 Top Support and Seat Arm

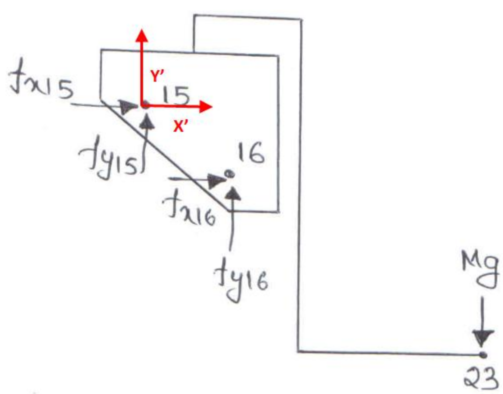


Figure 4-5: Top Support and Seat Arm FBD

$$M.G.(x_{23} - x_{15}) - f_{y16}.(x_{16} - x_{15}) - f_{x16}.(y_{15} - y_{16}) = 0$$

$$f_{y15} + f_{y16} - M.G = 0$$

$$f_{x15} + f_{x16} = 0$$

6.2.4 Pin 13

$$f_{x13} + f_s.\cos(\beta) - f_{a1}.\cos(\theta) = 0$$

$$f_{y13} + f_s.\sin(\beta) - f_{a1}.\sin(\theta) = 0$$

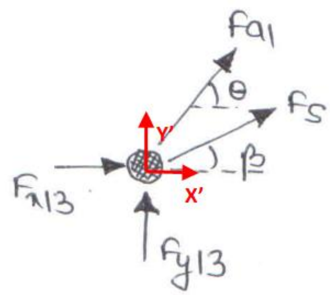


Figure 4-6: Pin 13 FBD

6.2.5 Pin 14

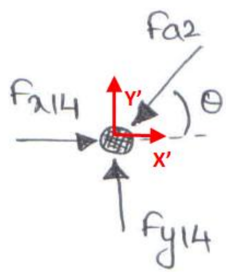


Figure 4-7: Pin 14 FBD

$$f_{x14} - f_{a2}.\cos(\theta) = 0$$

$$f_{y14} - f_{a2}.\sin(\theta) = 0$$

6.2.6 Pin 15

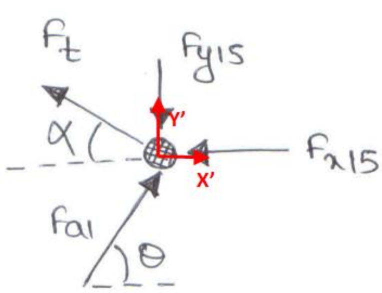


Figure 4-8: Pin 15 FBD

$$f_{a1}.\sin(\theta) + f_t.\sin(\alpha) - f_{y15} = 0$$

$$f_{a1}.\cos(\theta) - f_{x15} - f_t.\cos(\alpha) = 0$$

6.2.7 Pin 16

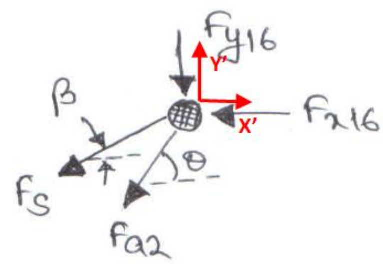


Figure 4-9: Pin 16 FBD

$$f_{a2}.\sin(\theta) - f_s.\sin(\beta) - f_{y16} = 0$$

$$f_{a2}.\cos(\theta) - f_s.\cos(\beta) - f_{x16} = 0$$

6.2.8 Support Column

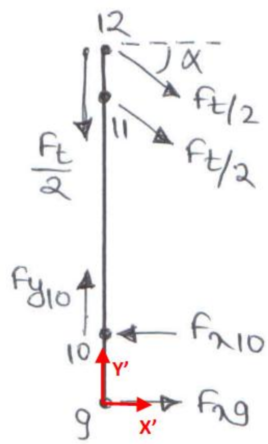


Figure 4-10: Support column FBD

$$f_{x9} - f_{x10} + f_t.\cos(\alpha) = 0$$

$$f_{y10} - \frac{f_t}{2} - f_t.\sin(\alpha) = 0$$

$$f_{x10}.(y_{10} - y_9) - \frac{f_t}{2}.(y_{11} - y_9) - \frac{f_t}{2}.(y_{12} - y_9) = 0$$

6.2.9 Entire Lift except Base

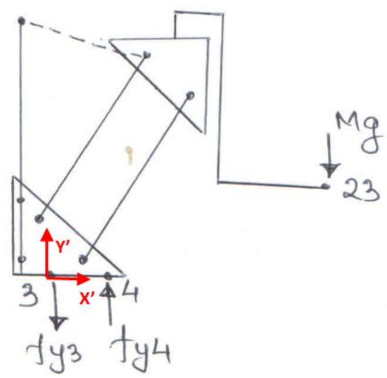


Figure 4-11: Entire lift except Base FBD

$$-f_{y3} + f_{y4} - M = 0$$

$$f_{y4}.(x_4 - x_3) - M.G.(x_{23} - x_3) = 0$$

6.2.10 Entire Lift

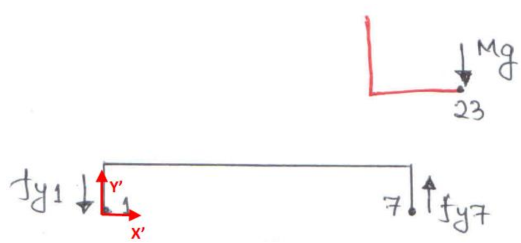


Figure 4-12: Entire Lift FBD

$$-f_{y1} + f_{y7} - M.G = 0$$

$$f_{y7}.(x_7 - x_1) - M.G.(x_{23} - x_1) = 0$$

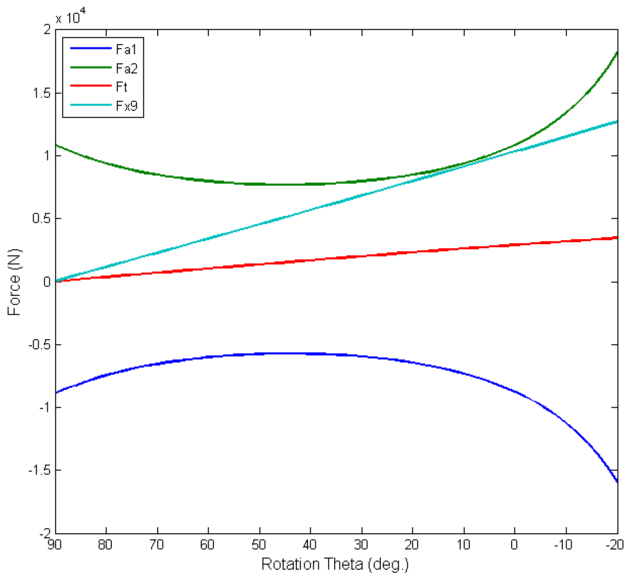
4.3. Solution

These set of 23 equations developed using force and moment balance of free body diagrams of individual parts are used to solve 23 unknowns:

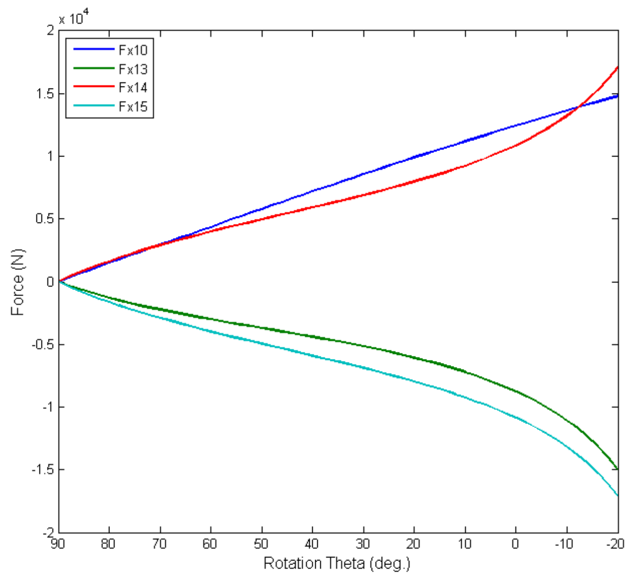
$$f_{a1}, f_{a2}, f_t, f_{x9}, f_{x10}, f_{x13}, f_{x14}, f_{x15}, f_{x16}, f_{x17}, f_{x18}, f_{x19}, f_{x20},$$

$$f_{y1}, f_{y3}, f_{y4}, f_{y7}, f_{y10}, f_{y13}, f_{y14}, f_{y15}, f_{y16}, f_{y19}$$

