DEPARTMENT OF MECHANICAL AND INDUSTRIAL ENGINEERING, UNIVERSITY OF TORONTO

REDESIGN OF SCISSOR JACK MECHANISM TO ACHIEVE CONSTANT INPUT FORCE

MIE 301: FINAL DESIGN PROJECT

DECEMBER, 10TH, 2020

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GROUP #4

1.0 Introduction:

A scissor jack is an essential tool for drivers that raises the side of the car to enable them to change a tire. However, the client has noticed that the mechanism requires a larger input force at the beginning of the cycle than at the end. This implies that many users may struggle to begin operating the scissor jack. Moreover, most drivers are usually alone and would therefore only be able to generate a small input force insufficient to begin lifting the car. Thus, we have been tasked by the client to redesign the jack such that the user is required to input a relatively constant turning force during the entire cycle of operation.

As the Engineering team, we understand this problem is often overlooked, although it is extremely relevant to drivers in Canada. With over 70% of Canada’s population driving [1], the need for a user-friendly jack is magnified. Furthermore, the extreme weather conditions during winter results in low tire pressures and an increased number of tire punctures [2]. Redesigning the mechanism will help ensure that users can replace a tire on their own whilst eradicating the inconvenience of being left stranded with a punctured tire due to their inability to operate the scissor jack.

1.1 Current Design - Scissor Lift Car Jack:

A scissor jack is a mechanism that transforms rotational motion into vertical motion, which allows the jack to be used to lift cars. The mechanism consists of six links, two sliders and one screw. Following the labels used in Figure 1 below, link 1 is the ground link whilst link 5 is the output link. Links 2, 4, 6 and 8 are rigid links of equal length with turning pairs at each of their ends. The screw is labelled as 9 and passes through the sliders labelled 7 and 8.

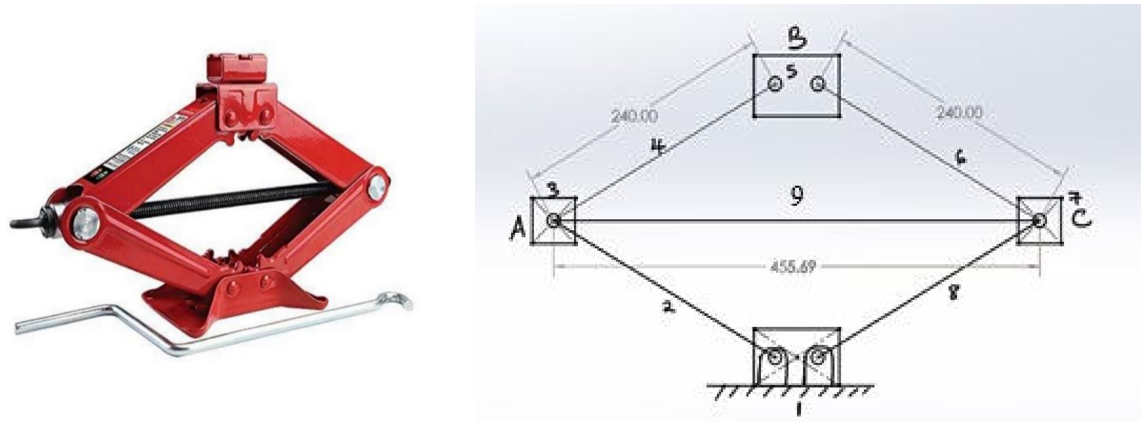


Figure 1: Original Car Jack Mechanism

The user inputs rotational motion into the mechanism via a crank that is connected to the screw (link 9). During the lifting motion, the input screw rotates and traverses to the right. This causes the sliding pair on the right to move in the opposite direction. As the sliding pairs approach each other, all rigid arms (links 2, 4, 6, 8) rotate about their respective turning pairs, and they assume a more vertical orientation. In doing so, the mechanism is able to extend upwards and generate the vertical force required to lift a vehicle.

