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SIZING OF A PNEUMATIC MECHANISM FOR STRETCHER LIFTING ASSISTANCE

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Abstract

The work of paramedics is physically demanding. Lifting a stretcher from the ground puts strain on the back and waist, which can lead to injuries over time. Our goal is to develop a support system that assists paramedics in the most difficult phase of lifting by using pneumatic actuators. The system operates with compressed air, which is refilled by a built-in compressor. In this project, we modeled the system and performed the necessary calculations to find the optimal solution.

Keywords*: stretcher, ambulance service, pneumatics, modeling.*

1. Introduction

The care of injured or ill individuals typically does not take place where the injury occurred or where the illness was contracted, but rather at a designated facility, namely a hospital. However, patients must be transported there, which requires the use of various transport vehicles, such as ambulances. One challenge can be getting the patient to the vehicle in the first place.

Since the goal is to minimize movement of the injured person in order to avoid worsening their condition, patients are transported lying down whenever possible, to prevent complications. For this purpose, a special stretcher is used, which can be folded down closer to ground level. This makes it easier and safer to place the patient on the stretcher, especially in cases where they are lying on the ground, which is common during accidents. After that, the stretcher—with the patient on it must be lifted from the ground and placed into the ambulance for transport.

This lifting operation is usually performed by two paramedics, positioned at either end of the stretcher. The process can be especially physically demanding, as it often involves lifting heavy weights, and must be repeated several times a day. Over time, this work can lead to various health problems, such as back pain, spinal injuries, and hernias.

This issue prompted us to look for a solution that would help paramedics in their work while protecting their health. The idea is to equip the stretcher with a system that assists in the lifting process, reducing the load that paramedics have to bear.

The task, therefore, is to supplement the stretcher with a system that helps during the first and most critical phase of lifting—approximately the first 30 to 40 centimetres. It is also important that the system be easy to install, so that major modifications to the stretcher are not required. Furthermore, it is important that the system be as lightweight as possible.

We concluded that a pneumatic system would be suitable for this task, as pneumatic actuators can be controlled quickly and have a relatively low weight compared to the force they can exert. A pneumatic system could also make it easier to design a control mechanism where the speed of lifting is primarily determined by the paramedics themselves.

For example, if the system is capable of lifting 80 kilograms on its own and a 90-kilogram patient is placed on it, the stretcher will not begin to rise until the paramedics assist with an additional force equivalent to more than 10 kilograms. In such a case, there is a significant benefit to having a stretcher equipped with an assistive lifting system.

With these considerations in mind, we examined a specific stretcher model and studied how it could be equipped with a mechanism capable of fulfilling this task.

2. The stretcher model

Since one of our main goals is to develop a functional physical system, our first priority when starting the project was to acquire a paramedic stretcher that we could use as a prototype.

This was important not only to have a tangible device on which we could perform measurements and carry out modifications, but also to ensure that we are working with a type of stretcher that is actively used in our environment, making the model relevant and up to date.

The examined stretcher is shown in **Fig.1** and is a Medirol-branded model.

Following this, we created a three-dimensional model of the stretcher. This was done in Autodesk Inventor using reverse engineering techniques, as we were working with an existing product for which no documentation or CAD model was available. Therefore, we constructed the model through a series of measurements, aiming to replicate the real stretcher's dimensions and movements as accurately as possible. This is illustrated in **Fig. 2**.

The front two and rear two legs of the stretcher are connected, meaning they can move together. Additionally, the front and rear legs are linked by a central rod, so all the legs move simultaneously.

Next came the design and sizing of the mechanism. This task was significantly simplified by the 3D model, as it allowed the motion to be examined from multiple perspectives and provided a clear understanding of the feasibility of integrating additional mechanisms.

To find the optimal solution, we explored several possible designs to assess their feasibility and functionality. Based on this analysis, we were able to determine which version would be the most worthwhile to develop and improve further.

3. Study of recommended solutions

3.1. I^st recommended solution

In the first proposed solution, a disc is attached to the rod that connects the two legs. A pneumatic actuator is mounted on each side of the disc, with their other ends fixed to the frame of the stretcher near the lying surface.