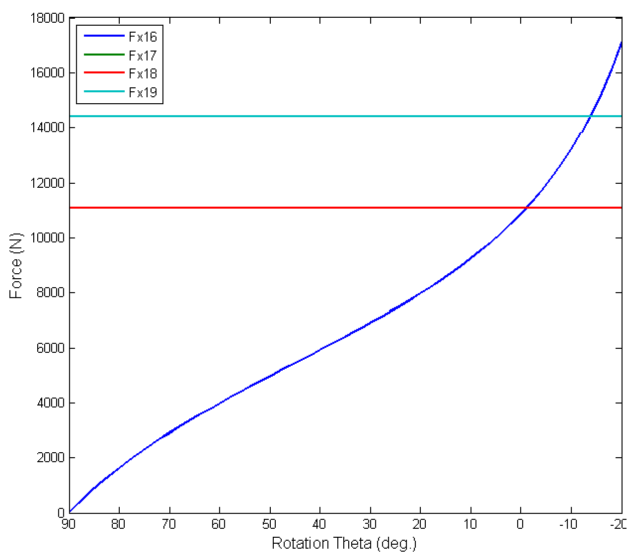
A MATLAB code was used to simulate the kinematic movement of the design and solve the set of 23 equations (Appendix A4). A few forces remain constant throughout the rotation of parallelogram arms, a few reach an absolute maximum when $\theta = 90°$ (start of rotation) or $\theta = 0°$ (arms are horizontal) or $\theta = -20°$ (end of rotation). Variation of all these forces with rotation of parallelogram arms θ has been shown in the figure below.



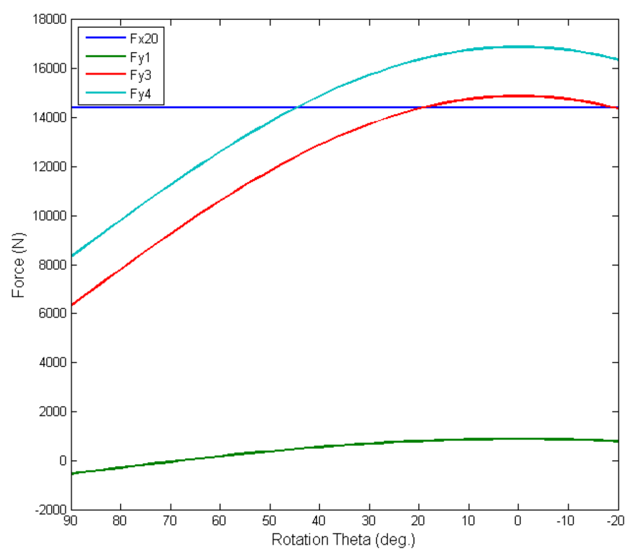
(a)



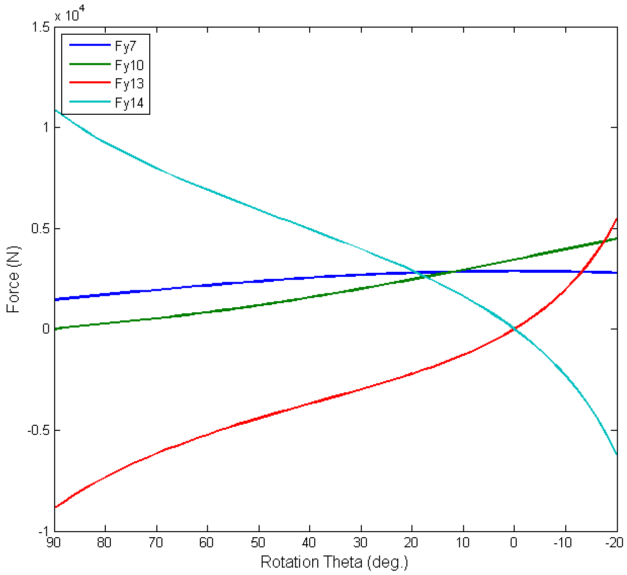
(b)



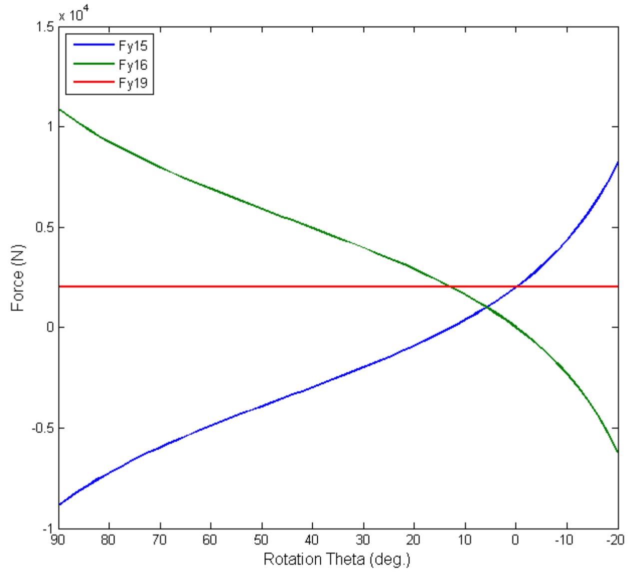
(c)



(d)



(e)



(f)

Figure 4-13: Variation of forces with rotation of arm

Force Name	**Maximum force value (N)**	$\boldsymbol{\theta_{max-force}}$ **(degree)**
f_{a1}	-15978	$-20°$
f_{a2}	18193	$-20°$
f_t	3455	$-20°$
f_{x9}	12713	$-20°$
f_{x10}	14794	$-20°$
f_{x13}	-15015	$-20°$
f_{x14}	17096	$-20°$
f_{x15}	-17096	$-20°$
f_{x16}	17096	$-20°$
f_{x17}	11084	Constant
f_{x18}	11084	Constant
f_{x19}	14409	Constant

Force Name	**Maximum force value (N)**	$\boldsymbol{\theta_{max-force}}$ **(degree)**
f_{x20}	14409	Constant
f_{y1}	875	$0°$
f_{y3}	14886	$0°$
f_{y4}	16887	$0°$
f_{y7}	2876	$0°$
f_{y10}	4486	$-20°$
f_{y13}	-8872	$90°$
f_{y14}	10873	$90°$
$f_{y15,}$	-88722	$90°$
f_{y16}	10873	$90°$
f_{y19}	2001	Constant

Table 4-2: Maximum value of forces and corresponding angle

For each of the forces, the maximum value reached and the corresponding angle has been tabulated in table 4-2. Note that the x and y components of force at key-points 13, 14, 15 and 16 reach their maximum values at different angles. Hence it is appropriate to combine the components and evaluate the resulting force. Figure below shows the resultant forces. F14 and F16 are identical. Maximum force occurs at $\theta = -20°$. Corresponding components of the force have been tabulated in table 4-3.

