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ARTIFICIAL KNEE JOINT FOR PROSTHETIC LEG OF ABOVE KNEE AMPUTEE

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ABSTRACT

This report gives a brief description on work done in 1st stage, project statement, and work done in second stage. This report also includes the work done in second stage which is identification of different types of artificial knee joint on the basis of number of link, detailed analysis of artificial knee joint with Stephenson six bar mechanism. A simulation was done on MSC Adams and the results are compared to the natural movement of knee.

Keywords: *Artificial Knee, MSC Adams, Dixion Determinant.*

I. INTRODUCTION

Many people have worked on artificial knee joint for prosthetic leg and every year a new kind of design come up which resolves the disadvantages of previous design. A large number of patents are there for artificial knee joint dating back from 1901. Although the current design do not imitate the natural knee joint, but progress in that area has been made by introducing microcontroller, actuators and sensors (active artificial knee joint) to imitate the natural gait patter. In such kind of prosthesis external power is being used to assist the human motion. But people are coming up with new design where power assistance is not required and knee joint is purely mechanical in nature, because active artificial knee joint is quite expensive and hence difficult to afford. This report presents a knee joint which uses six bar mechanism for the movement. It is seen that mechanism with higher number of linkage imitates the gait patter better than those with lower number of links. But not much work is done with six bar mechanism and still they are not in commercial production.

II. ARTIFICIAL KNEE JOINT

Passive knee joint is nothing but a multi-bar mechanism. There are three categories in which they are classified. The categories are according to number of linkages used. We will briefly look at each of them. But before that we will look at the mechanical equivalent of human knee joint.

- **a)** Four-bar linkage mechanism
- **b)** Five-bar linkage mechanism
- **c)** Six- bar linkage mechanism (Stephenson mechanism)

Mechanical equivalent of human knee joint

The knee has many critical geometrical characteristics because the two cruciate ligaments and the two leg bones form a very sophisticated and precise mechanism, called a four-bar hinge.

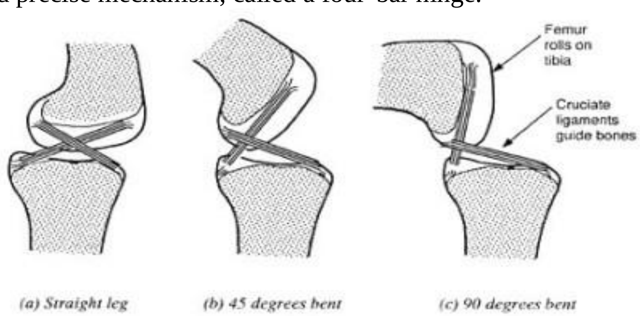

Fig 1.Human Knee mechanism

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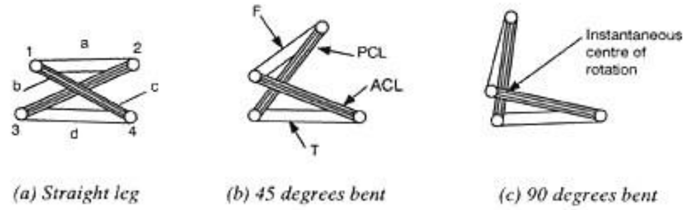

Fig 2.Knee as a four bar mechanism

The four-bar hinge mechanism of the knee is shown at various stages of rotation in Fig 2. These stages of rotation are schematically presented in to show clearly how the four-bar hinge works. Following inferences can be drawn from the above figure.

- ✓ The cruciate ligaments form the two crossed bars (b and c) while the upper and lower bones effectively form the other two bars (a and d).
- ✓ The cruciate ligaments are attached to the bones at (points 1, 2, 3 & 4).
- ✓ One important feature of the four-bar hinge is that the instantaneous centre of rotation approximately coincides with the crossover point of the cruciate ligaments. This crossover point moves as the joint opens and closes so that the knee does not have a fixed point of rotation.
- ✓ The knee joint is a particularly sophisticated kind of four-bar hinge, because the cruciate ligaments are not rigid and have to be kept taut by the rolling action of the bones

Artificial knee joint with four-bar linkage mechanism

Because of similarity of human knee joint construction with the four-bar mechanism, initially when the first artificial knee joint was made it was a four bar mechanism. Hence, four bar linkages in knee mechanism is very common.