This configuration in its folded state is shown in **Fig. 3** and in its fully extended state in **Fig.4**.

Fig. 1. *The Medirol brand stretcher.*

Fig. 2. *Model of the stretcher.*

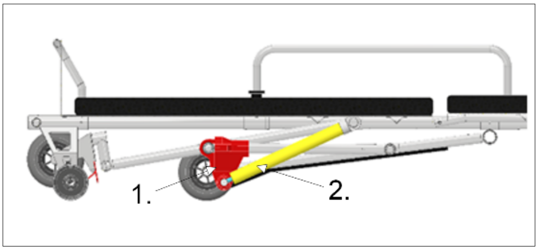

Fig. 3. *I^st. recommended solution in the folded position: 1. Disk, 2. Hydraulic cylinder.*

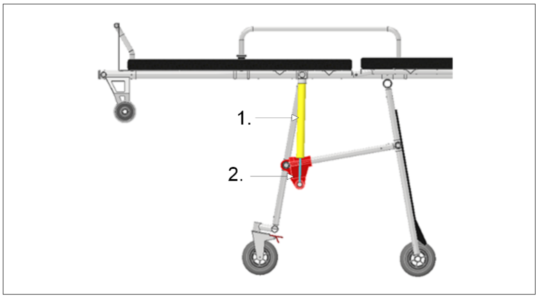

Fig. 4. *I^st. recommended solution in the extended position: 1. Hydraulic cylinder, 2. Disk.*

The concept here is to apply force to the rod connecting the legs using the pneumatic actuators. Lifting is achieved by pulling the central rod, which forces the mechanism to open.

In addition to creating the model, we also performed some calculations related to the sizing of the pneumatic actuators [1].

$$G_t = G \cdot \cos\alpha = 800 \cdot \cos 14 = 776.23\ N \quad (1)$$

$$M_{G_t} = G_t \cdot l_G = 776.23 \cdot 0.416 = 322.91\ Nm \quad (2)$$

$$M_{G_t} = M_{F_m} \quad (3)$$

$$M_{G_t} = F_m \cdot l_F \quad (4)$$

$$F_m = \frac{M_{G_t}}{l_F} = \frac{322.91}{0.114} = 2832.58\ N \quad (5)$$

$$p_m = \frac{F_m}{A_m} \quad (6)$$

$$A_m = \frac{F_m}{p_m} = \frac{2832.58}{0.8} = 3540.67\ mm^2 \quad (7)$$

$$A_m = \pi \cdot \frac{D_m}{2} \quad (8)$$

$$D_m = 2 \cdot \sqrt{\frac{A_m}{\pi}} = 2 \cdot \sqrt{\frac{3540.67}{\pi}} = 67.14\ mm \quad (9)$$

where:

- G the applied force;
- G_t the component of the applied force perpendicular to the lever arm;
- α is the angel between G and G_t;
- M_{Gt} is the torque exerted by the force G_t around the upper joint of the left leg;
- l_G is the lever arm corresponding to the force G_t;
- F_m the force created by the cylinder;
- M_{Fm} is the torque applied by the force F_m at the joint of the middle rod on the pulley side, this exerts an effect on the connecting rod;
- l_F is the lever arm corresponding to the force F_m;
- p_m the pressure occurring in the hydraulic cylinder;
- A_m piston surface area;
- D_m diameter of the piston.

After analysing the results of the calculations, we concluded that this solution would require excessively high force and a large actuator.

On one hand, the operation would place too much strain on the stretcher's frame structure, and on the other hand, a large-diameter actuator would also mean increased weight—especially when factoring in the air tank.

For these reasons, we began to look for an alternative solution.

3.2. 2nd recommended solution

In the second recommended solution, we applied the same logic as in the first one, which is to pull the connecting rod and lift the bed through it. A picture of this in the folded position can be seen in Fig. 5.

These two solutions were developed in parallel, as the calculations related to actuator sizing are the same in both cases. This means that the required actuator size and the forces involved are identical. The difference between the two solutions lies in the orientation of the actuator and the fact that, in this case, the mechanism is operated using a single actuator. The mechanism in its open position is shown in Fig. 6.

Since in this case we are also talking about excessively large forces, we rejected this solution as well and started to examine the situation from a different approach.

