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A gravity balancing assistant arm design in 3-D for rehabilitation of stroke patients

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Abstract. A gravity balancing assistant arm design in 3-D is a mechanical mechanism consisted of springs, rigid rods, joints and sliders, which can be modified to the geometry and inertia of the arm of stroke patients. This mechanism is designed without any controllers and motors, based solely on mechanical principles, to achieve a relative balance of gravitational potential energy and elastic potential energy, thereby reducing the burden on the arm of a stroke patient to facilitate rehabilitation. To achieve this function, first, the center of gravity of the patient's arm will be positioned, and then the mounting position of the spring on the assistant arm will be determined. In this paper, the following objectives will be achieved: (i) the calculation of the gravitational potential energy and the elastic potential energy in the mechanism (ii) the simplification of the potential energy equation and the elimination of the coefficient of the items related to the angle. (iii) The comparison between 2-D and 3-D cases of the mechanism. (iv) The motion process of simulating the mechanism using MATLAB (v) Using MATLAB to create the energy plots (vi) Using SolidWorks to construct the prototype of the mechanism (vii) Describe the practical application and future extensions of this mechanism.

1 Introduction

The gravity balancing mechanism means that in a set of mechanisms composed of springs, rigid links, joints and sliders, where the sum of the gravitational potential energy and the elastic potential energy is kept constant. [1]This mechanism is widely used in industrial and medical rehabilitation. [2]For example, in industrial, it is usually necessary to balance robotic arm's own gravity to achieve more precise control objectives. [3]In a rehabilitation field, gravity balance can reduce the patient's weight and facilitate rehabilitation. It also increases the reliability and safety of the mechanism by reducing the use of motors and control

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modules. However, the existing gravity balance mechanism is mostly limited to two dimensions. [4]Therefore, it is necessary to design a simple and feasible three-dimensional gravity balance mechanism, which will be implemented in this paper.[5]

2 Design principle

This 3-D gravity balancing mechanism as shown in figure 1. It includes four rigid links, which are $\text{Link}-\overline{AD}$ (There are only rotation on this link, but not translation) $\text{Link}-\overline{BC}$, $\text{Link}-\overline{CD}$, $\text{Link}-\overline{DE}$; Two springs, which are $Spring-1$ and $Spring-2$; Four joints, which are $\text{Join}-A$, $\text{Join}-B$, $\text{Join}-C$ and $\text{Join}-E$; One slider, which is $Slider-D$ that can rotate in $Y-axis$, thus, this is a critical design for the whole mechanism. The 3-D model created by SolidWorks is shown in figure 2.

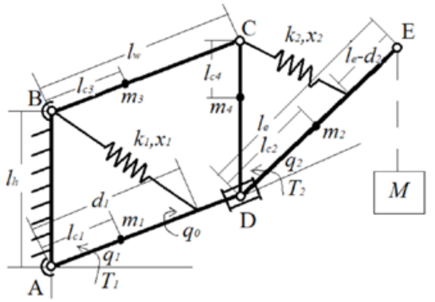

Fig. 1. 3-D Mechanism Diagram.

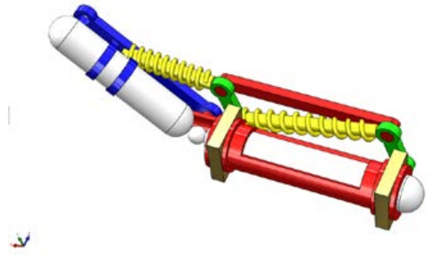

Fig. 2. 3-D Model.

3 Calculation

3.1 Find Spatial Position of m_2

For the next steps, it is going to be computed spatial position of center of mass of $\text{Link}-\overline{DE}$ at the beginning, by the geometric method and the law of cosines. Establish the spatial coordinate system as shown in figure 3. Thus, the 3-D coordinates of m_2 is:

$$[l_w C_1 + l_{c2}(C_1 C_2 - C_0 S_1 S_2), l_{c2} S_0 S_2, l_w S_1 + l_{c2}(S_1 C_2 - C_0 C_1 S_2)] \tag{1}$$

3.2 Calculating gravitational potential energy

First, the gravitational potential energy of all links will be computed.