1.2 Force Analysis of Current Design:

A force analysis was conducted on the current mechanism using force polygons. Drawing free body diagrams revealed that links 2, 4, 6, 8, and 9 are two-force members, whilst links 3, 5, and 6 are three-force members. There is symmetry in the mechanism ($|F_{45}| = |F_{43}| = |F_{23}| = |F_{12}|$) and thus only two force polygons were developed (links 5 and 3). The polygons and their derived results can be seen in figure 2 and table 1 below:

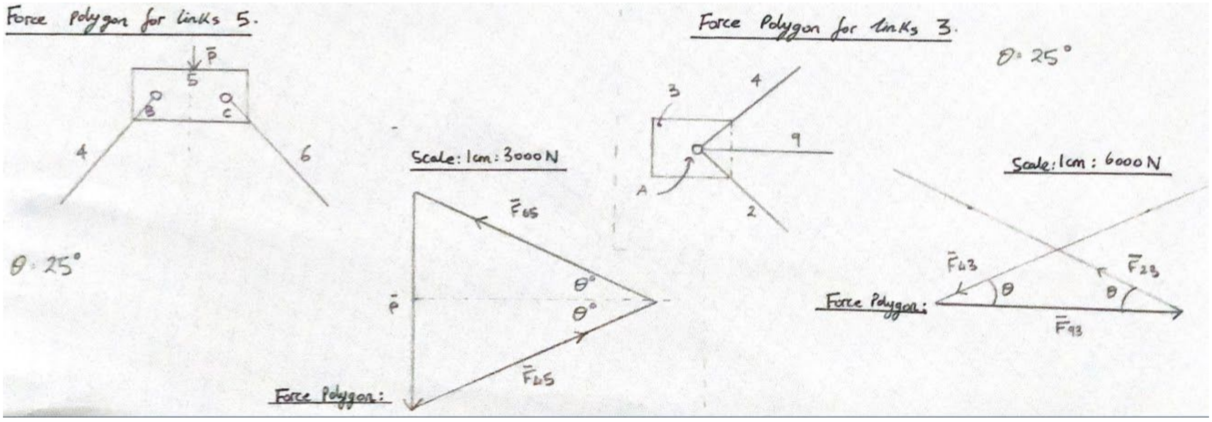


Figure 2 : Force Analysis with Force Polygons of Current Mechanism

Forces	Measured (cm)	Actual (N)
P	4.70	14,000
F_{45}	5.80	17,400
F_{65}	5.80	17,400
F_{93}	5.25	31,500
F_{23}	2.90	17,400
F_{43}	2.90	17,400

Table 1 : Results of Force Analysis on Current Mechanism

To investigate the input force, the force polygon of link 5 (Figure 2) was further analysed. It was deduced that $F_{45} = P/ 2\sin\theta$, where P is the weight of the load. This relationship shows that at a small angle (as would be the case at the start of the lifting process) the input force required (which would transmit the force F_{45}) would be very high. However, as θ increases F_{45} decreases, as does the required input force. For the proposed mechanism, the constraint on the design is that the input force required is constant throughout the cycle. Hence, the force transmission in the design must be altered.

1.3 Velocity Analysis of Current Design:

A velocity analysis was carried out on the current mechanism at both the initial and final positions. The position of the mechanism's links can be described by measuring the angle (θ) between links 4 and 9 in Figure 1. It was assumed that the starting angle, θ_0, would be 25°.

This meant that the starting height of the mechanism could be found using trigonometry, and was calculated to be 20 cm. The client expects the mechanism to lift a car at least 40 cm above the ground. Trigonometry was used once again to find θ_f which was equal to 70°. A simplified velocity polygon (without the screw) was then constructed for both θ_0 and θ_f:

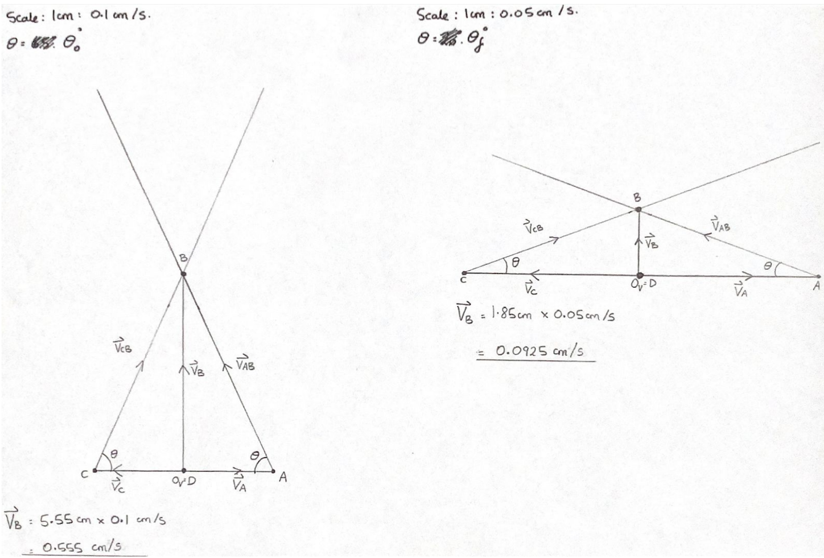


Figure 3: Velocity Polygon of Current Mechanism at θ_0 and θ_f

The following formula was used to find V_c:

$$V = \frac{n \cdot P}{1000 \cdot sin(\alpha)}$$

where V is the velocity of point C, n is the rotations per minute (rpm) of the screw, P is the pitch of the screw in millimetres, and α is the thread helix angle of the screw [3].

It was assumed that the diameter of the screw was 12mm. Research showed that the standard thread of the screw in North America is an ACME trapezoidal thread, meaning that the thread helix angle of the screw is at 30° [4]. This angle and diameter corresponds to a pitch P of 6mm [4]. The value of n was set to 25 rpm, as the manual speed of rotation of a crank should not exceed this value [5]. V_c was then found to be 0.25 cm/s.

Using the velocity polygons above we were able to calculate the speed of link 5 when the scissor jack was at its lowest and highest points. The two speeds were found to be 0.555 cm/s and 0.0925 cm/s respectively. To simplify the analysis, the two speeds found above were averaged which resulted in a speed of 0.33 cm/s. To calculate the time of displacement, and thus the duration of the living cycle, we divided the average speed found from 25 cm which was the expected distance travelled vertically. In doing so, the time of travel was found to be 76 seconds. Thus, one objective of the proposed design would be to try and obtain a displacement time within 72 - 80 seconds which would be a $\pm 5\%$ deviation from the original time found.

2.0 Project Requirements:

2.1 Client Request:

The client identified that the current scissor jack mechanism is flawed because the mechanism requires a large initial input force to start using the mechanism that reduces as the jack extends. The client has further realised that the input force is largely wasted in the horizontal direction when the jack is at its lowest point. Thus, we have been tasked with redesigning the scissor jack to ensure that users are required to input a relatively constant turning force throughout the entire lifting cycle.

Analysis in the previous section highlighted that the client's problem arises due to the changing angle between the screw and output links when the mechanism is in operation. Therefore, the proposed design will focus on keeping the angular relation between the links and screw constant. Also, to maintain familiarity and ease of use, the method of user input (i.e using a handle to turn the screw) will not be changed.

2.2 Constraints:

To be considered appropriate, the proposed design must abide by the following constraint:

- The chosen solution must allow for a realistic, constant input turning force throughout the entire cycle. This would solve the issue of the initial input force being too high for some users to generate.

2.3 Objectives:

The following objectives were set to meet the client request as well as retain positive attributes of the previous design. A proposed design that meets all of these objectives will be considered ideal.

1. Deployment Time:
    - The new mechanism should complete the lifting process in a similar time frame of the original scissor jack (72 seconds - 80 seconds).
2. Minimum Load:
    - The new mechanism should be able to provide at least 14,000 N of an upwards lifting force [6].
3. Provide an Upward Linear Output:
    - The new mechanism should provide an output in an upward linear trajectory to ensure that the car being lifted is not tipped or dislodged through the process.
4. Input Force:
    - The new mechanism should be designed to work with an input of 110 Nm [6]. This is due to 220 N being the recommended maximum exertion force by hand, and assuming a 50 cm handle.
5. Displacement:
    - The jack must extend 20 cm; starting from 20-25cm above the ground, the vehicle should be lifted until it is at least 40cm above the ground [6].

3.0 Proposed Solution:

The next section will provide an in-depth review of the proposed design that overcomes the issue faced by the client. In this design, we aim primarily to counter the issue of the user having to input an non-uniform force during the operational cycle.

3.1 Limitations of the Proposed Solution:

To remain within the scope of the course, assumptions and simplifications were made which resulted in the following limitations:

1. The material of the design is not considered, and as such, the results in the later analysis sections do not reflect any real life scenarios. Rather, they provide a general overview of the mechanism movement and capabilities.
2. To perform mechanical simulations, it is assumed the user will input a constant rotational force. However, this is unlikely due to human errors and use case factors. Therefore, there is a degree of inaccuracy in the simulations.
3. The objectives of the design were benchmarked using a single (given) scissor jack. Therefore, while the proposed design improves upon this particular jack, it cannot be said that it improves upon all scissor jacks.
4. For simplification of calculations and simulations, friction, screw backlash and other resistive forces were not considered.