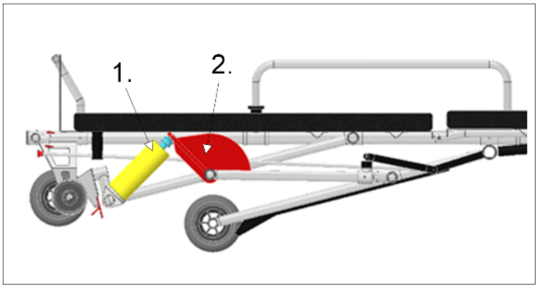

Fig. 5. 2nd. recommended solution in the folded position: 1. Hydraulic cylinder, 2. Disk.

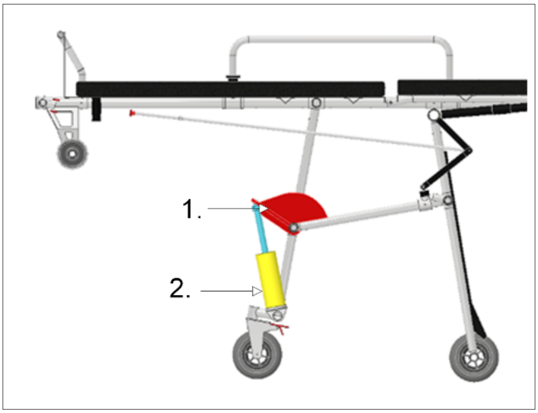

Fig. 6. 2nd. recommended solution in the extended position: 1. Disk, 2. Hydraulic cylinder.

3.3. 3rd recommended solution

In the third solution, the idea was to mount one end of the hydraulic cylinder to the rod connecting the two rear legs, and the other end to the bed's sleeping surface. This implementation is shown in **Fig. 7.**

In this case, to size the hydraulic cylinder, we examine whether the force exerted by the cylinder at the joint where the rear leg connects to the sleeping surface creates enough torque to counterbalance the torque exerted by the load at the same joint. The mechanism in the open position is shown in **Fig. 8**.

$$M_G = G \cdot l_G \tag{10}$$

$$M_{F_m} = F_e \cdot l_{F_m} \tag{11}$$

$$F_e = F_m \cdot \cos\beta \tag{12}$$

$$G \cdot l_G = l_{F_m} \cdot F_m \cdot \cos\beta \tag{13}$$

$$F_m = \frac{G \cdot l_G}{l_{F_m} \cdot \cos\beta} = \frac{800 \cdot 0.814}{0.411 \cdot \cos 65} = 4224.91\ N \tag{14}$$

$$p_m = \frac{F_m}{A_m} \tag{15}$$

$$A_m = \frac{F_m}{p_m} = \frac{4224.91}{0.8} = 5281.13\ mm^2 \tag{16}$$

$$A_m = \pi \cdot \frac{D_m}{2} \tag{17}$$

$$D_m = 2 \cdot \sqrt{\frac{A_m}{\pi}} = 2 \cdot \sqrt{\frac{5281.13}{\pi}} = 82.0\ mm \tag{18}$$

where:

- G the load;
- β is the angle between F_m and F_e;
- M_G the torque created by the load force;
- l_G is the lever arm corresponding to the M_G force;
- F_m the force exerted by the cylinder;
- F_e is the component of F_m that is perpendicular to the lever arm and performs the lifting;
- M_{Fm} the torque exerted by the hydraulic cylinder, around the upper joint of the left leg;
- l_{Fm} the lever arm corresponding to the torque M_{Fm}.

After performing the necessary calculations for sizing, we found that the results were even more unfavourable than the previous ones. This meant that we needed to find an alternative solution in order to find the optimal one.

3.4. 4th. recommended solution

In the previous solutions, the hydraulic cylinder had to exert a large force, which resulted in it needing to have a large mass and size. Therefore, we sought a method that would reduce the force exerted by the hydraulic cylinder.

One solution to this is to use lifting pulleys, as with a lifting pulley, the exerted force can be doubled. With this, we can create a pulley system that increases the exerted force (**Fig.9**).

According to the design of the model shown above, the rope, which passes through the pulleys, is fixed at one end, while the other end is attached to the rod of the hydraulic cylinder.

