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Optimization of Ankle-Foot Prosthesis with Active Alignment by Passive Elements

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Abstract: Today, often ankle's active prosthesis is used for transtibial amputated people's walking, because these prostheses have some advantages such as increasing power and decreasing metabolism. In most of active prosthesis in order to create a movement or increase the force at the push-off, electrical actuators are used like a motor. In cases where a higher-power motor is necessary, the capacity, weight and using electricity in motor become increased, which causes problem for people with an amputation. This research is conducted to optimize ankle prosthesis with use of an active alignment which is made by experts. In this prosthesis to reduce the motor power, a passive element of spring is used in order to save energy while walking and release it in push-off. After setting spring position in the prosthesis, the dynamic and kinematic analysis are done and eventually the amount of used force in both modes of spring and non-spring would be compared. The results show that the presence of spring in the selected mechanism would cause motor to perform force increase and power reduction to mechanism at the push-off phase.

Keywords: Prosthesis, active, ankle-foot, spring, optimization

1. Introduction

Often made prosthesis before 90s were passive mode and no external driving force was used to move them. But the attempts were on having passive prosthesis which were like a healthy foot. The primary sample of these prosthesis could be mentioned as Bowler's in 1919 in which it was tried to simulate tendon's movement by a flexible belt which was set at the back of heel. Gradually, the use of energy saver passive elements like spring were increased due to copy from artificial ankle-foot more than a healthy ankle-foot. For example, the project which launched in 1988 by Voisin had included two springs between feet and shin [1]. In prosthesis with spring, before push-off an elastic energy is saved and at the push-off that energy would be released. But the amount of produced action at the push–off phase is more than saved energy before that. This trouble causes problems such as slow walking, stable mechanical properties in prosthesis after change in speed or in terrain, increase in metabolism to produce more energy in order to move passive prosthesis and creating asymmetric pattern in walking [2].

To solve these problems, designers used active elements in their designs instead of passive elements in order to create necessary power and force for movement. Active structured prosthesis can reduce metabolism by using electrical or pneumatic actuator, even when its weight is two times more than passive structured one [2]. In 1998, the first active

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prosthesis which was moving by a pneumatic actuator was made by Klute et al. in USA [3-5]. According to their report, the created prosthesis produced output force of 110 Nm that could rotate the artificial ankle-foot 30 degrees.

Electrical actuators are used more than pneumatic actuators because they have some advantages such as high responding speed, high power and easy to control. The biggest drawback in these actuators is the use of heavier battery to create higher power. This matter leads to limitation in using electrical actuators. After many surveys, researchers noticed that if they use a passive element energy saver beside motor actuator then they can reduce the necessary force a lot. The important issue is this, the passive elements must be performed in a condition that at the push-off phase impose its saved energy to body of prosthesis. In recent years and in designing active prosthesis, using this method have become more. To mention prosthesis which used both active and passive elements, we can name SPARKy that the first sample was made by Hitt et al. in 2007. This powerful prosthesis is designed for military purposes and they used foot tendon simulation in its design [6]. After a while the second sample by the name of SPARKy 2 and with a significant reduction in size and weight was designed [7]. In its final design that was called SPARKy 3, in 2008 the research team could provide a prosthesis for fast walking and even jumping, they had used low size motor with lower power and two springs in series with the motor [7]. A year after, in 2009, Au et al. at the research section of MIT, performed a prosthesis that caused metabolism reduction while walking and enabled a fast walking. In this prosthesis two series spring and a spring in parallel with actuator were used that not only saves energy but also reduce sudden pressure and hit while placing the heel on the ground [2]. Also in 2012, Bergelin et al. made a prosthesis without considering natural size and weight of foot that was aimed to imitate natural moment of ankle-foot. In this prosthesis they had used four links mechanism and a coil-spring in order to save energy and release it while push-off phase [8]. Two years later, in 2014, Cherelle et al. provided a prosthesis by the name of AMP which used a magnetic lock mechanism to save energy. In this prosthesis the motor starts to work before push-off phase initiation and pull the spring. Shortly after beginning the push-off phase the magnetic lock would be opened and the energy inside spring would be released. At the swing phase, motor rotates in reverse and magnetic locks would be closed in order to return prosthesis to its original state [9]. Realmuto et al. have used a different structure to reduce necessary power in motor. Their design was shown in 2015 and could decrease 74% of maximum torque in actuator. This prosthesis uses a parallel elastic structure that has a nonlinear cam and follower mechanism to move. Also, in conducted calculation to design this structure, convex optimization rank 3 was done in order to decrease motor energy [10]. The prosthesis with a movable link of MACCEPA that was made in 2015 by Fabian et al. is a new design that its mechanical section causes adjustable stiffness. Despite the low range of motion angle, this prosthesis is compatible with different states. Using spring and attached link mechanism, reduce necessary energy a lot [11].