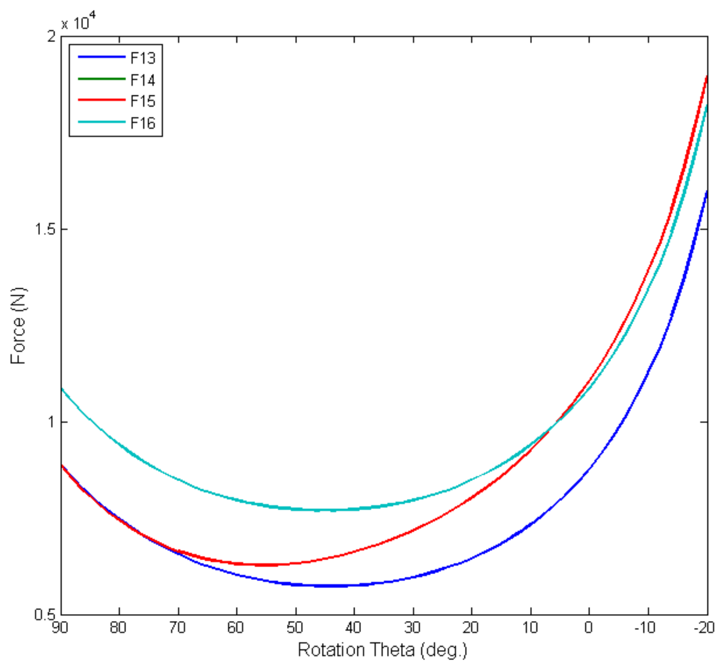


Figure 4-14: Variation of resultant-force at points 13, 14, 15 and 16 with rotation of arm

Point	**Resultant force (N)**	**x-component, f_x (N)**	**y-component, f_y (N)**
13	15978	-15015	5464
14	18193	17096	-6222
15	18971	-17096	8223
16	18193	17096	-6222

Table 4-3: Resultant force and components at $\boldsymbol{\theta = -20°}$

In this chapter we analyzed the variation of forces on parts with rotation of parallelogram arms and captured their maximum value. These will be used to analyze the stress in all parts of the lift in next chapter and design them for appropriate strength.

Chapter 5

Design for Strength

Chapter 2 covered the development of link lengths to achieve the design requirements like ADA guidelines, low down-force, etc. In chapter 3 the basic shapes of all links and members that would comprise the 3D model were developed. The kinematic dimensions were also incorporated in the 3D model.

In this chapter the cross-section of each part of the design has been developed in detail so that it has the desired strength for expected loading conditions. Each part has been analyzed independently using ANSYS. Boundary conditions applied are in accordance to the developed 3D model. The forces determined in chapter 4 have been used to load the model in ANSYS.

After analyzing each part, maximum equivalent stress, maximum deflection, resulting safety factor, and dimension of cross-section used for analysis has been tabulated.

5.1. Material

Stainless Steel 304 was chosen as the material for the lift because of its easy availability and excellent corrosion resistant properties.

Property	**Value**
Tensile yield strength	1103 MPa
Ultimate tensile strength	1276 MPa
Modulus of elasticity	189.6 GPa
Poisson’s ratio	0.28
Mass density	7.8 Mg/m^3

Table 5-1: Mechanical properties of Stainless Steel 304 (Cold Rolled)
(Courtesy: Norton [23])

5.2. Strength design for Base

Cross Section: Square Cross Section ($50\ mm\ \times 50\ mm$), Wall thickness: $4\ mm$

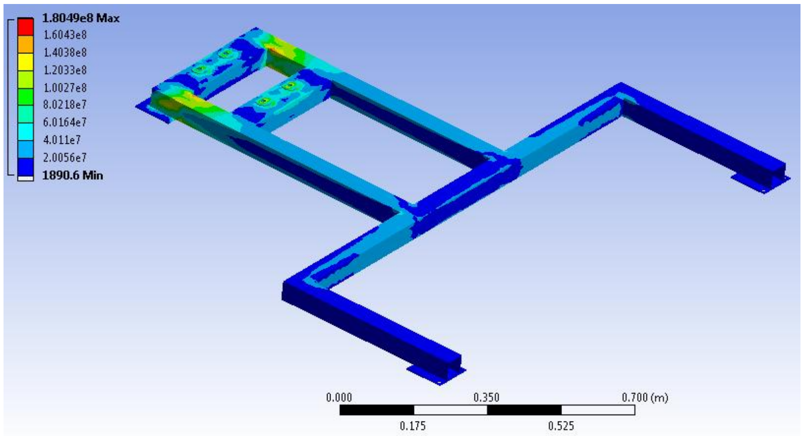


Figure 5-1: Equivalent stress of Base

Max. Von Mise's Stress	Max. Deflection	Safety Factor
180.5 MPa	8 mm	6.1

5.3. Strength design for Bottom Support

Cross Section: Sheet Metal, Wall thickness: $4\ mm$

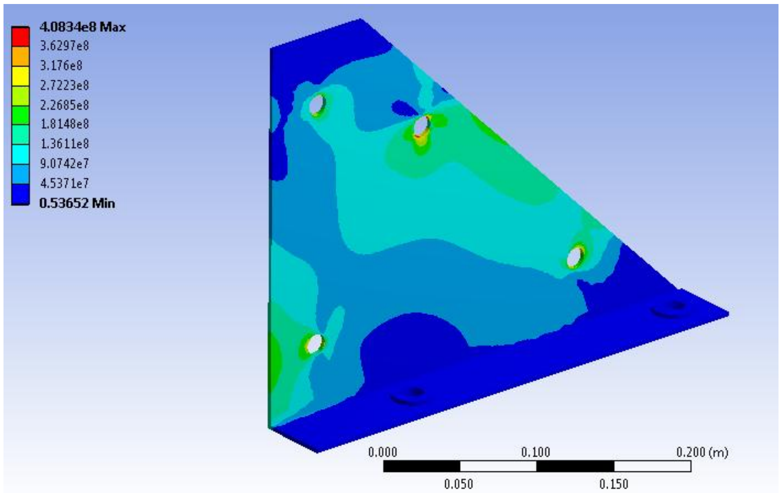


Figure 5-2: Equivalent stress of Bottom Support

Max. Von Mise's Stress	Max. Deflection	Safety Factor
408 MPa	0.3 mm	2.7

5.4. Strength design for Rotating Arm

Cross Section: Square Cross Section ($50\ mm\ \times 50\ mm$), Wall thickness: $2\ mm$

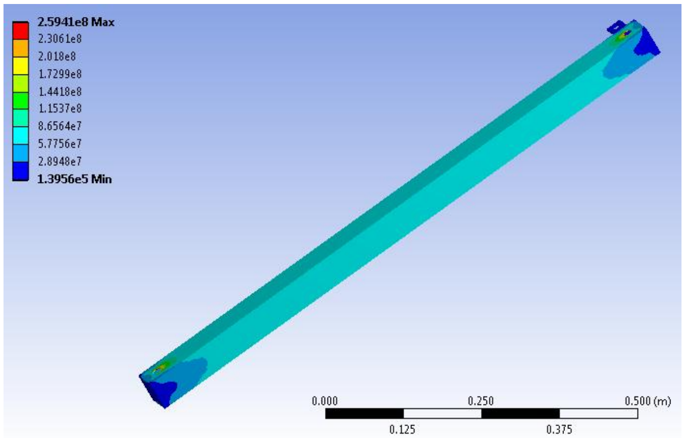


Figure 5-3: Equivalent stress of Rotating Arm

Max. Von Mise's Stress	Max. Deflection	Safety Factor
259 MPa	0.3 mm	4.2

5.5. Strength design for Top Support

Cross Section: Sheet Metal, Wall thickness: $4\ mm$

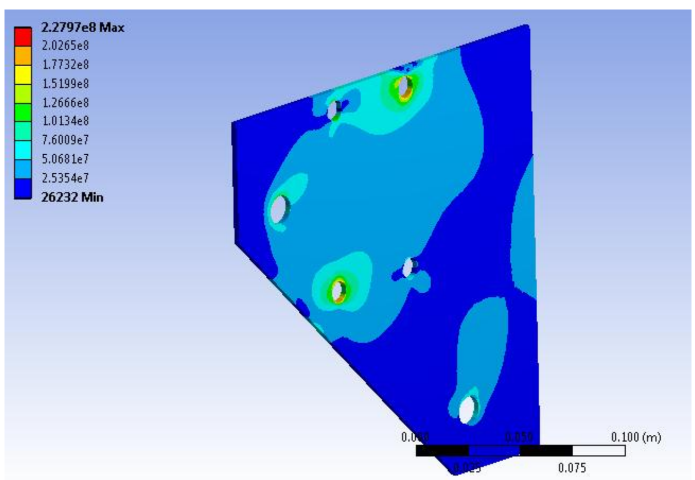


Figure 5-4: Equivalent stress of Top Support

Max. Von Mise's Stress	Max. Deflection	Safety Factor
227 MPa	0.036 mm	4.8

5.6. Strength design for Seat Arm

Cross Section: Square Cross Section $(50\ mm\ \times 50\ mm)$, Wall thickness: $3\ mm$