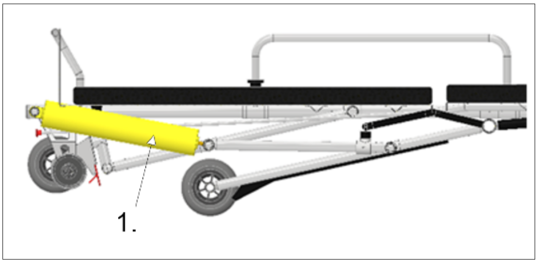

Fig. 7. *3nd. recommended solution in the folded position: 1. Hydraulic cylinder, 2. Disk.*

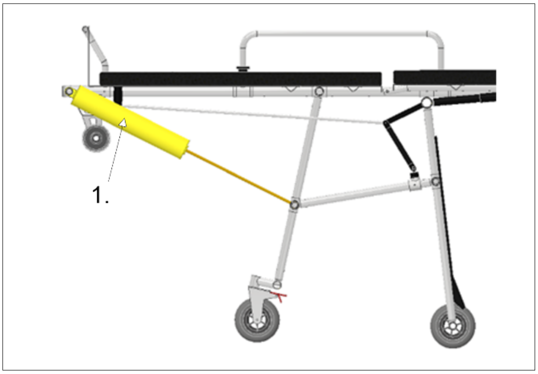

Fig. 8. *3nd. recommended solution in the extended position: 1. Hydraulic cylinder.*

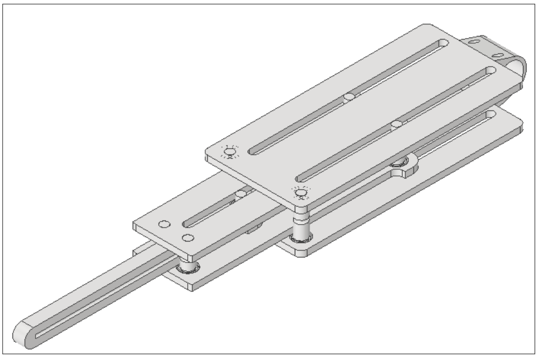

Fig. 9. *Csometric view of the pulley lifting system.*

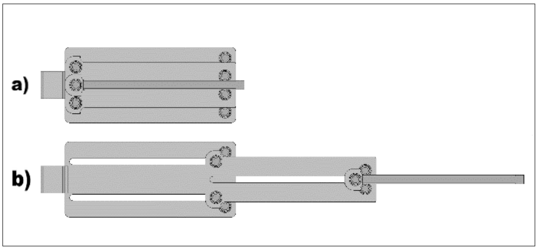

Fig. 10. *Pulley system: a) open position and b) collapsed position.*

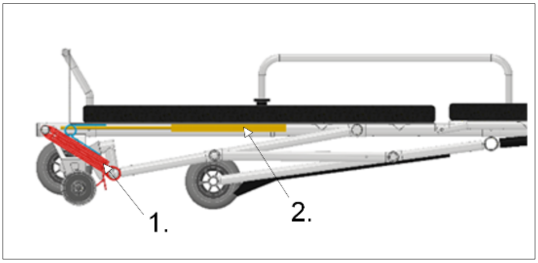

Fig. 11. *4$^{th.}$ Recommended solution in the collapsed position: 1. Pulley mechanism, 2. Hydraulic cylinder.*

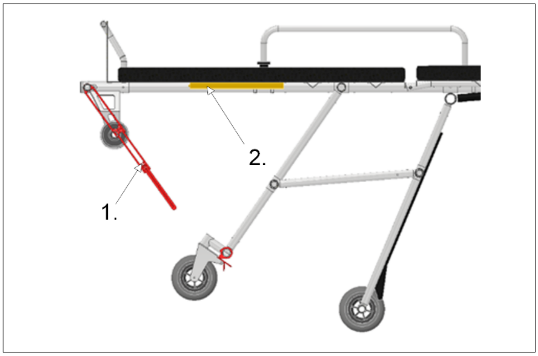

Fig. 12. *Partially extended position: 1. Pulley mechanism, 2. Hydraulic cylinder.*