Fig 3. A four bar artificial knee joint

This is a quite structurally simple device to replace the natural knee joint but the problem is it is suitable only for walking. Other functions erformed by knee are not possible like squatting and running. In situations like walking on inclined plane need some modifications in the structure of links which make is difficult to use such four bar knee joint.

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Artificial knee joint with five-bar linkage mechanism

This type of artificial knee joint is very uncommon. And is hardly used anywhere for the mass production of artificial knee joint. In the figure show there are five links and there is a spring between link 3 and 4. So link 3 and 4 usually act as one link.

The four bar knee joint do not provide stability during ankle landing and smooth knee bending during toe-off. In this kind of five bar knee joint this limitation are overcome by the virtue of mechanism link design.

But because of complicated structure of link making this knee joint it is not used in commercial production. A four bar mechanism knee joint with some added mechanism is preferred because of its structural simplicity.

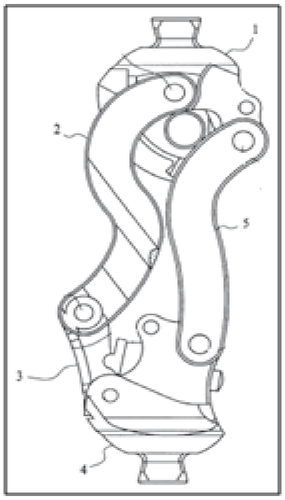

Fig 4. Five bar knee joint

III. KNEE JOINT WITH SIX-BAR LINKAGE MECHANISM

Artificial knee joint with six-bar linkage Stephenson mechanism

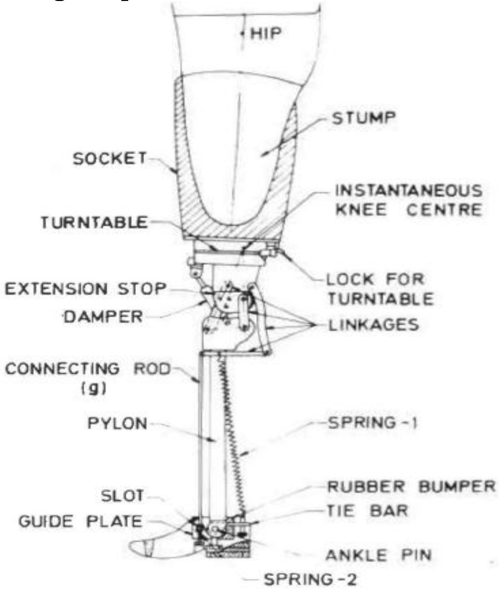

Fig 5 Prosthetic leg with artificial knee joint using six bar mechanism

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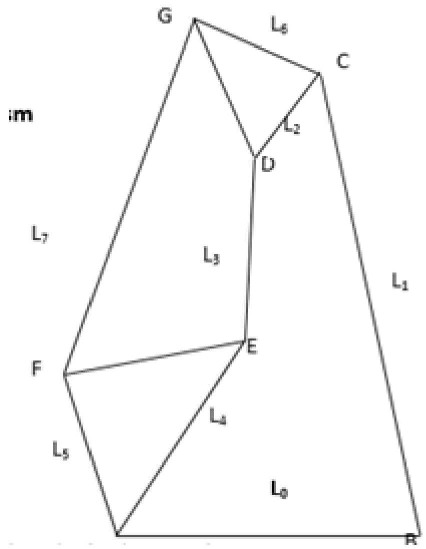

Analysis of six-bar linkage mechanism
Link “x” is directly attach to the thigh socket where as link “y” is attached to a tube and act as a shank unit

The above six bar mechanism consist of two loop. Hence it can be solve theoretically by using loop equations. Here we have considered the x axis along the forward movement of the prosthetic leg. Now considering the vector position of links of both loops in this coordinate system and measuring the orientation of each link we have.