In this research the selected prosthesis for optimization is a kind of prosthesis with an active alignment which was designed recently and released in 2016. This prosthesis was made by Kennedy LaPre et al. and its prototype that was developed as a test could decline the pressure on the remain limb [12]. Also designers have tried to design electrical section smaller and with lower size but higher motor power in comparison with active prosthesis. Therefore, in this research they have tried to reduce motor using power by adding an energy saver element to prosthesis structure like a spring. To analyze the subject in details and by determining the spring place, kinematic and dynamic analysis were performed in order to check and investigate the impact of spring in mechanism, at the following you see the details.

2.How to optimize prosthesis ankle-foot

2.1. Kinematic analysis

In this prosthesis as visible at Fig. 1, a four links mechanism is used that includes known and unknown parameters and an input that have important role in kinematic analysis. We can see parameters' position carefully in Fig. 1, that are shown separately and clearly in Table 1. By conducting kinematical analysis, the amount of unknown parameters which are in fact the angles of each links of mechanism would be reached. By finding amount of angles we can calculate the angular velocity and angular acceleration of each links. Also, the obtained amount and values in this section could be used in performing dynamic analysis. It is important to mention that the third link in this mechanism is fixed and attached to sole of feet and parameter $\theta_{3\text{-foot}}$ determines angle of third link with sole of foot. Also, ball screw is the value of input that its end is attached to motor and by motor rotation in different directions its length would be changed.

In this report, two methods of calculation and Simulink of MATLAB software were used to obtain unknown parameters of dynamic and kinematic section. In computational method due to having four unknown parameter we need four equations that by writing circles relationship in mechanism, the kinematic equations can be obtained as follows:

$$\begin{aligned} &L_1\cos\theta_1 + L_4\cos\theta_4 - L_{ac}\cos\theta_{ac} = 0 \\ &L_1\sin\theta_1 + L_4\sin\theta_4 - L_{ac}\sin\theta_{ac} = 0 \\ &-L_2\cos\theta_2 + L_3\cos\theta_3 - L_{ac}\cos\theta_{ac} = 0 \\ &-L_2\sin\theta_2 + L_3\sin\theta_3 - L_{ac}\sin\theta_{ac} = 0 \end{aligned} \quad (1)$$

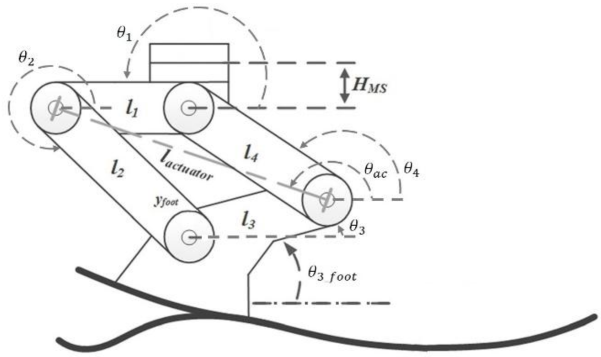

Fig. 1. The used mechanism in ankle prosthesis with an active alignment

Table 1.
Shows necessary parameters and values for kinematic analyzing

Design Parameters	Outputs	Input (mm)
L_1 = 54.7mm	θ_2	L_{ac} = 100.5 - 126.5
L_2 = 77.4mm	θ_3	
L_3 = 65.2mm	θ_4	
L_4 = 77.4mm	θ_{ac}	
H_{MS} = 17mm		
θ_1 = 180˚		
$\theta_{3\text{-foot}}$ = 10.2˚		

in which L is length of links and θ is ankle between links and horizontal axis.