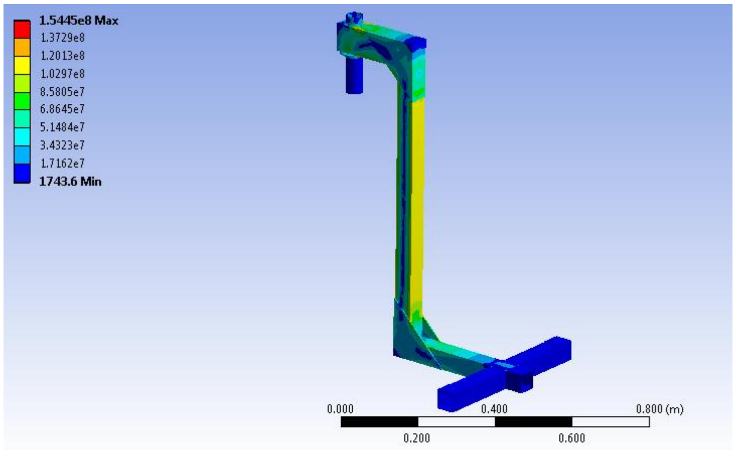


Figure 5-5: Equivalent stress of Seat Arm

Max. Von Mise's Stress	Max. Deflection	Safety Factor
154 MPa	10 mm	7.1

5.7. Strength design for Support Column

Cross Section: Square Cross Section $(50\ mm\ \times 50\ mm)$, Wall thickness: $2\ mm$

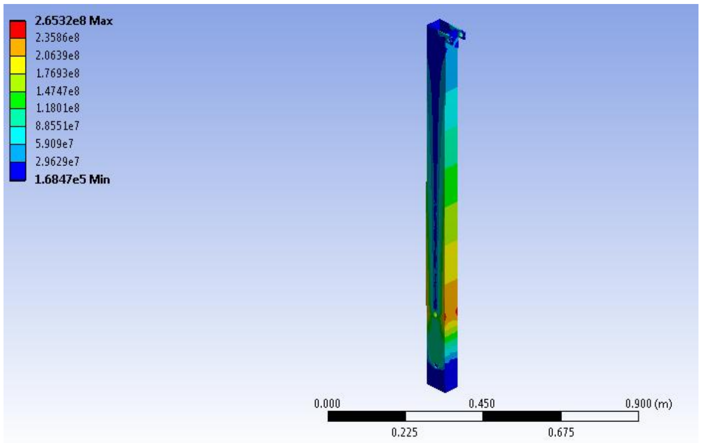


Figure 5-6: Equivalent stress of Support Column

Max. Von Mise's Stress	Max. Deflection	Safety Factor
265 MPa	11 mm	4.1

Chapter 6

Fabrication

A basic insight about the required cross-section dimension was developed in Chapter-5. With that understanding and availability of materials in market the lift is fabricated. In this chapter, the fabrication process of each part has been presented. A list of OEM parts has also been provided.

6.1. Raw Materials

Type	Specification	Used in part
Sheet Metal 1 (SS 304)	Thickness: 4 mm	Top Support, Bottom Support, Support Column
Hollow Channel 1 (SS 304)	Square Cross-Section (50 mm by 50 mm) Wall thickness: 1.5 mm	Base, Rotating Arm, Support Column, Seat Arm
Hollow Shaft 1 (SS 304)	Outer diameter: 60 mm Inner diameter: 50 mm	Seat Arm
Hollow Shaft 2 (SS 304)	Outer diameter: 46 mm Inner diameter: 36 mm	Seat Arm
Solid Shaft 1 (SS 304)	Outer diameter: 22 mm	Rotating Arm

Table 6-1: List of raw materials

Figure 6-1: Some of the raw materials used in the prototype

6.2. Fabrication of Base

Base is fabricated using hollow-channel-1. Sequence of operations is as follows:

- Cutting of channels to required dimensions
- Drilling of holes on individual channels on a milling bed
- Arranging and arresting all the channels on a wooden base (fixture for welding)
- Welding of channels

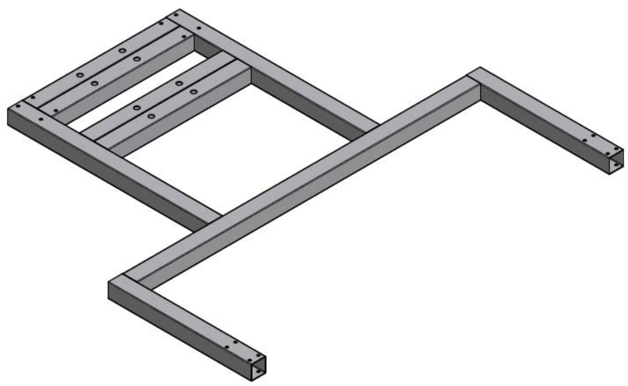


Figure 6-2: CAD of Base

6.3. Fabrication of Bottom-Support

Bottom-Support is fabricated using sheet-metal-1. Sequence of operations is as follows:

- Laser cutting of sheet metal
- Bending of blank
- Fillet-welding of load-rings to the two holes that will carry rotating arm
- Reaming of holes post-welding

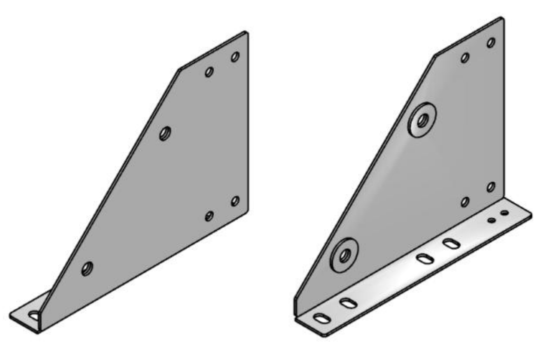


Figure 6-3: CAD of Bottom-Support (Left and Right)

6.4. Fabrication of Rotating-Arm

Rotating Arm is fabricated using hollow-channel-1 and solid-shaft-1. Sequence of operations is as follows:

- Hollow Channel 1
    - Cutting channel to required length
    - Plugging nylon-bush at two ends of the channel
    - Drilling holes on channel on a milling bed
- Solid Shaft 1
    - Cutting shaft to required length
    - Facing on lathe
    - Turning on lathe
    - Threading on lathe
- Press fit solid-shaft-part into hollow-channel-part

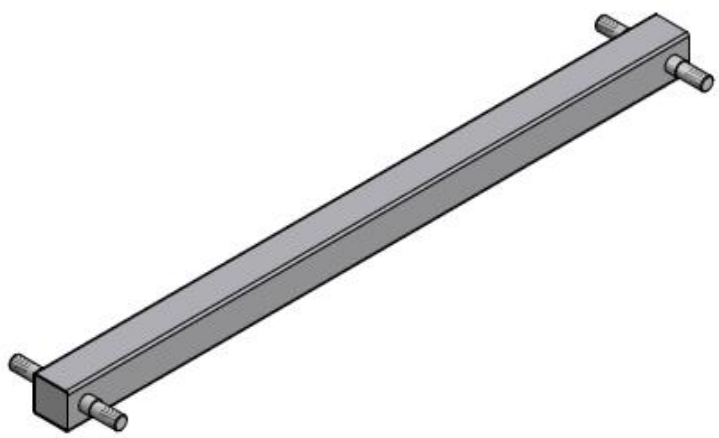


Figure 6-4: CAD of Rotating-Arm

6.5. Fabrication of Top-Support

Top-Support is fabricated using sheet-metal-1. Sequence of operations is as follows:

- Laser cutting of sheet metal
- Bending of blank
- Fillet-welding of load-rings to the two holes that will carry rotating arm
- Reaming of holes post-welding