<u>Loop equation for ABCDEA</u>

$$l_4 \cos\theta_4 - l_1 \cos\theta_1 + l_2 \cos\theta_2 + l_3 \cos\theta_3 - l_0 = 0$$
$$l_4 \sin\theta_4 - l_1 \sin\theta_1 + l_2 \sin\theta_2 + l_3 \sin\theta_3 = 0$$

Can also be written as

$$l_4 e^{i\theta_4} - l_1 e^{i\theta_1} + l_2 e^{i\theta_2} + l_3 e^{i\theta_3} - l_0 = 0 \cdots\cdots 1$$

<u>Loop equation for ABCGFA</u>

$$l_7 \cos\theta_7 + l_5 \cos(\theta_4 + \alpha) - l_1 \cos\theta_1 + l_6 \cos(\theta_2 - \beta) - l_0 = 0$$
$$l_7 \sin\theta_7 + l_5 \sin(\theta_4 + \alpha) - l_1 \sin\theta_1 - l_6 \sin(\theta_2 - \beta) = 0$$

Can also be written as

$$l_7 e^{i\theta_7} + l_5 e^{i(\theta_4+\alpha)} - l_1 e^{i\theta_1} + l_6 e^{-i(\theta_2-\beta)} + l_0 = 0$$
$$or\ l_7 e^{i\theta_7} + l_5 e^{i\theta_4} * e^{i\alpha} - l_1 e^{i\theta_1} + l_6 e^{-i\theta_2} * e^{i\beta} - l_0 = 0 \cdots\cdots 2$$

Can also be written as

Where l is the length of different links and θ is the angle made by the corresponding links with the X axis in the give coordinate system

Conjugate of equation 1 and 2 are

$$l_4 e^{-i\theta_4} - l_1 e^{-i\theta_1} + l_2 e^{-i\theta_2} + l_3 e^{-i\theta_3} - l_0 = 0 \cdots\cdots 3$$
$$l_7 e^{-i\theta_7} + l_5 e^{-i\theta_4} * e^{i\alpha} - l_1 e^{-i\theta_1} + l_6 e^{i\theta_2} * e^{i\beta} - l_0 = 0 \cdots\cdots 4$$

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Let $\boldsymbol{\Theta_j = e^{i\theta_j}}$ then the four equation will become

$$\boldsymbol{l_4\Theta_4 - l_1\Theta_1 + l_2\Theta_2 + l_3\Theta_3 - l_0 = 0 \equiv F1}$$
$$\boldsymbol{l_7\Theta_7 + l_5\Theta_4 * e^{i\alpha} - l_1\Theta_1 + l_6\Theta_2^{-1} * e^{i\beta} - l_0 = 0 \equiv F2}$$
$$\boldsymbol{l_4\Theta_4^{-1} - l_1\Theta_1^{-1} + l_2\Theta_2^{-1} + l_3\Theta_3^{-1} - l_0 = 0 \equiv F1'}$$
$$\boldsymbol{l_7\Theta_7^{-1} + l_5\Theta_4^{-1} * e^{i\alpha} - l_1\Theta_1^{-1} + l_6\Theta_2 * e^{i\beta} - l_0 = 0 \equiv F2'}$$

Now we will solve for $\boldsymbol{\Theta_j}$ from these four complex equations. They can be solved by using Dixon Determinant method. Now in these equations $\boldsymbol{\Theta_4}$ is input to the mechanism. So we have to solve for $\boldsymbol{\Theta_j}$, *j*=1, 2, 3, 7

The Dixon determinant

We suppress $\boldsymbol{\Theta_1}$ so now we have four equation and only three variables $\boldsymbol{\Theta_2}$,$\boldsymbol{\Theta_3}$ and $\boldsymbol{\Theta_7}$. Now Dixon determinant is constructed by inserting all four F1, F2, F1'and F2' as the first row and then sequentially replacing the three variables by $\boldsymbol{\alpha_j}$