By solving kinematic equations, the angle of each link could be obtained like the Eq. (2).

$$\begin{aligned} \theta_2 &= \cos^{-1}\left(\frac{L_3^2 - L_2^2 - L_{ac}^2}{2L_2L_{ac}}\right) + \cos^{-1}\left(\frac{L_4^2 - L_1^2 - L_{ac}^2}{2L_1L_{ac}}\right) \\ \theta_3 &= \cos^{-1}\left(\frac{L_3^2 - L_2^2 + L_{ac}^2}{2L_3L_{ac}}\right) + \cos^{-1}\left(\frac{L_4^2 - L_1^2 - L_{ac}^2}{2L_1L_{ac}}\right) \\ \theta_4 &= \cos^{-1}\left(\frac{L_1^2 + L_4^2 - L_{ac}^2}{2L_1L_4}\right) \\ \theta_{ac} &= \cos^{-1}\left(\frac{L_4^2 - L_1^2 - L_{ac}^2}{2L_1L_{ac}}\right) \end{aligned} \quad (2)$$

But for using MATLAB software it is necessary to draw various sections of mechanism in the Simulink inside the software. In this simulation the prismatic actuator is used instead of ball screw in order to perform actuator replacement more carefully (Fig. 2). Therefore the length of prismatic actuator is considered equal to changes in ball screw inside the main mechanism, it means 26 mm and total length of two links of L_{ac1} and L_{ac2} are equal to minimum length of ball screw. Also as it is assumed that the attachment between L_1 and shin is fixed and by considering the place of shin as a ground of mechanism, L_1 in simulation is considered as a ground of mechanism, too.

2.3. Using passive element

Mostly the active prosthesis function is in a form that at the beginning of gait cycle and before push-off phase, the prosthesis consumes less force because in this condition the prosthesis has a complete contact with earth and doesn't need high power for motion. The most necessary force in gait cycle belongs to push-off phase in which the prosthesis need to consume high force to separate from ground. In active prosthesis the necessary force for stepping foot form ground is supplied by actuator. In mentioned prosthesis in the research which is an active one, before push-off phase the ball screw would be opened mostly and the height of prosthesis relines, and while stepping the foot from ground the length of ball screw decreases and height of

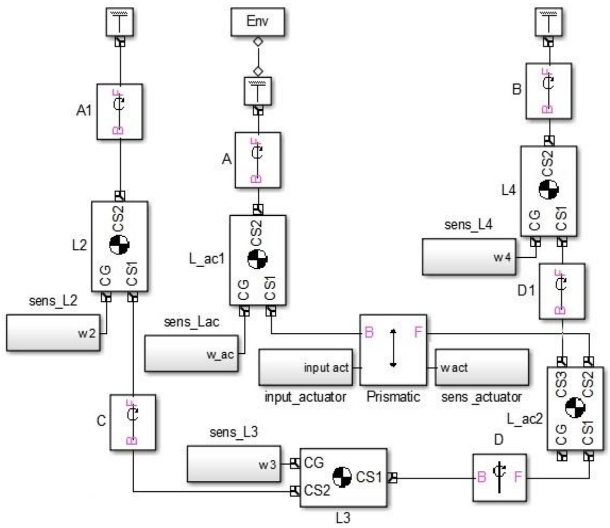

Fig. 2. Simulating mechanism in Simulink of MATLAB

prosthesis increases in order to supply the force necessary to place in.