3.2 Description of the Proposed Solution:

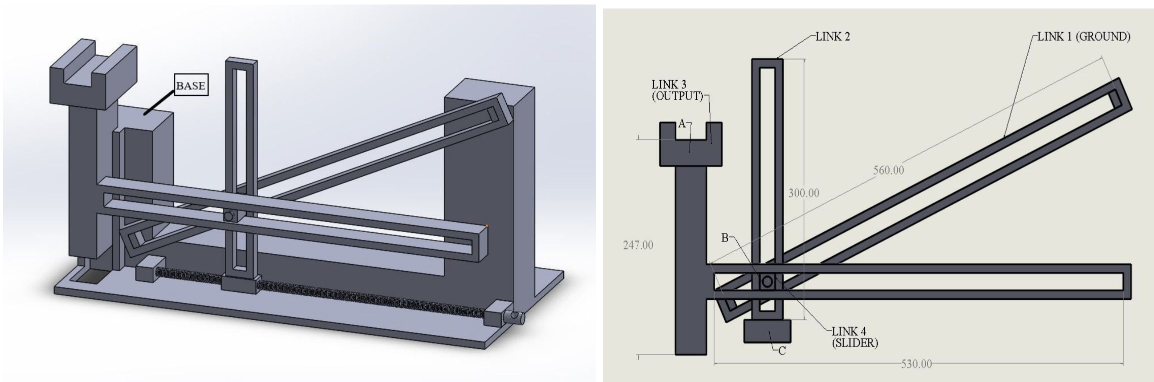


Figure 4: Proposed Mechanism

As seen in figure 4, the mechanism consists of 4 links (one of which is a slider), a screw and a base support. Link 1 is slotted and fixed to the base at an angle of 25 degrees to the horizontal. Link 2 is also slotted and its lower end is threaded to match the screw. This results in link 2 converting the rotational input from the screw to linear motion. Link 3 is specially designed such that it has a horizontal-slotted protrusion that allows it to interact with the other links while maintaining a strictly vertical (up/down) motion. Link 4 is a slider which slides within the slots of links 1, 2 and 3 and is responsible for transferring the horizontal motion of link 2 into the vertical motion of link 3.

The mechanism operation is as follows: using a handle, the user turns the screw clockwise resulting in the horizontal motion of link 2 to the right. This motion produces a force on the slider which causes it to simultaneously slide up link 1 and horizontally along link 3. This sliding produces an upward force on link 3,causing it to move vertically upward to perform a lift. To lower link 3, the user must simply rotate the screw counter-clockwise. This will cause link 2 to move to the left, thus reversing the action of the forces such that the slider produces a downward force on link 3.

4.0 Techniques used for Analysis:

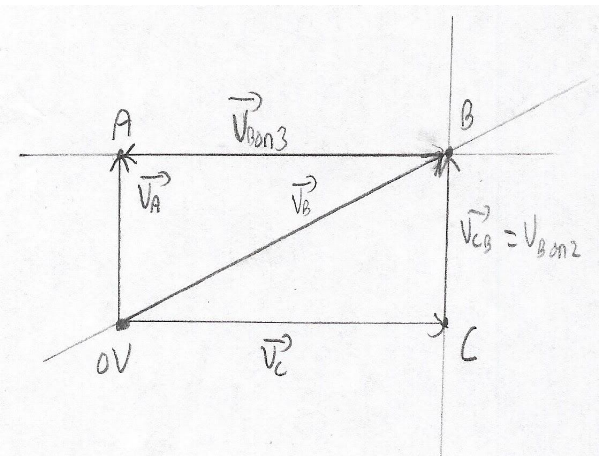
To perform a high-level kinematic analysis, both Matlab and SolidWorks software were used. These helped to perform force, velocity and trajectory analyses for the proposed design.

The results of the analyses will be used to test if the proposed design meets the requirements specified above. This shall be highlighted in a table at the end of this section.

<u>4.1 Link Optimisation:</u>
The general mechanism motion was altered by changing the lengths of the links in a Solidworks sketch of the mechanism. Initially, the lengths of the links and their respective angles were modified so that the mechanism outputs a vertical motion from a rotational input. Thereafter, the mechanism's links were adjusted such that the mechanism achieved a vertical displacement of 20cm. These changes were implemented and tested through Solidworks motion simulations.