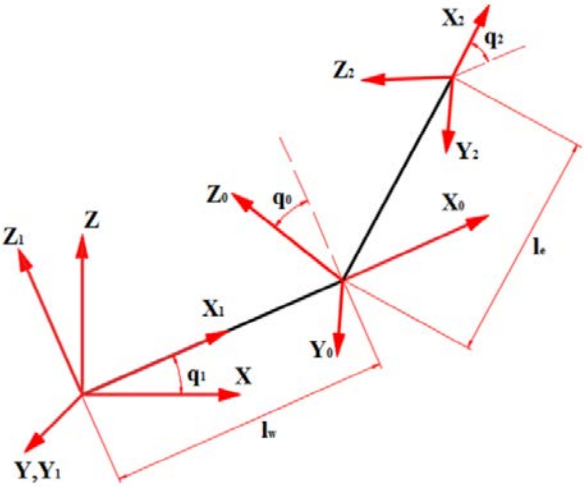

Fig. 3. Space coordinates system.

Compute the gravitational potential energy of $Link-\overline{AD}$:

$$V_{g1} = m_1 g(l_{c1}S_1 + l_h) \tag{2}$$

Compute the gravitational potential energy of $Link-\overline{DE}$:

$$V_{g2} = m_2 g(l_w S_1 + l_{c2}S_1C_2 - l_{c2}C_0C_1S_2 + l_h) \tag{3}$$

Compute the gravitational potential energy of $Link-\overline{BC}$:

$$V_{g3} = m_3 g l_{c3} C_1 \tag{4}$$

Compute the gravitational potential energy of $Link-\overline{CD}$:

$$V_{g4} = m_4 g(l_w S_1 + l_{c4}) \tag{5}$$

Thus, the total system gravitational potential energy of all links is:

$$V_g = m_1 g l_h + m_2 g l_h + m_4 g l_h + (m_1 g l_{c1} + m_2 g l_w + m_3 g l_{c3} + m_4 g l_w)S_1 \\ + m_2 g l_{c2} S_1 C_2 - m_2 g l_{c2} C_0 C_1 S_2 \tag{6}$$

3.3 Calculating elastic potential energy

Second, the elongation and the elastic potential energy of the springs will be computed.

Compute the elongation(squared) of $Spring-1$:

$$x_1^2 = l_h^2 + d_1^2 - 2l_h d_1 S_1 \tag{7}$$

Compute the elongation(squared) of $Spring-1$:

$$x_2^2 = l_h^2 + d_2^2 - 2l_h d_2(S_1C_2 - C_0C_1S_2) \tag{8}$$

Thus, the total system elastic potential energy of all the springs is:

$$V_S = \frac{1}{2}k_1(l_h^2 + d_1^2) + \frac{1}{2}k_2(l_h^2 + d_2^2) \\ - k_1l_hd_1S_1 - k_2l_hd_2(S_1C_2 - C_0C_1S_2) \tag{9}$$

3.4 Simplify potential energy equation

It was known that the principle of Gravity Balancing is the constant potential energy in any robot configuration. Therefore, the potential energy equation is:

$$V_g + V_s = Const. \tag{10}$$

Write the full equation down:

$$m_1gl_h + m_2gl_h + m_4gl_h + (m_1gl_{c1} + m_2gl_w + m_3gl_{c3} + m_4gl_w)S_1 + \\ m_2gl_{c2}(S_1C_2 - C_0C_1S_2) + \frac{1}{2}k_1(l_h^2 + d_2^2) + \frac{1}{2}k_1(l_h^2 + d_2^2) - \\ k_1l_hd_1S - k_2l_hd_2(S_1C_2 - C_0C_1S_2) = Cont. \tag{11}$$