In this prosthesis in order to reduce consuming power in motor, the spring must be placed inside the mechanism in a condition that during push-off phase be able to release his saved energy to prosthesis, and then in other states save the energy inside itself. To apply this, two points of the prosthesis are selected for placing the spring to approach each other before push-off and during push-off become far from each other and then release energy of the spring. The two selected points are shown in Fig. 3 between links number 4 and 3, because the angle between these two links would increase while push-off and in other states the angle between them reclines.

2.3. Dynamic analysis

By using dynamic equation, we can calculate the torque and input force in each joints of mechanism. One of the method of obtaining dynamic equation is Newton-Euler method. Newton's equations cause a relationship between applied force and the caused linear acceleration. Also these equations define a relationship between applied torque in the mechanism and rotational acceleration in a rigid body.

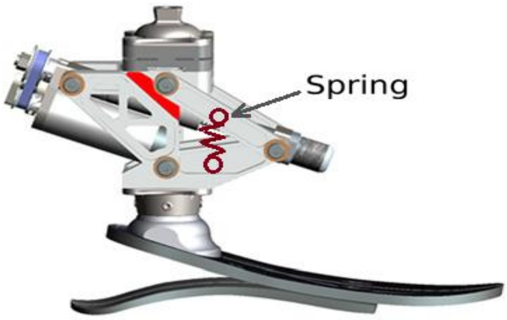

Fig. 3. Ankle-foot prosthesis [12] and spring position on it

By drawing the free-body diagram of each dynamic rigid structure link and by determining forces, the Newton-Euler equation is written. These equations perform the relationship between forces, moment of inertia and acceleration of each rigid body. For instance, for extracting Newton-Euler equation, at first the free body diagram of link 4 would be drawn as shown in Fig. 4. This link is attached to link number 3 and 1 and in this respect the forces 1 and 6 release on this link horizontally and vertically. By attaching spring to this link, the spring force must be considered inside the free body diagram and be added to Newton-Euler equations.

According to free body diagram of link 4 which is shown in Fig. 4, the Newton-Euler equation of this link is defined as Eq. (3).

$$
\begin{aligned}
&\Sigma F_X = m_4 a_{G_4X} \rightarrow F_{X_1} + F_{X_6} \\
&\qquad - F_{sp}\cos\alpha = m_4 a_{G_4X} \\
&\Sigma F_Y = m_4 a_{G_4Y} \rightarrow F_{Y_1} + F_{Y_6} \\
&\qquad - F_{sp}\sin\alpha - m_4 g = m_4 a_{G_4Y} \\
&\Sigma M = I_4 a_4 \rightarrow -L_{G_4X_1}F_{X_1} + L_{G_4Y_1}F_{Y_1} \\
&\qquad -L_{G_4X_6}F_{X_6} + L_{G_4Y_6}F_{Y_6} \\
&\qquad -L_{G_4X_{sp}}F_{X_{sp}} + L_{G_4Y_{sp}}F_{Y_{sp}} = I_4 a_4
\end{aligned}
\tag{3}
$$

in which m is mass, F is force, a is acceleration, g is earth's gravity acceleration and I is moment of inertia.

In Newton-Euler equations of this link the spring force F_{sp} is added too, and its amount could be calculated in Eq. (4). The value of this force is dependent to constant of spring and changes in its length.

$$F_{sp} = k(l_x - l_0) \tag{4}$$

in which k is spring constant, l0 is primary length of spring and l_x is spring length in different situations of the mechanism.

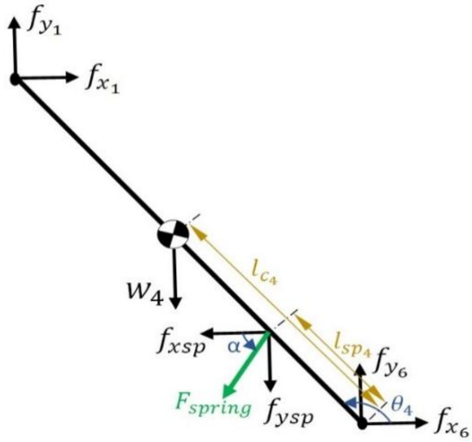

Fig. 4. Free body diagram of link 4

In order to determine any changes in length of spring, its length would be calculated in any time and is shown by l_x. the value of l_x could be calculated by Eq. (5).