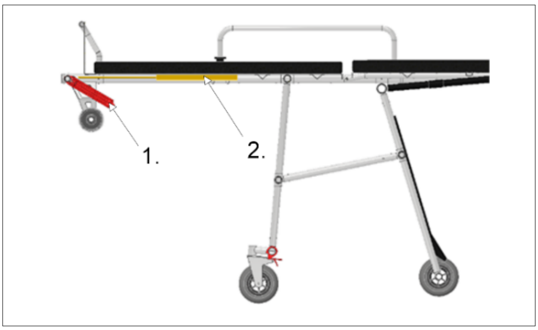

Fig. 13. *Fully raised position of the stretcher: 1. Pulley mechanism, 2. Hydraulic cylinder.*

A cross-section of the pulley system in its collapsed state can be seen in **Fig. 10.a.** In this case, two lifting pulleys are connected to each other, allowing us to increase the force with which we pull the rope by four times. The lift can extend approximately 2.5 times compared to the collapsed state. **Fig. 10.b.** shows the system in its fully extended state.

This pulley system is installed in a similar way to how the pneumatic actuator was installed in the previous solutions. However, in this case, the actuator is attached to the lying surface of the stretcher, i.e., to the bottom of the stretcher. The actuator will pull the rope of the pulley system, causing it to open as a result.

Fig. 11 shows the system in its collapsed state. Our initial thought was to position the pulley system so that it would be perpendicular to the force arm in order to achieve a greater torque. However, in this case, we had limited space, and the useful lifting height would have been too small. Therefore, we placed it as shown in **Fig. 12.** With this arrangement, we can lift the bed by about 30 centimetres. Another advantage of this solution is that we can attach the end of the pulley system to an existing rod.

When the pulley system is fully extended, the legs are not completely opened yet. The pulley system only rests on the rod connecting the legs, but it is not securely attached, allowing the legs to be fully extended once the lifting system reaches its maximum extension. After this, the paramedics would need to lift the bed using their own strength, but by this point, they are beyond the critical lifting height. This intermediate position is shown in **Fig. 12.**

For the hydraulic cylinder to pull the rope, its extended position must be the default. That is, when the hydraulic cylinder rod retracts, it also pulls the rope along with it. By pulling the rope, the pulley mechanism opens, which in turn assists in lifting the stretcher. Once the lifting mechanism is fully extended, the legs still need to be fully opened. While the stretcher legs lower completely, the pulley mechanism also retracts back to its starting position, assisted by a spring that compensates for the weight of the mechanism. The hydraulic cylinder rod then extends, ensuring that the mechanism can collapse. Thus, it returns to its original state. The fully extended position is shown in **Fig. 13.**

The bed's collapsed height from the ground is 286 mm. Once the pulley system reaches its maximum lifting extension, the bed reaches a height of 622 mm. This means we can lift it by 336 mm. If the legs are fully extended, the bed will be 884 mm high. In other words, with the system in place, the paramedics need to lift the bed by 262 mm from a height of 622 mm. This is a significantly more favourable situation compared to performing the same task without the system.

For this solution, we also performed the hydraulic cylinder sizing, which was done in a similar way to the previous solution.

$$M_G = G \cdot l_G \tag{19}$$

$$M_{F_{cs}} = F_e \cdot l_{F_{cs}} \tag{20}$$

$$F_e = F_{cs} \cdot \cos\beta \tag{21}$$

$$G \cdot l_G = l_{F_{cs}} \cdot F_{cs} \cdot \cos\beta \tag{22}$$

$$F_{cs} = \frac{G \cdot l_G}{l_{F_{cs}} \cdot \cos\beta} = \frac{800 \cdot 0.814}{0.71 \cdot \cos 60} = 1857.9\ N \tag{23}$$

$$F_m = \frac{F_{cs}}{4} = \frac{1857.9}{4} = 464.47\ N \tag{24}$$

$$p_m = \frac{F_m}{A_m} \tag{25}$$

$$A_m = \frac{F_m}{p_m} = \frac{464.47}{0.8} = 580.59\ mm^2 \tag{26}$$

$$A_m = \pi \cdot \frac{D_m}{2} \tag{27}$$

$$D_m = 2 \cdot \sqrt{\frac{A_m}{\pi}} = 2 \cdot \sqrt{\frac{580.59}{\pi}} = 27.189\ mm \tag{28}$$

where:

- G is the load;
- β the angle between F_m and F_e;
- M_G the torque exerted by the load force;
- F_{cs} the force exerted by the pulley system;
- l_G the lever arm corresponding to the torque M_G;
- F_m the force exerted by the cylinder;
- F_e is the component of F_m that is perpendicular to the lever arm and performs the lifting;
- M_{Fm} the torque exerted by the hydraulic cylinder;
- l_{Fm} the lever arm corresponding to the torque M_{Fm}.

It is evident that with the introduction of the pulley system, the size of the hydraulic cylinder and the force it needs to exert have been significantly reduced, as the results of the above relationships show [2]. Based on this, we looked into whether such a component is available on the market. According to the usage criteria, a 32 mm diameter, 310 mm stroke length hydraulic cylinder from the MB Series [3], can be used, which is shown in Fig. 14.

Another important sizing task was determining the dimensions of the pulley mechanism. Here, we examined the shear and deflection of the pulleys' axes, as well as calculated their maximum deflection. Based on this, we determined the appropriate diameter with an adequate safety factor for the given length. We considered the largest load and designed according to all the pulley axes. Then, we calculated the required wall thickness around the respective axes. After that, we sized the thinnest element of the pulley system for deflection and compression.

For the pulleys and their axes, we chose S275 structural steel (EN1993-1-1), which has a tensile strength of 370-530 MPa (ultimate), an allowable deflection stress of 275 MPa, and a Young's modulus of 210 GPa [4]. For the framework of the pulley system, we selected AlMg (EN-AW 5083), which has a crushing strength of 159 MPa (ultimate_crushing) and a Young's modulus of 72 GPa [5]. The necessary calculations are shown below.

$$M = F \cdot \frac{l}{2} = 928.5 \cdot \frac{15}{2} = 6963.75\ Nmm^2 \tag{29}$$

$$\sigma = \frac{M}{\frac{\pi \cdot d^3}{32}} \tag{30}$$

$$\tau = \frac{F}{\frac{\pi \cdot d^2}{4}} \tag{31}$$

$$\sigma_{ekv} = \sqrt{\sigma^2 + 4 \cdot \tau^2} \tag{32}$$

$$\sigma_{ekv} = \sqrt{\frac{1024 \cdot M^2}{\pi^2 \cdot d^6} + \frac{64 \cdot F^2}{\pi^2 \cdot d^4}} = \sqrt{\frac{1024 \cdot 6963.75^2}{\pi^2 \cdot 5.5^6} + \frac{64 \cdot 928.5^2}{\pi^2 \cdot 5.5^4}} = 433.444\ \frac{N}{mm^2} < \sigma_{krit} \tag{33}$$

Fig. 14. *MB Series cylinder (∅32×310).* [3]

$$I_z = \frac{\pi \cdot d^4}{64} = \frac{\pi \cdot 5.5^4}{64} = 20.128\ mm^4 \tag{34}$$

$$\upsilon = \frac{2 \cdot F \cdot l^3}{48 \cdot E \cdot I_z} = \frac{2 \cdot 928.5 \cdot 15^3}{48 \cdot 210000 \cdot 20.128} = 0.0502\ mm \tag{35}$$

where:
- F is the half of the load;
- M the torque exerted by the load;
- σ bending stress;
- τ shear;
- l the lever arm corresponding to the torque M;
- σ_{ekv} combined shear and bending stress;
- I_z second-order torque;
- E Young-modulus;
- υ maximum deflection.

Based on the above calculations, it is clear that if we consider the diameter to be 5.5 mm, the stress values remain below the allowable limits. We then multiplied this diameter by a safety factor of 1.27 and chose a shaft diameter of 7 mm.