<u>4.2.1 Mobility Analysis:</u>
The mobility of the mechanism, m, was found to be : m = 3(4-1) - 2(4) = 1. To confirm that this was the actual mobility, we used the CAD model on SolidWorks and observed that by adding one additional constraint to the sketch, the mechanism became fully constrained.

<u>4.2.2 Velocity Analysis:</u>
The velocity of the proposed mechanism was analyzed using polygons, loop analysis and SolidWorks simulations. Velocity polygons were created for the mechanism with its output link in both the highest and lowest positions. The same results were obtained in each case. This is expected since the velocity of the driving link and the angles between the links are constant throughout the motion. The velocity polygon and results can be seen in figure 5 below:



Results:

Component	Measured (cm)	Velocity (cm/s)
$\vec{V}_C$	5.0	0.250
$\vec{V}_{CB}$	2.4	0.120
$\vec{V}_B$	5.7	0.285
$\vec{V}_A$	2.4	0.120
$\vec{V}_{Bon3}$	5.0	0.25

Figure 5: Velocity Polygon of Proposed Mechanism

The time taken for the lifting process was then calculated by dividing the vertical displacement of 20cm by the vertical speed of the output link. This time was found to be 167 seconds.

<u>4.2.3 Trajectory and Position Analysis:</u>
The trajectory analysis for the proposed mechanism was completed using Matlab. Equations were created to display the links and describe the movement of the mechanism over the course of the lifting cycle. The blue dashed lines on the left of the plot below show the movement of the output link from its initial to final position. Thus, the proposed design satisfies the objective of linear vertical motion and would ensure structural balance during the lifting of heavy loads.

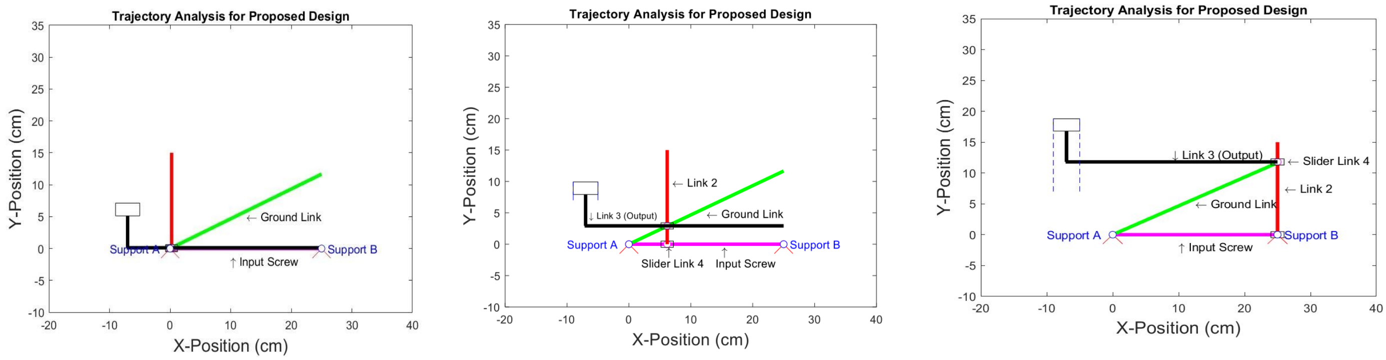


Figure 7: Traces of Link Movement through Different Points in the Lifting Cycle
(From left: Initial Position, Position at Half of Lifting Cycle, Final Position)

For simplification, the model created in MATLAB was scaled down relative to the actual dimensions of the proposed design. However, the velocities of the moving links were set as those calculated using the velocity analysis techniques mentioned above. SolidWorks was used to calculate both the stroke and timing ratio of the mechanism from the known limit positions. Using the 'motion analysis' feature of SolidWorks, the timing ratio was found to be 1 and the stroke, 20cm.