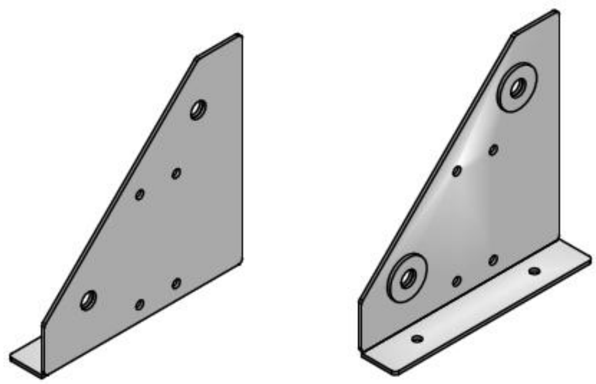


Figure 6-5: CAD of Top-Support (Left and Right)

6.6. Fabrication of Seat-Arm

Seat Arm is fabricated using hollow-channel-1, hollow-shaft-1 and sheet-metal-1. Sequence of operations is as follows:

- Hollow-Channel-1
  - Cutting channels to required length
  - Boring (of edge) on milling bed (for one of the parts that needs to be welded to hollow-shaft-1 later)

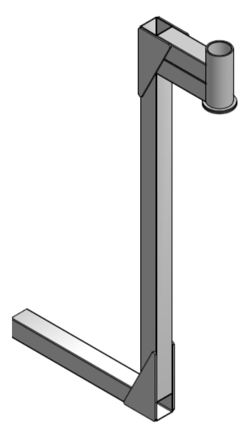


Figure 6-6: CAD of Seat-Arm

- Hollow Shaft 1
  - Cutting shaft to required length
  - Facing on lathe
  - Boring on milling bed

- Laser cutting of sheet-metal-1
- Arrange sheet-metal-parts, hollow-channel-parts and hollow-shaft-parts on a wooden base and clamp using nails/C-clamp.
- Weld all parts
- Press fit bearing into the hollow-shaft-part

6.7. Fabrication of Seat-Arm-Support

Seat Arm Support is fabricated using hollow-shaft-2, and sheet-metal-1. Sequence of operations is as follows:

- Hollow-Shaft-2
    - Cutting shaft to required length
    - Facing on lathe
    - Turning on lathe
    - Surface grinding
- Laser cutting of sheet-metal-1
- Arrange sheet-metal-parts and hollow-shaft-parts on a wooden base and clamp using nails/C-clamp.
- Weld all parts

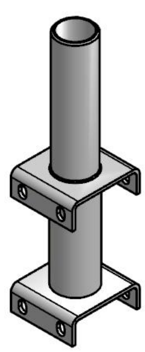


Figure 6-7: CAD of Seat-Arm-Support

6.8. Fabrication of Support-Column

Seat Arm Support is fabricated using hollow-channel-1, solid-shaft-1 and sheet-metal-1. Sequence of operations is as follows:

- Hollow Channel 1
    - Cutting channel to required length
    - Plugging nylon-bush at two ends of the channel
    - Tack-welding the two cut parts together
    - Drilling holes on welded part on a milling bed
- Solid Shaft 1
    - Cutting shaft to required length
    - Facing on lathe
    - Turning on lathe
    - Threading on lathe
- Press fit solid-shaft-part into hollow-channel-part
- Laser cut sheet-metal-1
- Fasten laser-cut part to hollow-channel-part using nut and bolt

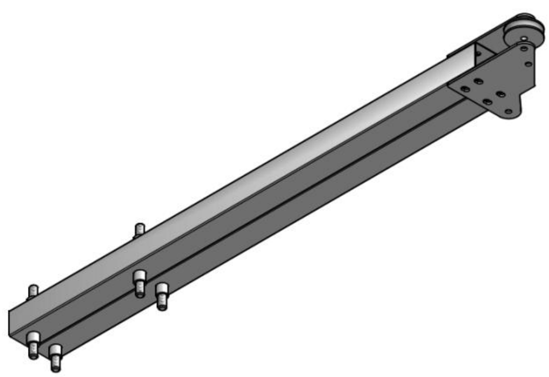


Figure 6-8: CAD of Support-Column

6.9. OEM Parts

Original equipment parts included:

- Fasteners (nut and bolt)
- Bearings
- Tension cable
- Pulley
- Cable Clamp
- Motor and accessories

Figure 6-9: Some of the OEM Parts

Figure 6-10: Sheet metal parts

Figure 6-11: Hollow channel parts

Figure 6-12: Fabricated prototype

6.10. Cost of prototype

Table below summarizes the cost incurred during fabrication of the prototype.

Material or Item	Specification	Quantity	Cost (INR)
Raw Materials			
SS 304 Hollow Channel	Cross Section: 50 mm $\times$ 50 mm Wall Thickness: 1.5 mm	24 Kg	6000
SS 304 Solid Shaft	OD: 22 mm	3 Kg	750
SS 304 Hollow Shaft	OD: 46 mm, ID: 36 mm	1 Kg	250
SS 304 Hollow Shaft	OD: 60 mm, ID: 50mm	1 Kg	250
SS 304 Sheet Metal	Wall Thickness: 4 mm	40 Kg	10000
Nylon	Cross Section: $50\ mm \times 50\ mm$	6 Kg	600
Machining			
Turning and Milling	N/A	16 Hours	7000
Laser Cutting	N/A	40 Meters	5000
Arc Welding	N/A	8 Hours	1000
OEM Parts			
Castor	Wheel OD: 14 mm, Load: 200 Kg	4 Nos.	1400
Fasteners	SS Nuts and Bolts	62 Nos.	4000
Tension Cable	Cable OD 4 mm, Load: 200 Kg	6 Meters	150
Pulley	Pulley OD: 35 mm, ID: 10 mm	2 Nos.	100
Bearings	HK4520 (4), HK3017(2)	6	1200
Motor	12 V, 36 N-m	1	7000
Total			**44700**

Table 6-2: Cost of prototype

Chapter 7

Conclusion

A device which makes swimming pools accessible for physically challenged has been designed and developed. The design process covered the following stages: market survey, patent study, customer survey, kinematic analysis, force analysis, strength analysis, solid modeling, fabrication- scaled-down wooden prototyping and full-scale metal prototyping. The developed prototype has been tested at partial loading condition (35 Kg).

7.1. Advantages over existing pool-lifts

- Lift can be positioned and used at corner of pool without creating any obstruction at pool edge.
- The lift-design is of the category which does not require any fixture to pool deck. For lifts under this category, high counter-weights are used to avoid toppling into the water. But this design requires significantly low counter-weights for operation.
- The lift design requires reduced-force to be applied while raising the person out of the pool, either manually or by a powered actuator
- The lift design requires reduced-force to be applied while swiveling the person after he is seated, either manually or by a powered actuator
- Lift can act both as **stationary and mobile** equipment. Existing designs can act only as one of these and not both.
    - A person can be transferred safely to the device when the device is stationed at the pool corner. Here it acts as **stationary** equipment.
    - A person can be transferred safely to the device when the device is located away from the pool corner, say near the changing/dressing room. Following the transfer, the device can be moved/rolled to the pool-corner with the person sitting on the device. Here it acts as **mobile** equipment.

- Ease of transfer of a person from wheel-chair to the lift. This is ensured by having ample empty space below the seat of the lift which allows a wheel chair to be brought very close to the lift-chair.
- The lift-actuator system is easy to maintain and can be adapted to various lift arm lengths.
- Modularity was a key design constraint. The developed prototype can be used to make a fixed-deck pool-lift by removing the base of the lift and having appropriate fixture on pool-deck.

7.2. Future Work

- Lift design (parallelogram arm dimensions) may need to be changed based on pool-gutter configuration.
- Attempts can be made to make the current lift design compact.
- Multiple variants of pool-lifts are possible based on: (a) fixture i.e. portable or fixed (b) location of lift on pool-deck and (c) location of transfer of individual to the lift. Other pool-lift designs may be developed based on the criteria selected

Detailed patent-study and market-study of swimming pool lifts helped develop an insight into various designs and technologies already being used and what may be improved. In particular, importance of design for manufacture and assembly was strongly realized during the course of the project. Numerous fabrication processes were practically experienced during the course of the project.