$$l_x = \sqrt{\frac{l_3^2}{2} + \frac{l_4^2}{2} - 2\frac{l_3}{2}\frac{l_4}{2}\cos\left(\pi + \theta_{3-foot} - \theta_4\right)} \qquad (5)$$

For obtaining the spring's primary length value we should calculate it when it's in a normal state and without applying any external force. If the spring is between two links of 3 and 4, its primary length can be calculated by replacing θ_{4min} instead of θ_4 in Eq. (5). After determining dynamic equation of all links, 21 equations are obtained that by solving them the driving forces of each link is gained. By getting the forces in accordance to actuator we can investigate the actuator's consumed amount of power. The simpler way to get this force in a gait cycle is using simulation by MATLAB. By considering hip joint as a ground, thigh and shin are added to MATLAB and to mechanism because motion of hip and knee are influential at the position of ankle-foot, therefore the motion of these two joints must be considered in dynamic structure. In dynamic simulation, three input: hip, knee, and actuator must be applied in a gait cycle and the spring must be added to mechanism, too (Fig. 5).

3.Results and discussion

3.1.Results of kinematic and dynamic analysis

In kinematic section, after drawing the mechanism, the suitable input is applied - that here it is considered as a one opening and closing of actuator

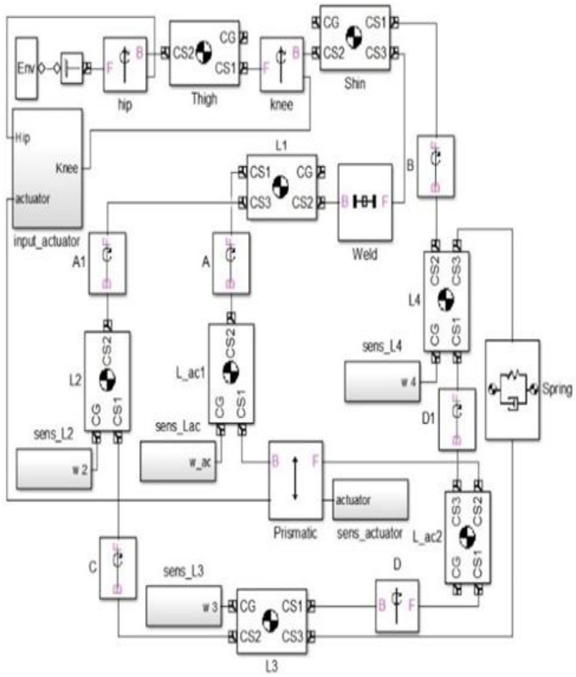

Fig. 5. Simulating dynamic structure in Simulink of MATLAB

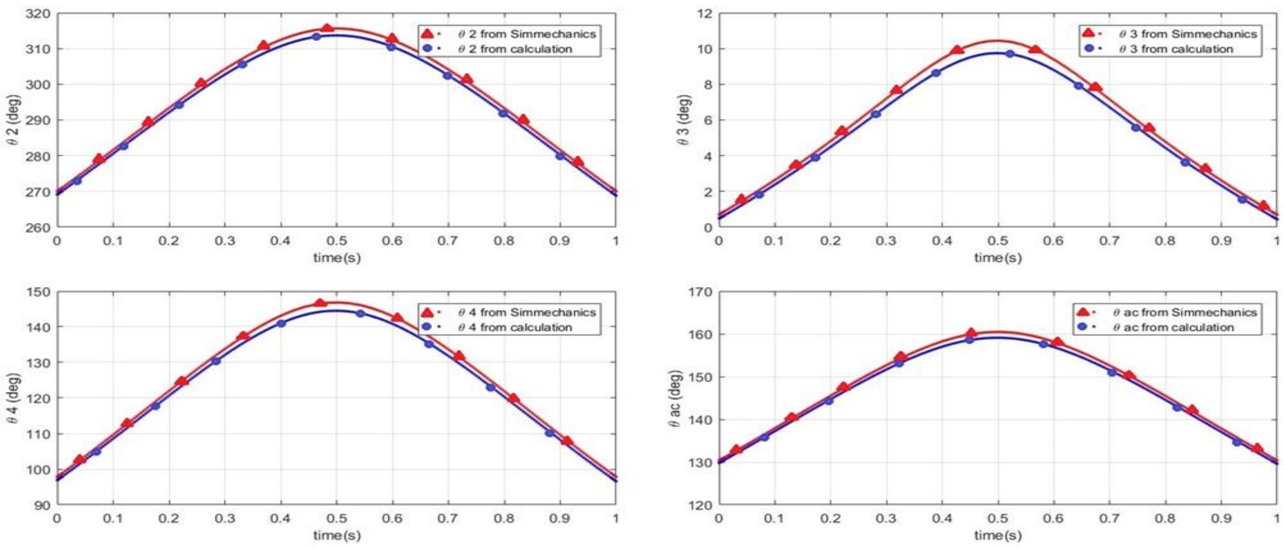

Fig. 6. Obtained angles from calculation and MATLAB

- and finally then output that is the result of calculation method and MATLAB software are compared with each other (Fig. 6). The results show that both obtained values from both methods are approximately equal and they have a small difference that is because of different way of calculation in ours and MATLAB.