<u>4.2.4 Force Analysis:</u>
The force analysis was initiated at link 3 (output), followed by link 4 (slider) and completed at link 2. Newtonian mechanics was used to consider the forces acting on links 2 and 3 as the forces on these links did not intersect at a certain point in space. Link 3 experienced the weight of the vehicle (W), the force from the slider (F_{43}) and a reactive force to balance the moment. A force polygon was constructed (figure 10) to analyse the forces acting on link 4. Using the polygon, it was deduced that the forces interact at a single point, thus eradicating any acting moments. From this force polygon, we were able to calculate the force acting on link 2 (F_{42}). This force was balanced by the linear force inputted from the screw (F_{12}). In order to ensure no moment acted on link 2, it was assumed that the screw provided a counteractive moment which is beyond the scope of analysis.

In the analysis below, it was shown that an input force of 48 N was required to lift a weight of 14,000 N. Combining this result with the assumptions below, it was confirmed that the objective of obtaining an input force below 220N was achieved.

The following assumptions were made to perform the force analysis:

- To perform a thorough force analysis, the team will have to consider material selection which is outside the current scope. The proposed design uses the same screw as the scissor jack. Combining this information with the 48N input force derived, implies that the design will be able to support the 14,000N.
- All rotational input force is converted to linear motion, inertial forces are negligible and the force analysis is performed only at the upper limit position.
- The input screw provided an opposing moment to that caused by the force couple acting on link 2.

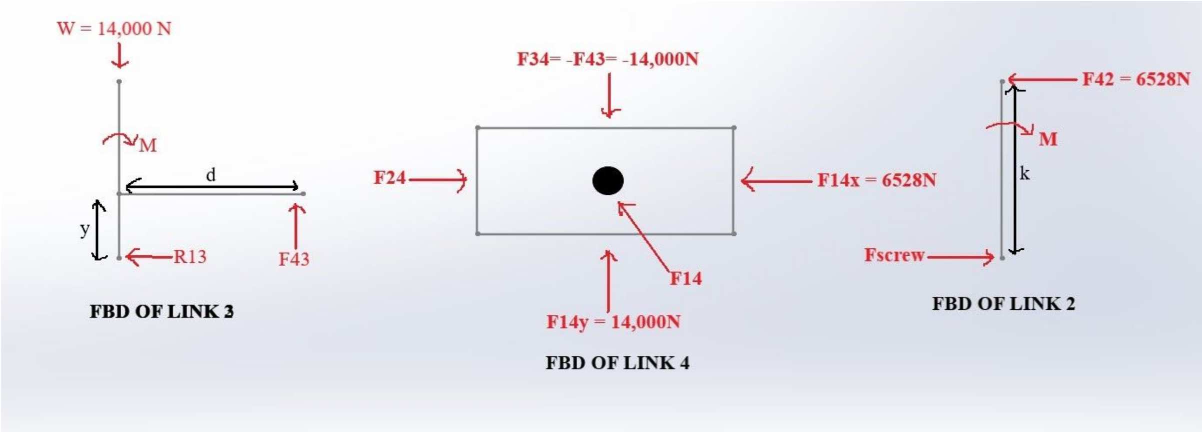
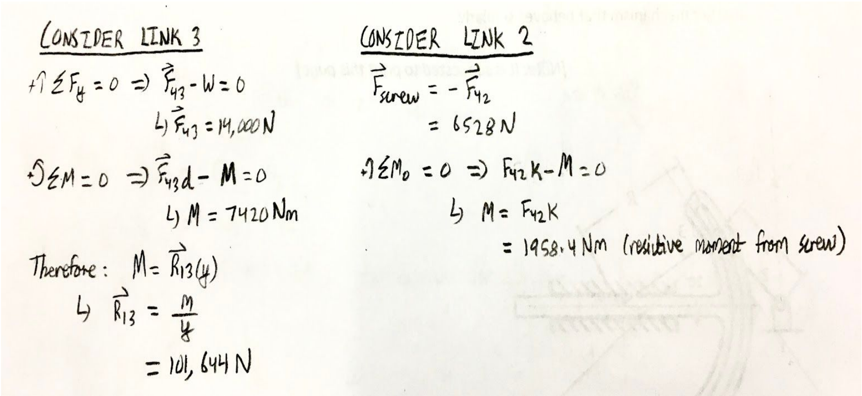


Figure 8: Free body diagrams of links 3, 4 and 2.