APPENDIX A1

```
%************************  Design 1  ******************************
clear;

%*******************  Defining Input Variables  ********************
a=0.70;
b=0.14;
c=0.35;
d=0.60;
e=0.40;
f=0.405;
g=0.20;
h=0.10;
i=0.595;
j=a;
l=1.2;
LCH=0.30;
LCV=0.40;

W=204;
y=5;
G=9.81;
start=90;
stop=-30;

d_theta=1;                 % Incremental angle for calculations
d_theta=-(pi/180*d_theta);  % Converting to radians

M=0;
Fy=0;
R1=0;
R2=0;
Theta=start;

%********************* Generating Animated View *******************

%Pool dimensions
X0=[-2  0 0 2 0 0];
Y0=[0 0 -h -h -h -1];

for t=start*pi/180:d_theta:stop*pi/180;

    %Platform
    X1=[-i-f-g -f-g -f-g -f-g -f-g -f-g -g];
    Y1=[0 0 c b+c b+c+j 0 0];

    %Parallelogram linkage
    X2=[-f-g (a*cos(t)-f-g) (a*cos(t)-f-g) (j*cos(t)-f-g) -f-g];
    Y2=[c (a*sin(t)+c) (a*sin(t)+b+c) (j*sin(t)+b+c) b+c];

    %Linear actuator
    beta=atan((Y1(5)-Y2(4))/(-X1(5)+X2(4)));
    X3=[X2(4) X1(5) X2(4)-l*cos(beta)];
    Y3=[Y2(4) Y1(5) Y2(4)+l*sin(beta)];

    %Chair vertical arm
    X4=[X2(3) X2(3)];
    Y4=[Y2(3) Y2(3)-b-d];

    %Chair horizontal seat
```

```
    X5=[X4(2) (X4(2)+e) (X4(2)+e+LCH)];
    Y5=[Y4(2) Y4(2) Y4(2)-LCV];

    %Force Calculations
    m=(y*(a+b)+W)*G*a*cos(t)+(W*G*e/2);
    fy=W*G+y*G*(2*(a+b)+c+j);
    r1=(fy*f-m)/(i+f);
    r2=fy-r1;

    M=[M m];
    Fy=[Fy fy];
    R1=[R1 r1];
    R2=[R2 r2];
    Theta=[Theta t*180/pi];

    %Plot
    plot(X0,Y0,'b')
    hold on

    plot(X1,Y1,'-ko','LineWidth',2,'MarkerFaceColor','k','MarkerSize',4)
    plot(X2,Y2,'r','LineWidth',2)
    plot(X3,Y3,'-bo','LineWidth',2,'MarkerFaceColor','k','MarkerSize',4)
    plot(X4,Y4,X5,Y5,'LineWidth',2)

    axis([-1.5  1.5  -1.5  1.5])
    axis('square')
    hold off
    pause(0.001);
end

pause(0.01);
d_theta=-d_theta;

for t=stop*pi/180:d_theta:start*pi/180;

    %Platform
    X1=[-i-f-g -f-g -f-g -f-g -f-g -f-g -g];
    Y1=[0 0 c b+c b+c+j 0 0];

    %Parallelogram linkage
    X2=[-f-g (a*cos(t)-f-g) (a*cos(t)-f-g) (j*cos(t)-f-g) -f-g];
    Y2=[c (a*sin(t)+c) (a*sin(t)+b+c) (j*sin(t)+b+c) b+c];

    %Linear actuator
    beta=atan((Y1(5)-Y2(4))/(-X1(5)+X2(4)));
    X3=[X2(4) X1(5) X2(4)-l*cos(beta)];
    Y3=[Y2(4) Y1(5) Y2(4)+l*sin(beta)];

    %Chair vertical arm
    X4=[X2(3) X2(3)];
    Y4=[Y2(3) Y2(3)-b-d];

    %Chair horizontal seat
    X5=[X4(2) (X4(2)+e) (X4(2)+e+LCH)];
    Y5=[Y4(2) Y4(2) Y4(2)-LCV];

    %Plot
    plot(X0,Y0,'b')
    hold on

    plot(X1,Y1,'-ko','LineWidth',2,'MarkerFaceColor','k','MarkerSize',4)
    plot(X2,Y2,'r','LineWidth',2)
    plot(X3,Y3,'-bo','LineWidth',2,'MarkerFaceColor','k','MarkerSize',4)
```

```
    plot(X4,Y4,X5,Y5,'LineWidth',2)

    axis([-1.5  1.5  -1.5  1.5])
    axis('square')
    hold off
    pause(0.001);
end

Fy(:,1)=[];
M(:,1)=[];
R1(:,1)=[];
R2(:,1)=[];
Theta(:,1)=[];

plot(Theta,Fy,Theta,M,Theta,R1,Theta,R2,'LineWidth',1.5);
legend('Force fy','Moment mom','Force r1','Force r2','Location','NorthWest')
```

APPENDIX A2

```
%*****************************  Design 2  ******************************

clear;

%**********************  Defining Input Variables  *********************
a=1.32;
b=0.26;
c=0.30;
d=1.17;
e=0.205;
f=0.205;
g=0.20;
h=0.10;
i=0.795;
j=a;
l=1.8;
LC=0.30;

W=204;
y=5;
G=9.81;
start=90;
stop=-36;

d_theta=1;                  % Incremental angle for calculations (in degree)
d_theta=-(pi/180*d_theta);  % Converting to radians

M=0;
Fy=0;
R1=0;
R2=0;
Theta=0;

%*********************** Generating Animated View **********************

%Pool dimensions
X0=[-2  0 0 2 0 0];
Y0=[0 0 -h -h -h -1];

for t=start*pi/180:d_theta:stop*pi/180;

    %Platform
    X1=[-i-f-g -f-g -f-g -f-g -f-g -f-g -g];
    Y1=[0 0 c b+c b+c+j 0 0];

    %Parallelogram linkage
    X2=[-f-g (a*cos(t)-f-g) (a*cos(t)-f-g) (j*cos(t)-f-g) -f-g];
    Y2=[c (a*sin(t)+c) (a*sin(t)+b+c) (j*sin(t)+b+c) b+c];

    %Linear actuator
    beta=atan((Y1(5)-Y2(4))/(-X1(5)+X2(4)));
    X3=[X2(4) X1(5)];
    Y3=[Y2(4) Y1(5)];

    %Chair vertical arm
    X4=[X2(3) X2(3)];
    Y4=[Y2(3) Y2(3)-b-d];

    %Chair horizontal seat
    X5=[(X4(2)-e) (X4(2)+e) (X4(2)+e) (X4(2)-e) (X4(2)-e)];
```

```
    Y5=[Y4(2) Y4(2) Y4(2)-LC Y4(2)-LC Y4(2)];

    %Force Calculations
    m=(y*(a+b+d)+W)*G*a*cos(t);
    fy=W*G+y*G*(2*(a+b)+c+j+d);
    r1=(fy*f-m)/(i+f);
    r2=fy-r1;

    M=[M m];
    Fy=[Fy fy];
    R1=[R1 r1];
    R2=[R2 r2];
    Theta=[Theta t*180/pi];

    %Plot
    plot(X0,Y0,'b')
    hold on

    plot(X1,Y1,'-ko','LineWidth',2,'MarkerFaceColor','k','MarkerSize',4)
    plot(X2,Y2,'r','LineWidth',2)
    plot(X3,Y3,'-bo','LineWidth',2,'MarkerFaceColor','k','MarkerSize',4)
    plot(X4,Y4,X5,Y5,'LineWidth',2)

    axis([-2  2  -2  2])
    axis('square')
    hold off
    pause(0.001);
end

pause(0.01);
d_theta=-d_theta;

for t=stop*pi/180:d_theta:start*pi/180;

    %Platform
    X1=[-i-f-g -f-g -f-g -f-g -f-g -f-g -g];
    Y1=[0 0 c b+c b+c+j 0 0];

    %Parallelogram linkage
    X2=[-f-g (a*cos(t)-f-g) (a*cos(t)-f-g) (j*cos(t)-f-g) -f-g];
    Y2=[c (a*sin(t)+c) (a*sin(t)+b+c) (j*sin(t)+b+c) b+c];

    %Linear actuator
    beta=atan((Y1(5)-Y2(4))/(-X1(5)+X2(4)));
    X3=[X2(4) X1(5) X2(4)-l*cos(beta)];
    Y3=[Y2(4) Y1(5) Y2(4)+l*sin(beta)];

    %Chair vertical arm
    X4=[X2(3) X2(3)];
    Y4=[Y2(3) Y2(3)-b-d];

    %Chair horizontal seat
    X5=[(X4(2)-e) (X4(2)+e) (X4(2)+e) (X4(2)-e) (X4(2)-e)];
    Y5=[Y4(2) Y4(2) Y4(2)-LC Y4(2)-LC Y4(2)];

    %Plot
    plot(X0,Y0,'b')
    hold on

    plot(X1,Y1,'-ko','LineWidth',2,'MarkerFaceColor','k','MarkerSize',4)
    plot(X2,Y2,'r','LineWidth',2)
    plot(X3,Y3,'-bo','LineWidth',2,'MarkerFaceColor','k','MarkerSize',4)
    plot(X4,Y4,X5,Y5,'LineWidth',2)
```

```
    axis([-3  3  -3  3])
    axis('square')
    hold off
    pause(0.001);
end

Fy(:,1)=[];
M(:,1)=[];
R1(:,1)=[];
R2(:,1)=[];
Theta(:,1)=[];

plot(Theta,Fy,Theta,M,Theta,R1,Theta,R2,'LineWidth',1.5);
legend('Force fy','Moment mom','Force r1','Force r2','Location','NorthWest')
```