In dynamic solving mode, in order to investigate the impact of force spring, output in the event of actuator Fa in both modes spring presence and spring absent, is obtained as shown in Fig. 7. Blue chart is without spring mode and the red chart shows the forces by presence of spring. As it is visible, presence of spring in a mechanism leads to force increase at the push-off and at the beginning of stance phase the force chart has milder motion than without spring

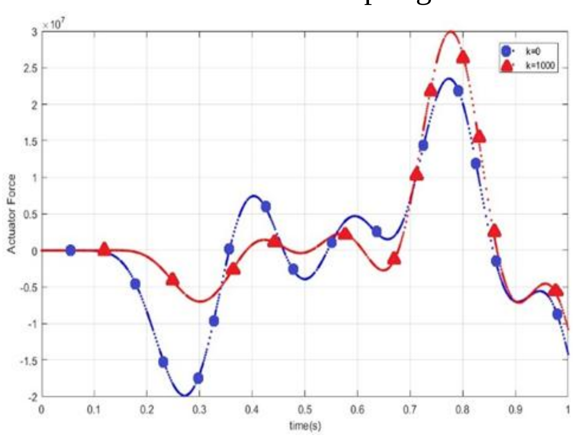

Fig. 7. The force value in parallel with actuator in both states of spring presence and lack of spring in mechanism

mode, because in this part the spring is in saving energy condition.

3.2. Changing spring constant and comparing the output

According to calculations, by changing spring constant, the value of force F_a would change too. Thus, by increasing constant k in spring relation, its saved energy must rise too, and by reclining spring constant, the force inside the spring decreases too. By changing spring constant, the impact on F_a force is shown on Fig. 8. In this figure, the chart k=0 indicates without spring mode and other charts show k values between 500 to 1500. In both modes that k is equal to 500 and 1000, and range of change at the beginning of stance phase is less than k modes of zero, 1200 and 1500. Reduction in values of changes at the beginning of stance phase leads to recline of fluctuations, thus both k modes equals to 500 and 1000 are better than other conditions. Among these both modes, the value of force at the push-off moment and at the k condition is equal to 1000 and its more than the condition of k equal to 500. Therefore, the most optimized state for spring constant is 1000.

3.3. Changing spring position and comparing the output

By placing spring on different places in mechanism, the value of saved forces would be changed. Spring by being placed between links of 1-2, 2-3, 3-4 and 4-1, would have different reactions.