Then, simplify the above equation by eliminate coefficients of the items related to angles(q_0, q_1, q_2):

$$m_1gl_h + m_2gl_w + m_3gl_{c3} + m_4gl_w = k_1l_hd_1 \tag{12}$$

$$m_2gl_{c2} = k_2l_hd_2 \tag{13}$$

That is to say, in the gravity balancing status for this mechanism, the springs' stiffness coefficient are:

$$k_1 = \frac{(m_1l_{c1} + m_2l_w + m_3l_{c3} + m_4l_w)g}{l_hd_1} \tag{14}$$

$$k_2 = \frac{m_2gl_{c2}}{l_hd_2} \tag{15}$$

As can be seen from the above results, for different patients, the spring stiffness coefficient(k_1 and k_2) and the distance between $PointA$ and $PointB$ (l_h) can be adjusted to fit different arms.

3.5 Comparing with 2-D mechanisms

The 3-D mechanisms design is based on the 2-D mechanisms. When q_0 keep 0 and $Slider-D$ that can not rotate in $Y-axis$, the 3-D mechanisms is equivalent to 2-D mechanisms.

Table 1. Symbols and notations.

Symbol	Notation
m_1	The mass of $Link-\overline{AD}$
m_2	The mass of $Link-\overline{DE}$
m_3	The mass of $Link-\overline{BC}$
m_4	The mass of $Link-\overline{CD}$
l_{c1}	The distance from center of mass of $Link-\overline{AD}$ and $\text{Joint}-A$
l_{c2}	The distance from center of mass of $Link-\overline{DE}$ and $\text{Joint}-D$
l_{c3}	The distance from center of mass of $Link-\overline{BC}$ and $\text{Joint}-B$
l_{c4}	The distance from center of mass of $Link-\overline{CD}$ and $Jo\text{int}-C$
l_h	The length between $\text{Joint}-A$ and $\text{Joint}-B$
l_w	The length between $\text{Joint}-B$ and $Jo\text{int}-C$
l_e	The length between $\text{Joint}-D$ and $\text{Joint}-E$
d_1	The length between $\text{Joint}-A$ and fixed position of $Slider-1$ on $Link-\overline{DE}$
d_2	The length between $\text{Joint}-C$ and fixed position of $Slider-2$ on $Link-\overline{DE}$
c_1	cos(q1)
q_1	The angle between $Link-\overline{AD}$ and horizontal line
q_2	The angle between the extension cord of $Link-\overline{AD}$ and $Link-\overline{DE}$
k_1	The stiffness coefficient of $\text{Spring}-1$
k_2	The stiffness coefficient of $\text{Spring}-2$
x_1	The elongation of $\text{Spring}-1$
x_2	The elongation of $\text{Spring}-2$
T_1	The Torque of $Link-\overline{AD}$
T_1	The Torque of $Link-\overline{DE}$

4 Animation and analysis

In order to highlight the effect in animation simulation, assuming $k_1=6g$, $k_2=g$. Using MATLAB to implement animation shown in figure 4. The blue lines are rigid links and the green lines are springs. From the animation, it can be seen that this mechanism works very well.

From the System Potential Energy plot shown in figure 5, it can be seen that in this system, as the gravitational potential energy increases, the elastic potential energy decreases; Otherwise, the opposite. They can always maintain relative total potential energy equilibrium. Therefor, the previous calculation result are correct, since the the sum of gravitational potential energy and elastic potential energy keeps constant.

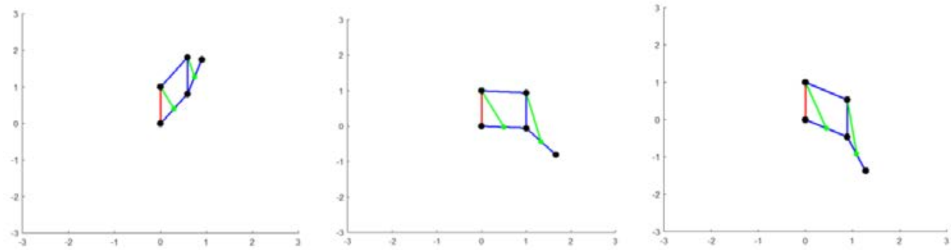

Fig. 4. MATLAB Animation.