APPENDIX A3

```
%*****************************  Design 5  ******************************
clear;

%**********************  Defining Input Variables  *********************
a=0.23;
b=0.77;
c=0.35;
d=0.10;
e=0.32;
f=0.10;
g=0.21;
h=sqrt(a^2+b^2);
i=0.37;
l=0.60;

k=0;

phi=atan(b/a);

d_theta=2;                  % Incremental angle for calculations (in degree)
d_theta=-(pi/180*d_theta);  % Converting to radians

%*********************** Generating Animated View **********************
dx=0.07;
dy=0.1;
A=[dx dx dx];
B=[dy dy dy];

Fx=0;
Fy=0;
Fl=0;
R1=0;
R2=0;

Theta=0;

y=50;
M=100;
G=9.81;

%Pool dimensions
X0=[-1  0 0 1 0 0];
Y0=[0 0 -f -f -f -1];

for t=180*pi/180:d_theta:44*pi/180;

    %Platform
    X1=[-i-a-e -a-e -a-e -a-e -dx-e -dx-e -dx-e -e -e];
    Y1=[0 0 d 0 0 d+dy 0 0 d];

    %Parallelogram linkage 1
    X2=[-e (a*cos(t)-e) (h*cos(t-phi)-e)];
    Y2=[d (a*sin(t)+d) (h*sin(t-phi)+d)];

    %Parallelogram linkage 2
    X3=X2-A;
    Y3=Y2+B;

    %Linear actuator
```

```
    beta=atan((Y2(2)-Y1(3))/(X2(2)-X1(3)));
    X4=[-a-e X2(2) l*cos(beta)-a-e];
    Y4=[d Y2(2) l*sin(beta)+d];

    %Chair vertical arm
    X5=[X3(3) X2(3) X2(3)];
    Y5=[Y3(3) Y2(3) (Y2(3)-c)];

    %Chair horizontal seat
    X6=[(X5(3)-g) (X5(3)+g)];
    Y6=[Y5(3) Y5(3)];

    %Force Calculations
    fl=((M*G*h*cos(t-phi))+(b*y*G*(((X2(2)+X2(3))/2)-X2(1)))+(a*y*G*((X2(2)-
    X2(1))/2)))/(cos(beta)*(Y2(2)-Y2(1))-sin(beta)*(X2(2)-X2(1)));

    if (t<(pi/2+phi))
        x=sqrt((X4(2)-X4(1))^2+(Y4(2)-Y4(1))^2);
        x0=0;
        fl=fl-k*(x-x0);
    end

    fy=M*G+(a+b+c)*y*G+fl*sin(beta);
    fx=fl*cos(beta);
    r1=(fx*d-fl*sin(beta)*a-fl*cos(beta)*d)/(a+i);
    r2=fy-fl*sin(beta)-r1;

    %Storing in array
    Fl=[Fl fl];
    Fy=[Fy fy];
    Fx=[Fx fx];
    R1=[R1 r1];
    R2=[R2 r2];
    Theta=[Theta t*180/pi];

    %Plot
    plot(X0,Y0,'b')
    hold on

    plot(X1,Y1,'-ko','LineWidth',2,'MarkerFaceColor','k','MarkerSize',4)
    plot(X2,Y2,'r',X3,Y3,'r','LineWidth',2)
    plot(X4,Y4,'-bo','LineWidth',2,'MarkerFaceColor','k','MarkerSize',4)
    plot(X5,Y5,X6,Y6,'LineWidth',2)

    axis([-1.3  1.3  -1.3  1.3])
    axis('square')
    hold off
    pause(0.00001);
end

pause(0.01);
d_theta=-d_theta;

for t=45*pi/180:d_theta:180*pi/180;

    %Platform
    X1=[-i-a-e -a-e -a-e -a-e -dx-e -dx-e -dx-e -e -e];
    Y1=[0 0 d 0 0 d+dy 0 0 d];

    %Parallelogram linkage 1
    X2=[-e (a*cos(t)-e) (h*cos(t-phi)-e)];
    Y2=[d (a*sin(t)+d) (h*sin(t-phi)+d)];
```

```
    %Parallelogram linkage 2
    X3=X2-A;
    Y3=Y2+B;

    %Linear actuator
    beta=atan((Y2(2)-Y1(3))/(X2(2)-X1(3)));
    X4=[-a-e X2(2) l*cos(beta)-a-e];
    Y4=[d Y2(2) l*sin(beta)+d];

    %Chair vertical arm
    X5=[X3(3) X2(3) X2(3)];
    Y5=[Y3(3) Y2(3) (Y2(3)-c)];

    %Chair horizontal seat
    X6=[(X5(3)-g) (X5(3)+g)];
    Y6=[Y5(3) Y5(3)];

    %Plot
    plot(X0,Y0,'b')
    hold on

    plot(X1,Y1,'-ko','LineWidth',2,'MarkerFaceColor','k','MarkerSize',4)
    plot(X2,Y2,'r',X3,Y3,'r','LineWidth',2)
    plot(X4,Y4,'-bo','LineWidth',2,'MarkerFaceColor','k','MarkerSize',4)
    plot(X5,Y5,X6,Y6,'LineWidth',2)

    axis([-1.3  1.3  -1.3  1.3])
    axis('square')
    hold off
    pause(0.00001);
end
Fx(:,1)=[];
Fy(:,1)=[];
Fl(:,1)=[];
R1(:,1)=[];
R2(:,1)=[];
Theta(:,1)=[];

plot(Theta,Fl,Theta,Fx,Theta,Fy,Theta,R1,Theta,R2,'LineWidth',1.5);
legend('Fl','Fx','Fy','R1','R2','Location','NorthWest')
```