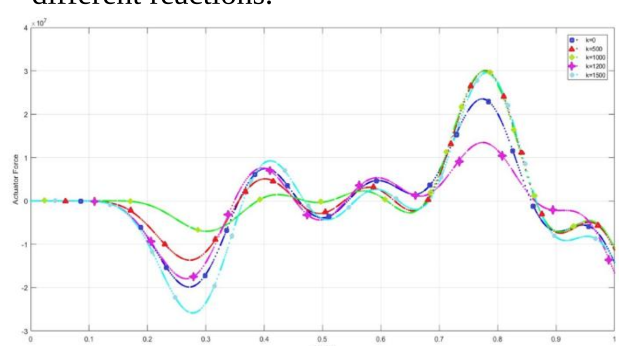

Fig. 8. Force chart in the event of actuator for a spring with different constant

According to previous section, the best spring constant is equal to 1000 that contains the least sudden changes and the most force range in push-off phase. Therefore, in this section the value of spring constant for all conditions is equal to 1000. As you can see in Fig. 9, spring placement on both positions of 2-3 and 3-4, would increase the force at the push-off phase; But the difference between these two positions is exactly at the beginning of stance phase. Before push-off the chart of 2-3 position has more fluctuation rather than 3-4 position, so the position 3-4 based on sudden change reduction is better than 3-2 position. On the other hands, the amount of force at the push-off in both positions of 1-2 and 4-1 is less than position of 2-3, therefore the most optimized of spring placement is between link 3 and 4.

5. Conclusion

In this research the prosthesis which has a motor

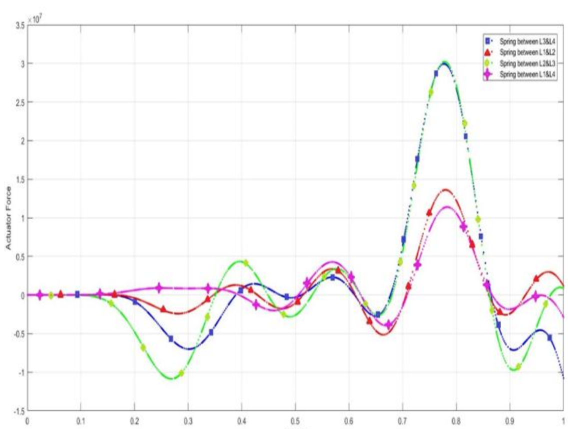

Fig. 9. Force chart in the event of actuator for different spring placement

with higher power than any other recent made prosthesis would be selected for optimizing purposes. By conducting kinematic analysis with both methods of calculation and MATLAB, the values of applied mechanism angles in the prosthesis get obtained and compared. The results of this comparison indicates the accuracy of obtained values for mechanism link angles. After conducting kinematic analysis, the spring is added to mechanism and its position inside the structure would be checked and determined by using dynamic equations. The investigations show that presence of spring in the mechanism leads to increase of force in the event of actuator at push-off phase. As a result, the necessary force for motor in order to create a motion would recline majorly. Eventually, for more investigation on impact of spring in the mechanism, the constant of spring and its position in the software is changed. The result chart of this changes shows that the spring by constant of 1000 has the most force at the push-off and has the least sudden changes before push-off. Also the determined primary position in this research that is between link 3 and 4 is exactly the most optimized place and form of spring.

6. Suggestion

After conducting analysis and simulations in this research, by adding a passive element to the selected active prosthesis, we succeeded in an outstanding reduction of motor power. But it is believed that the combination of active and passive structure is not the only solution to reduce power of electrical section. Thus, in this section we suggest that after conducting this research, the combination of active elements with low power and the electrical motor with lower power rather than previous motor, become under investigation. So in the future, It’s better to analyze the placement condition of an active actuator with lower electric voltage like artificial muscle (IPMC) beside a lower power motor.

Nomenclature

θ	angle (degree)
L	length (m)
I	moment of inertia (kg/m2)
a	acceleration (m/s2)
m	mass (kg)
F	force (N)
k	spring constant (N/m)
α	angle between spring and x axis (degree)
G	earth's gravity acceleration (m/s2)

Subscripts

ac	actuator
X	X axis
Y	Y axis
sp	spring
1 to 4	number mechanism links
G	center of mass
0	primary characteristics
x	characteristics in different time

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