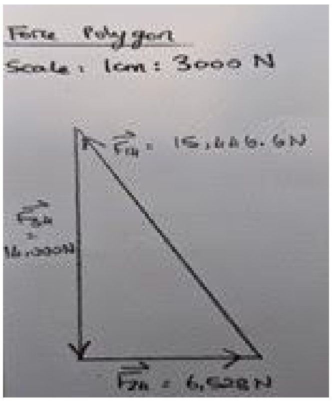


Figure 9 and 10: Force calculations for links 3 and 2 and Link 4 force polygon

To find the torque of the input screw, the following formula was used [3]:

$\tau = \frac{F_{screw} \times p}{2\pi \times \eta \times 1000}$, where: p = pitch of screw and η = efficiency

$= \frac{6528N \times 6mm}{2\pi \times 0.26 \times 1000}$ = 24Nm

Thus, the input force is: $F_{input} = \frac{\tau}{R}$, where: R = length of the input handle

$= \frac{24\,Nm}{0.5m}$ = 48N

4.3 Validation of Objectives and Constraints:

The following table was used to verify features of the proposed mechanism in comparison to the objectives targeted. The objectives were all given equal priority thus no ranking system has been included.

Number	Constraint	Objectives	Result
1	Requires a constant input force through lifting cycle	-	Constant Turning Force
2	-	Deployment Time of 72s - 80s	Deployment time of 164s
3	-	Support a Minimum Load of 14,000N	Supports at least 14,000N

4	-	Provide an Upwards Linear Output Trajectory	Provides an Upwards Linear Output Trajectory
5	-	Maximum Input Force of 220 N Required	Input of 48N required
6	-	Displacement of >=20cm from a starting height of 20-25cm	Allows for a displacement of 20cm from a starting height of 24.7cm

Table 2: Validation of Mechanism Based on Objectives and Constraints

As mentioned in section 2.1 of the document, it was concluded that the reason for the varying input force was due to a constant change in angle between the links and screw as the mechanism was in motion. Thus, in order to achieve a constant input force and satisfy the constraint, the proposed design exhibits a constant angle between the links and screw throughout the complete motion.

From the above table, it can be concluded that the majority of results achieved satisfy the objectives. However the differences in some objectives and their respective results were attributed to large approximations made during the analysis of both mechanisms. For example, the velocity analysis of the scissor jack involved using vector polygons to complete a graphical analysis and then averaging the speeds at different points in the lifting process. Instead, the team could conduct a vector loop analysis. Using this analytical method could reduce the inherent uncertainties of the original graphical analysis, resulting in a smaller difference between the objective and result for the mechanism deployment time. Furthermore, it should be noted that the deployment time of the proposed mechanism can be reduced by increasing the angle between link 1 and the horizontal. However, this would result in the mechanism being taller and unable to fit under the average car.

The team could also employ a practical approach to analyse the velocity of link B (see Figure 1). A suitable car model which is widely used globally is the “Toyota RAV-4” which weighs 1545 kg [7]. The mechanism used to lift the vehicle will be the “Big Red Scissor Jack”, which was the specified model in the problem statement. The team can measure the time taken for link B to travel from the lower limit position to the upper limit position. As the distance travelled by link B is known,the average velocity can be calculated and a precise deployment time can thus be deduced. The derived result would be a more feasible objective value for the proposed mechanism to achieve.

5.0 Conclusion:

The proposed design allows for a constant input force, satisfying the constraint and solving the client’s problem. However, in solving this problem, the design has a deployment time of 164 seconds which is twice as long as that of the scissor jack. This was mainly due to the assumptions made during the analysis that brought about significant uncertainty when comparing the current and proposed designs.

Nonetheless, this does not undermine the design since 164 seconds is a reasonable lifting time for a large load of 14,000N. The design provides an upward linear output with a stroke of 20cm from a starting height of 24.7cm. Thus, objectives 4 and 6 were achieved. The force analysis revealed that the design requires 48N of input force to lift 14,000N. Therefore, objectives 3 and 5 were met.

Overall, taking the assumptions and simplifications into account, this design is well suited for its purpose and the major constraint was met. The team recommends that the client reviews this document and provides feedback on the results of the analyses and respective assumptions undertaken. Using this feedback, the team will improve on the theoretical design, perform material research and create a physical prototype with which the client can perform tests. The team will then iterate this prototype until the client is satisfied.

6.0 References:

[1] I. Wagner, Number of licensed drivers in Canada 1994-2018, Transportation and Logistics, 20, April, 2020. [Online]. Available: https://www.statista.com/statistics/448557/number-of-licensed-drivers-in-canada/#statisticContainer. [Assessed Nov. 10, 2020].

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