$$\boldsymbol{\Delta} = \begin{vmatrix} \mathrm{F1}(\boldsymbol{\Theta 2}, \boldsymbol{\Theta 3}, \boldsymbol{\Theta 7}) & \mathrm{F2}(\boldsymbol{\Theta 2}, \boldsymbol{\Theta 3}, \boldsymbol{\Theta 7}) & \mathrm{F1'}(\boldsymbol{\Theta 2}, \boldsymbol{\Theta 3}, \boldsymbol{\Theta 7}) & \mathrm{F2'}(\boldsymbol{\Theta 2}, \boldsymbol{\Theta 3}, \boldsymbol{\Theta 7}) \\ \mathrm{F1}(\boldsymbol{\alpha 2}, \boldsymbol{\Theta 3}, \boldsymbol{\Theta 7}) & \mathrm{F2}(\boldsymbol{\alpha 2}, \boldsymbol{\Theta 3}, \boldsymbol{\Theta 7}) & \mathrm{F1'}(\boldsymbol{\alpha 2}, \boldsymbol{\Theta 3}, \boldsymbol{\Theta 7}) & \mathrm{F2'}(\boldsymbol{\alpha 2}, \boldsymbol{\Theta 3}, \boldsymbol{\Theta 7}) \\ \mathrm{F1}(\boldsymbol{\alpha 2}, \boldsymbol{\alpha 3}, \boldsymbol{\Theta 7}) & \mathrm{F2}(\boldsymbol{\alpha 2}, \boldsymbol{\alpha 3}, \boldsymbol{\Theta 7}) & \mathrm{F1'}(\boldsymbol{\alpha 2}, \boldsymbol{\alpha 3}, \boldsymbol{\Theta 7}) & \mathrm{F2'}(\boldsymbol{\alpha 2}, \boldsymbol{\alpha 3}, \boldsymbol{\Theta 7}) \\ \mathrm{F1}(\boldsymbol{\alpha 2}, \boldsymbol{\alpha 3}, \boldsymbol{\alpha 7}) & \mathrm{F2}(\boldsymbol{\alpha 2}, \boldsymbol{\alpha 3}, \boldsymbol{\alpha 7}) & \mathrm{F1'}(\boldsymbol{\alpha 2}, \boldsymbol{\alpha 3}, \boldsymbol{\alpha 7}) & \mathrm{F2'}(\boldsymbol{\alpha 2}, \boldsymbol{\alpha 3}, \boldsymbol{\alpha 7}) \end{vmatrix}$$

The elements of 1st row of this determinant are zero for value $\boldsymbol{\Theta_2}$, $\boldsymbol{\Theta_3}$ and $\boldsymbol{\Theta_7}$ since they satisfy the loop equations

Now every complex equation can be written as

$$\boldsymbol{F_k = c_{k4} + c_{k1}x + \sum_j^{2,3,7} c_{kj}\Theta_j} \qquad \textbf{And} \qquad \boldsymbol{F'_k = c'_{k4} + c'_{k1}x + \sum_j^{2,3,7} c'_{kj}\,\Theta_j^{-1}}$$

Where x denotes the suppressed variable $\boldsymbol{\Theta_1}$ now using these general form of complex loop equations and the matrix defined above we get. And subtracting 2nd row from 1st and 3rd from 2nd and so on we obtain a new matrix

$$\begin{matrix} \boldsymbol{C_{12}(\Theta_2\text{-}\alpha_2)} & \boldsymbol{C'_{12}(\Theta_2^{-1}\text{-}\alpha_2^{-1})} & \boldsymbol{C_{22}(\Theta_2\text{-}\alpha_2)} & \boldsymbol{C'_{22}(\Theta_2^{-1}\text{-}\alpha_2^{-1})} \\ \boldsymbol{C_{13}(\Theta_3\text{-}\alpha_3)} & \boldsymbol{C'_{13}(\Theta_3^{-1}\text{-}\alpha_3^{-1})} & \boldsymbol{C_{23}(\Theta_2\text{-}\alpha_3)} & \boldsymbol{C'_{22}(\Theta_3^{-1}\text{-}\alpha_3^{-1})} \\ \boldsymbol{C_{17}(\Theta_7\text{-}\alpha_7)} & \boldsymbol{C'_{17}(\Theta_7^{-1}\text{-}\alpha_7^{-1})} & \boldsymbol{C_{27}(\Theta_7\text{-}\alpha_7)} & \boldsymbol{C'_{27}(\Theta_7^{-1}\text{-}\alpha_7^{-1})} \\ \mathrm{F1}(\boldsymbol{\alpha 2}, \boldsymbol{\alpha 3}, \boldsymbol{\alpha 7}) & \mathrm{F1}(\boldsymbol{\alpha 2}, \boldsymbol{\alpha 3}, \boldsymbol{\alpha 7}) & \mathrm{F2'}(\boldsymbol{\alpha 2}, \boldsymbol{\alpha 3}, \boldsymbol{\alpha 7}) & \mathrm{F2'}(\boldsymbol{\alpha 2}, \boldsymbol{\alpha 3}, \boldsymbol{\alpha 7}) \end{matrix}$$

