1 Design of shoulder prosthesis

1.1 Explanation design

The goal of the project is to design a shoulder prosthesis using flexure mechanisms. The design consist of 6 wire flexures. These wire flexures are placed under an angle and the upper and the lower part of the design are connected to each other in the middle. (See figure 1) Both structures have three translational constraints and three rotational degrees of freedom (DOF's) at the connection point in the middle. The structure can thus rotate in the x,y and z- direction. This mechanism has the same DOF's as a ball joint, similar to a shoulder (prosthesis). It can rotate in the y and x-direction about 90 °and 45 °in the z-direction, without creating stresses that exceed the yield strength. The height of the structure is ca. 12 cm and the radius of the circle is ca. 7cm. These dimensions are small enough to fit inside a body. A satisfied requirement of the mechanism is that it should be able to withstand a force of 300N in the z-direction. This force is chosen because it resembles the gravitational force of a 30 kg mass. 30 kg might seem like a small mass considering that the world strongest man can lift a mass of 500kg. But it is not his shoulder joint that has to take this load. The shoulder tendons and muscles have to be able to withstand this load. The prosthesis only has to prevent the shoulder from dislocating and thus a force of 300N should be enough.

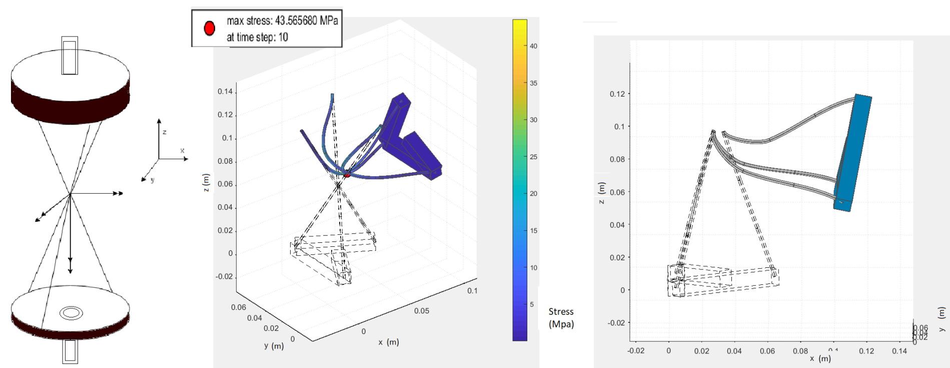

Figure 1: The design of the shoulder prosthesis (middle and left) and design with only lower half

1.1.1 Strong and weak points of the design

A strong point of the design is that it is relatively simple. Also the angle at the connection points of the wire when subjected to an external load will not get to large contrary to a design which consist of only the upper or lower half of this design. (see right figure in figure 1). Since this angle stays relatively small, also the stresses in those connection points stay relatively small compared to a design consisting of only the upper or lower half of this design. The structure can be attached to the bones using a bolt. This bolt will be located at the center of the circle. (See figure 1) When rotating the arm in the most outward position or when rotating the arm around the z-axis, shortening could become a problem. Nevertheless, the arm in a human body is attached to the body in a flexible way, relatively small deflections should not be a problem.

A stress concentration at the connection point in the middle of the mechanism is present during rotation. Still, the structure can rotate without exceeding the yield strength with the set requirements. It is recommended to make this connection point in the middle of the mechanism thicker. This will result in a smaller stress concentration and a larger safety factor.

1.2 Design explanation of shoulder prosthesis

Since the flexure wires are not placed parallel, it is harder to hand-calculate the maximum stresses and deflections. Therefore the problem will be simplified in order to perform the hand-calculations. During deflections in the x-direction, it is assumed that only the lower half of the design moves. (see figure 1) The maximum stress calculations in the z-direction will be done on the top half of the design. It is assumed that the same maximum stresses will be obtained as if the whole design would have been considered. To calculate the stress in the connection point in the middle of the mechanism, the total force is divided by the area of this connection point, which is assumed to be 1.3 times the area of a flexure wire. Because of the rigid body, the forces perpendicular to the wire flexure are neglected in the left of figure 2. (Thereby also the moment). Furthermore, during bending (see right figure 2) the forces parralel to the wire flexure are neglected, because of the small contribution to the deflection. Buckling is not analysed, because muscles prevent buckling from happening during compression. The material chosen is PA46, a nylon. [1] The structure's height is ca. 12 cm and the distance between the wire flexures is 6 cm. The wire flexures have a diameter of 2.1 mm. It is not certain if the chosen material can be 3D printed.

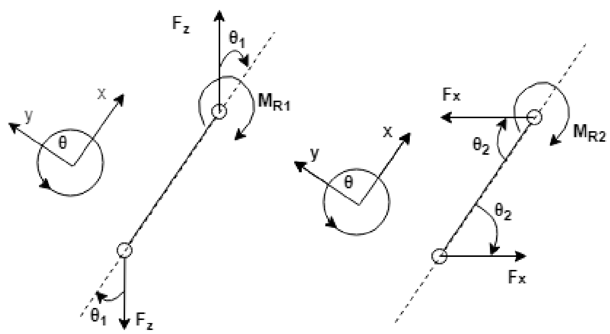

Figure 2: Simplified free body diagrams of a force applied in the z-direction (left) and x-direction(right)

1.2.1 Bending with a force of 1 N in the x-direction

$$v(x) = -\frac{F_x \cdot sin(\theta_2) L x^2}{2EI} + \frac{F_x \cdot sin(\theta_2) x^3}{6EI} \qquad (I = \frac{\pi D^4}{64}) \tag{1}$$