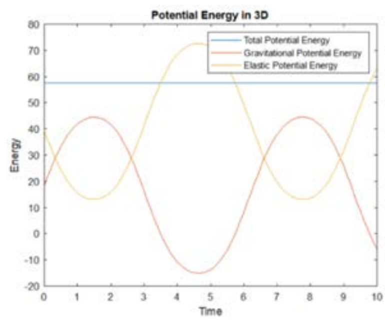

Fig. 5. System Potential Energy in 3-D.

The goal of this 3-D mechanism design is to reduce the burden of the patient, so it is necessary to verify the result. As can be seen from the torque comparison diagram of figure 6, adding a springs can obviously reduce the torques, which means that this design can significantly reduce the burden on the patient's arm.

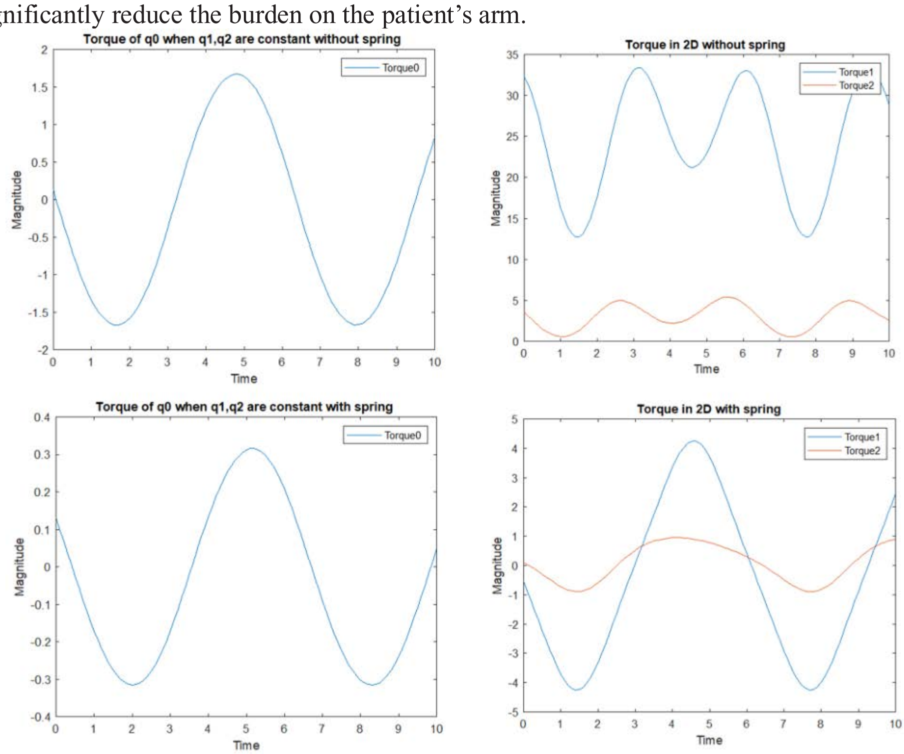

Fig. 6. Torque comparation in different cases.

5 Conclusions

A gravity balancing mechanism in 3-D for stroke patients recovering was successfully designed. The design principle, free-body diagram and 3-d model created by SolidWorks are depicted in the preceding part of the report. The gravitational potential energy and the elastic potential energy in the mechanism were calculated. After implement the animation and analysis, this 3-D mechanism was proved to be feasible, which can added one extra degree of freedom to the forearm of the stroke patient (rotating around the normal vector of the arm section). If it's used in practice, it will significantly reduced the burden on the arm of a stroke patient.[6]

6 Future extensions

An actual prototype should be made, and it needs to conduct clinical trials to get more data to modified the design.Also, this mechanism can be applied to the stroke patients leg so that the tibia can be rotated around the normal vector of the section of the leg. [7]In addition, this mechanism may implemented to industrial robots to improve work accuracy and reduce energy consumption.[8]

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