Note that $\boldsymbol{\Theta_j\text{-}\alpha_j\text{=} - \Theta_j\alpha_j(\Theta_j^{-1}\text{-}\alpha_j^{-1})}$ So for $\boldsymbol{\Theta_j\text{=}\alpha_j}$ Value of the above determinant is zero Hence we take out these extraneous as common factor. So the resultant determinant will be

$$\textbf{Delta} = \begin{matrix} \boldsymbol{-\,C_{12}(\Theta_2\alpha_2)} & \boldsymbol{C'_{12}} & \boldsymbol{-\,C_{22}(\Theta_2\alpha_2)} & \boldsymbol{C'_{22}} \\ \boldsymbol{-\,C_{13}(\Theta_3\alpha_3)} & \boldsymbol{C'_{13}} & \boldsymbol{-\,C_{23}(\Theta_2\alpha_3)} & \boldsymbol{C'_{22}} \\ \boldsymbol{-\,C_{17}(\Theta_3\alpha_3)} & \boldsymbol{C'_{17}} & \boldsymbol{-\,C_{27}(\Theta_7\alpha_7)} & \boldsymbol{C'_{27}} \\ \mathrm{F1}(\boldsymbol{\alpha 2}, \boldsymbol{\alpha 3}, \boldsymbol{\alpha 7}) & \mathrm{F1}(\boldsymbol{\alpha 2}, \boldsymbol{\alpha 3}, \boldsymbol{\alpha 7}) & \mathrm{F2'}(\boldsymbol{\alpha 2}, \boldsymbol{\alpha 3}, \boldsymbol{\alpha 7}) & \mathrm{F2'}(\boldsymbol{\alpha 2}, \boldsymbol{\alpha 3}, \boldsymbol{\alpha 7}) \end{matrix}$$

This determinant expands to form a polynomial which is of this form

Delta = $\boldsymbol{A^T[W]t = 0}$

Where **A** and **t** are vector n=monomial

$$A = \begin{matrix} \alpha 2 \\ \alpha 3 \\ \alpha 7 \\ \alpha 2\alpha 7 \\ \alpha 3\alpha 7 \\ \alpha 2\alpha 3 \end{matrix} \qquad t = \begin{matrix} \Theta 2 \\ \Theta 3 \\ \Theta 7 \\ \Theta 2\Theta 7 \\ \Theta 3\Theta 7 \\ \Theta 2\Theta 3 \end{matrix}$$

Now W is a square matrix and det (W) will give us the polynomial in $x=\Theta_1$.

IV. RESULTS

Length of all link are listed below.