Filling in equation 1 for L is the length of one wire flexure gives:

$$v(0.0695) = -\frac{\frac{1}{3} \cdot sin(56) \cdot 0.0695 \cdot 0.0695^2}{2 \cdot 0.6e9 \cdot \frac{\pi 0.0021^4}{64}} + \frac{\frac{1}{3} \cdot sin(56) \cdot 0.0695^3}{6 \cdot 0.6e9 \cdot \frac{\pi 0.0021^4}{64}} = -0.0540m \tag{2}$$

The stiffness is the force divided by the dispacement:

$$k = \frac{F}{v} = \frac{1}{0.0540} = 18.5kN/m \tag{3}$$

1.2.2 Applying a force of 300N in the z-direction

$$u(L) = \frac{FL}{AE} = \frac{F_z \cos\theta_1 L}{AE} = \frac{\frac{-300}{3} \cdot \cos 34° \cdot 0.0695}{\pi \cdot 0.00105^2 \cdot 0.6 \cdot 10^9} = -0.0055m \tag{4}$$

The wireflexure can only move in the z-direction, because of the connection with the rigid body when pulled. Thereby the deflection has to be corrected to be able to compare it to the Spacar model.

$$v_{corrected}(x) = (x^2 - (d)^2)^{0.5} - ((x + u(L))^2 - d^2)^{0.5} = -0.0064 \quad (d = diameter\, of\, circle(figure1)) \tag{5}$$

The stiffness is thereby:

$$k = \frac{F_z}{v} = \frac{300}{0.0064} = 47kN/m \tag{6}$$

Stress inside the middle point of structure:

$$\sigma = \frac{F}{A} = \frac{\cos\theta_1 \cdot F_z}{\pi r^2} = \frac{\cos 34° \cdot 300}{\pi \cdot 0.00105^2 \cdot 1.3} = 42MPa \tag{7}$$

[1] CES edupack 2017, Granta Design Limited, 2017

1.3 Design shoulder prosthesis in Spacar

As shown in figure 1 the model consists of six flexure wires. These six flexure wires are connected at three connection points. One connection point is located in the middle. The three flexure wires on the lower half are connected to the upper arm. The three flexure wires on the upper half are connected to the glenoid (shoulder bone). This is simulated as the fixed world. The upper arm is simulated as a rigid body in spacar. This rigid body was supposed to have the shape of an equilateral triangle, but since it is not possible in spacar to connect those three rigid bodies to form an equilateral triangle, the model shown in figure 3 was designed. This model has a non-closed rigid body ending in the centre of the design such that the external forces can act at that point, equally distributing the forces over the whole design. By thickening this rigid body, there will not be a stress concentration there, allowing to find the maximum stress concentration in the wire flexures. Three types of calculations will be used for this model. First deflection and stress will be calculated in the z-direction. The deflection will be used to find the stiffness in the z-direction. Next the deflection will be calculated in the x-direction, which will be used to find the stiffness in the x-direction. At last, the stresses during rotation will be calculated.

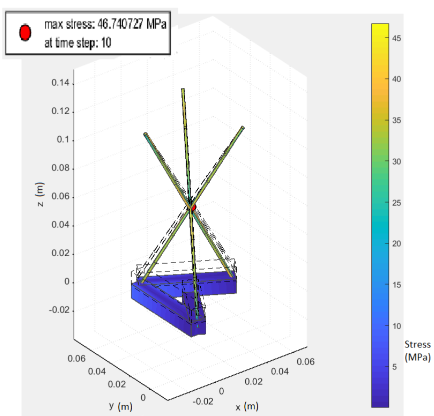

Figure 3: Shoulder prosthesis in Spacar, applying -300 N in z-direction

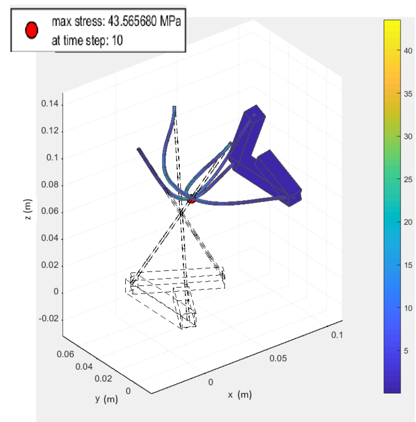

Figure 4: Maximum stress in middle when bending 100 degrees

1.3.1 Carrying a load of 300 N

When applying a load of -300 N (see figure 3) at the tree connection points of the rigid body, a displacement of -0.0087 m in the z-direction occurs according to Spacar. The stiffness of the structure along the z-axis is thereby 34 kN/m. The manual calculation result in a displacement of -0.0064 m, which gives a stiffness of 47 kN/m. The small difference tells us that the simplified model of the structure used in the manual calculations closely resembles the model produced in Spacar.
When applying a load of -300 N distributed over the 3 wireflexures, Spacar gives a stress of about 47 MPa in the middle (see figure 3). The manual calculation gives a stress of 42 MPa. The small difference tells us that the simplified model of the structure used in the manual calculations closely resembles the model produced in Spacar.

1.3.2 Applying a 1 N load in the x-direction

When applying a load of 1 newton in the x-direction of the structure, the resultant displacement (combining x-, z-, and y-deflection) gives 0.061 m and thus a stiffness of 16,4 N/m. The manual calculations give a displacement of 0.054 m and a stiffness of 19 N/m. The small difference tells us that the simplified model of the structure used in the manual calculations closely resembles the model produced in Spacar.

1.3.3 Additional stresses

When bending the structure about 100 degrees, the stresses in the middle are about 44 MPa. (see figure 4). Furthermore, when the structure is rotated 50 degrees about the z-axis, the maximum stress is 15 Mpa. Both will not exceed the yield strength. Thereby the structure can handle those rotations.