APPENDIX A4

```
%******************** Design 4 ***********************
clear;
a=850;
%********************************************
x1=0;        y1=-188.8;
x2=0;        y2=0;
x3=50.8;     y3=y2;
x4=249.2;    y4=y2;
x5=750.8;    y5=-4;
x6=1200;     y6=-4;
x7=1200;     y7=y1;
x8=-50.8;    y8=y2;
x9=x8;       y9=30;
x10=x8;      y10=y9+240;
x11=x8;      y11=(1050-60);
x12=x8;      y12=(1050+75);
x13=60;      y13=210;
x14=210;     y14=60;

%********************************************
start=90*pi/180;
stop=-20*pi/180;
step=-2*pi/180;

M=204*9.81;
k=0;
l0=715;

Theta=[0];
Fa1=[0];
Fa2=[0];
Ft=[0];
Fx9=[0];
Fx10=[0];
Fx13=[0];
Fx14=[0];
Fx15=[0];
Fx16=[0];
Fx17=[0];
Fx18=[0];
Fx19=[0];
Fx20=[0];
Fy1=[0];
Fy3=[0];
Fy4=[0];
Fy7=[0];
Fy10=[0];
Fy13=[0];
Fy14=[0];
Fy15=[0];
Fy16=[0];
Fy19=[0];

F13=[0];
F14=[0];
F15=[0];
F16=[0];

for t=start:step:stop
```

```
%*********************************************
x15=x13+a*cos(t); y15=y13+a*sin(t);
x16=x15+150;    y16=y15-150;
x17=x15+95;     y17=y15-90;
x18=x17;        y18=y17+130;
x19=x17;        y19=y15+96;
x20=x17;        y20=y19+100;
x21=x19+170;    y21=y19-10;
x22=x21;        y22=y21-929.2;
x23=x22+550;    y23=y22;
x24=x22+550;    y24=y22+50.8;

%*********************************************
fs=k*(sqrt((x16-x13)^2+(y16-y13)^2)-10)/1000;
alpha=atan((y12-y15)/(x15-x12));
beta=atan((y16-y13)/(x16-x13));

fx20=M*(x23-x19)/(y20-y19);
fx19=fx20;
fy19=M;

fx18=(fx20*(y20-y17)-fx19*(y19-y17))/(y18-y17);
fx17=fx18;

A=[0    0   0   0   0   0   0   0   0   (y15-y16)   (x16-x15);
0   0   0   0   0   0   0   0   1   0   1;
0   0   0   0   0   0   0   1   0   1   0;
0   0   0   0   sin(t)  0   sin(alpha)  0   -1  0   0;
0   0   0   0   cos(t)  0   -cos(alpha) -1  0   0   0;
0   0   0   0   0   sin(t)  0   0   0   0   -1;
0   0   0   0   0   cos(t)  0   0   0   -1  0;
1   0   0   0   -cos(t) 0   0   0   0   0   0;
0   1   0   0   -sin(t) 0   0   0   0   0   0;
0   0   1   0   0   -cos(t) 0   0   0   0   0;
0   0   0   1   0   -sin(t) 0   0   0   0   0];

B=[M*(x23-x15) M   0   0   0   fs*sin(beta)    fs*cos(beta)    -
fs*cos(beta)   -fs*sin(beta)   0   0];
B=B';

X=inv(A)*B;
fx13=X(1);
fy13=X(2);
fx14=X(3);
fy14=X(4);
fa1=X(5);
fa2=X(6);
ft=X(7);
fx15=X(8);
fy15=X(9);
fx16=X(10);
fy16=X(11);

fx10=ft/2*(y11-y9+y12-y9)/(y10-y9);
fx9=fx10-ft*cos(alpha);
fy10=ft*(0.5+sin(alpha));

fy4=M*(x23-x3)/(x4-x3);
fy3=fy4-M;

fy7=M*(x23-x1)/(x7-x1);
fy1=fy7-M;
```

```
    Fa1=[Fa1 fa1];
    Fa2=[Fa2 fa2];
    Ft=[Ft ft];
    Fx9=[Fx9 fx9];
    Fx10=[Fx10 fx10];
    Fx13=[Fx13 fx13];
    Fx14=[Fx14 fx14];
    Fx15=[Fx15 fx15];
    Fx16=[Fx16 fx16];
    Fx17=[Fx17 fx17];
    Fx18=[Fx18 fx18];
    Fx19=[Fx19 fx19];
    Fx20=[Fx20 fx20];
    Fy1=[Fy1 fy1];
    Fy3=[Fy3 fy3];
    Fy4=[Fy4 fy4];
    Fy7=[Fy7 fy7];
    Fy10=[Fy10 fy10];
    Fy13=[Fy13 fy13];
    Fy14=[Fy14 fy14];
    Fy15=[Fy15 fy15];
    Fy16=[Fy16 fy16];
    Fy19=[Fy19 fy19];

    f13=sqrt(fx13^2+fy13^2);
    f14=sqrt(fx14^2+fy14^2);
    f15=sqrt(fx15^2+fy15^2);
    f16=sqrt(fx16^2+fy16^2);

    F13=[F13 f13];
    F14=[F14 f14];
    F15=[F15 f15];
    F16=[F16 f16];

    Theta=[Theta t*180/pi];

    X1=[x1 x2 x3 x4 x5 x6 x7]; Y1=[y1 y2 y3 y4 y5 y6 y7];
    X2=[x8 x9 x10 x11 x12];  Y2=[y8 y9 y10 y11 y12];
    X3=[x13 x14 x16 x15 x13]; Y3=[y13 y14 y16 y15 y13];
    X4=[x17 x18 x19 x20]; Y4=[y17 y18 y19 y20];
    X5=[x19 x21 x22 x23 x24]; Y5=[y19 y21 y22 y23 y24];

    plot(X1,Y1,'-ko','LineWidth',2,'MarkerFaceColor','k','MarkerSize',6)
    hold on

    plot(X2,Y2,'-ro','LineWidth',2,'MarkerFaceColor','r','MarkerSize',6)
    plot(X3,Y3,'-bo','LineWidth',2,'MarkerFaceColor','b','MarkerSize',6)
    plot(X4,Y4,'-ro','LineWidth',2,'MarkerFaceColor','r','MarkerSize',6)
    plot(X5,Y5,'-bo','LineWidth',2,'MarkerFaceColor','b','MarkerSize',6)

    axis([-500  2000  -1000  1500])
    axis('square')

    hold off
    pause(0.001);
end

Theta(:,1)=[];
Fa1(:,1)=[];
Fa2(:,1)=[];
Ft(:,1)=[];
```

```
Fx9(:,1)=[];
Fx10(:,1)=[];
Fx13(:,1)=[];
Fx14(:,1)=[];
Fx15(:,1)=[];
Fx16(:,1)=[];
Fx17(:,1)=[];
Fx18(:,1)=[];
Fx19(:,1)=[];
Fx20(:,1)=[];
Fy1(:,1)=[];
Fy3(:,1)=[];
Fy4(:,1)=[];
Fy7(:,1)=[];
Fy10(:,1)=[];
Fy13(:,1)=[];
Fy14(:,1)=[];
Fy15(:,1)=[];
Fy16(:,1)=[];
Fy19(:,1)=[];

F13(:,1)=[];
F14(:,1)=[];
F15(:,1)=[];
F16(:,1)=[];

plot(Theta,Fa1,Theta,Fa2,Theta,Ft,Theta,Fx9,'LineWidth',1.5);
legend('Fa1','Fa2','Ft','Fx9','Location','NorthWest')

plot(Theta,Fx10,Theta,Fx13,Theta,Fx14,Theta,Fx15,'LineWidth',1.5);
legend('Fx10','Fx13','Fx14','Fx15','Location','NorthWest')

plot(Theta,Fx16,Theta,Fx17,Theta,Fx18,Theta,Fx19,'LineWidth',1.5);
legend('Fx16','Fx17','Fx18','Fx19','Location','NorthWest')

plot(Theta,Fx20,Theta,Fy1,Theta,Fy3,Theta,Fy4,'LineWidth',1.5);
legend('Fx20','Fy1','Fy3','Fy4','Location','NorthWest')

plot(Theta,Fy7,Theta,Fy10,Theta,Fy13,Theta,Fy14,'LineWidth',1.5);
legend('Fy7','Fy10','Fy13','Fy14','Location','NorthWest')

plot(Theta,Fy15,Theta,Fy16,Theta,Fy19,'LineWidth',1.5);
legend('Fy15','Fy16','Fy19','Location','NorthWest')

plot(Theta,F13,Theta,F14,Theta,F15,Theta,F16,'LineWidth',1.5);
legend('F13','F14','F15','F16','Location','NorthWest')

rr=20;
lf=sqrt((y15-y12)^2+(x15-x12)^2);
w=(lf*2/30)/rr;
wrpm=w*60/(2*pi);
torque=(ft/2)*rr/1000;
P=torque*w;
```

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