Next, we examined the required wall thickness around the shafts. Taking into account this diameter and the largest load force, we selected a radial bearing from SKF [6], with an inner diameter of 7 mm and an outer diameter of 14 mm. For simplicity, we equipped all the shafts with such bearings. When determining the wall thickness, we based our calculations on the outer diameter of the bearing.

$$\sigma_{sh} = \frac{2 \cdot F}{b \cdot (d_1 - d_2)} = \frac{2 \cdot 928.5}{5 \cdot (24 - 14)} = 18.579\ \frac{N}{mm^2} < \sigma_{krit\_zuzó} \tag{36}$$

where:
- F is the half of the load;
- b the height of the plate;
- σ_{sh} crushing stress;
- d_1 outer diameter;
- d_2 inner diameter.

It is evident that with the given diameter, the wall thickness is well below the allowable crushing stress limit. Therefore, we designed the mechanism with this wall thickness.

An important part of the sizing was ensuring that the last rod connecting to the leg had the proper size, as this piece has the smallest cross-sectional area and bears the greatest load. For this reason, we examined it for deflection and compression.

$$\sigma_{def} = \frac{F \cdot L}{A \cdot E} = \frac{1857.9 \cdot 199.5}{75 \cdot 72000} = 0.0686\ mm \tag{37}$$

$$I_z = \frac{y \cdot x^3}{12} = \frac{5 \cdot 15^3}{12} = 1402.25\ mm^4 \tag{38}$$

$$\sigma_{kih} = \frac{F \cdot \frac{L}{2}}{\pi^2 \cdot E \cdot I_z} = \frac{1857.9 \cdot \frac{199.5}{2}}{\pi^2 \cdot 72000 \cdot 1402.25} = 0.074\ mm \tag{39}$$

where:
- F is the load;
- L the length of the rod;
- σ_{def} degree of compression;
- σ_{kih} degree of deflection;
- A area, square profile;
- x height, larger value;
- y width, smaller value;
- E Young-modulus;
- I_z second-order torque.

According to these calculations, the width and height of the last rod meet the requirements, as only a small deflection appears at the centre. Based on this, we created the model of the pulley mechanism.

Before finalizing the shape of the pulleys, we needed to determine the diameter of the rope we wanted to use for the operation. The most obvious choice for this is steel wire. We searched for a product that meets the requirements, i.e., one that can withstand the given load. In the model, we considered a 3 mm diameter DIN 3055 standard anchor steel wire, which has a tensile strength of 1770 MPa [7]. Based on this, we can calculate its maximum load capacity.

$$A = \frac{\pi \cdot d^2}{4} = \frac{\pi \cdot 3^2}{4} = 7.07\ mm \tag{40}$$

$$F_{max} = A \cdot R = 7.07 \cdot 1770 = 12552\ N \tag{41}$$

$$F_{meg} = \frac{F_{max}}{n} = \frac{12552}{5} = 2504\ N \tag{42}$$

where:
- A is the cross-sectional area of the wire rope;
- d diameter of the wire rope;
- F_{max} the total tensile force;
- F_{meg} the permissible load force;
- n the safety factor.

The above calculations show that this type of steel wire is suitable for the task. After performing the preliminary calculations, we started modelling the pulley system in the three-dimensional design software. With this, we supplemented the existing assembly of the stretcher and obtained the model of the fourth recommended solution, which is the most favourable case so far.

4. Conclusions

At this point in the research, we have four different recommended solutions, each of which was analysed and discussed individually. In the first three cases, we found that a very large hydraulic cylinder would be required, and the force needed for lifting also turned out to be too high. It can be stated that so far, the last solution has proven to be the most favourable.

Going forward, it would be worth investigating what other options are available for integrating a mechanism. It could also be worth exploring whether it would be beneficial to install the lifting system elsewhere on the frame. In any case, the pulley lift is worth considering for other potential solutions as well.

Another possible direction for continuation would be to conduct a strength analysis of the bed's mechanism, which could show where the structural stress points are. Based on this, it could be determined whether reinforcements should be applied to the frame and, if so, where.

At the same time, it is worth focusing on developing the control system. In the current design, regardless of the load mass, the hydraulic cylinder exerts the same force. However, it would be more advantageous if this force varied proportionally with the load, and for this, a self-regulating solution would need to be developed, which would improve the system's performance.

Since one of the primary goals is to bring the research to fruition, it is important to find the optimal variant while considering both the assembly and load-bearing aspects.

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