L_1 =125mm L_2 = 19mm L_3 = 38mm L_4 = 75.5mm L_5 = 62.4mm L_6 = 29.5mm

L_7 = 81.3mm L_0 = 57mm

B = 93^0 $\alpha = 56^0$

Result of simulation

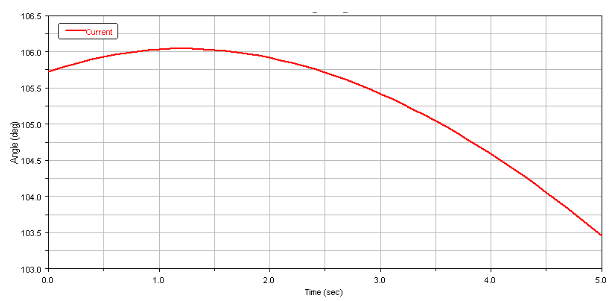

Fig 7 Value of θ_4 w.r.t time

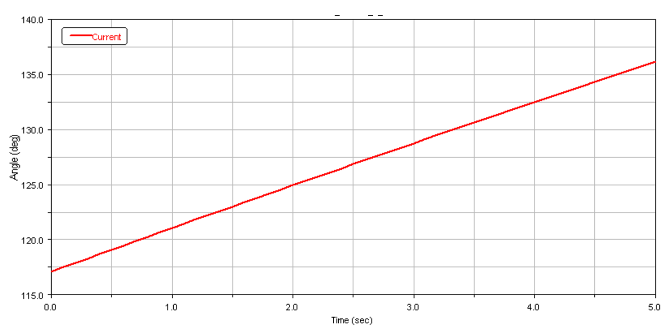

Fig 8 Value of θ_h w.r.t time

Here value knee angle is approximately same as value of $\mathbf{\theta_4}$ and where as value of $\mathbf{\theta_h}$ approximately same as hip angle

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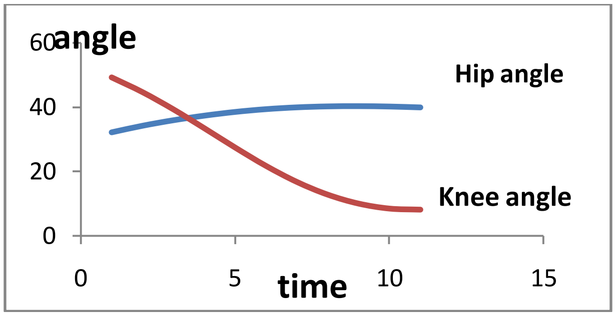

Fig 9 Experimental value of knee angle and hip angle

The above graph is obtained exprementallyat speed of 2mm/s with body mass 70 Kg and leg length approximatly 0.90m

5.3 Knee angle variation at different speed

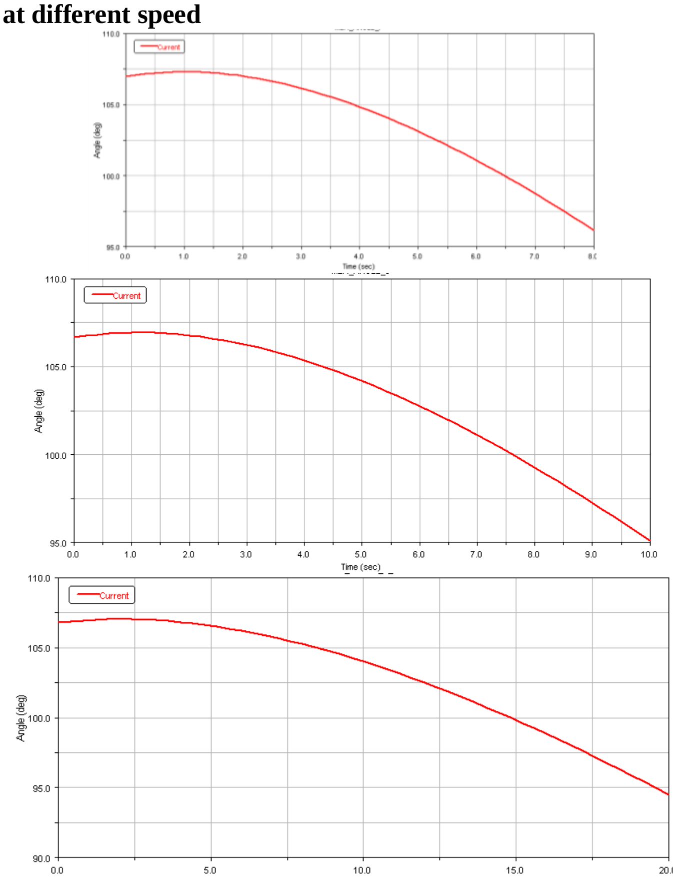

Fig 10 Knee angle variation at different speed 1st =1.5mm/sec, 2nd =1.0mm/s, 3rd = 0.5mm/sec

V. CONCLUSION

In this report mathematical analysis of six-bar linkage Stephenson mechanism for knee joint for above knee amputee prosthesis leg is presented. Dimensions and angular orientation of link are selected. A simulation on MSC Adams is done with various walking speed. A comparison is done with the natural knee joint.

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