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Improved design of sagittal femoral condylar geometry using TRIZ

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Abstract: To make artificial knee joints have lower long-term wear rate, a new method for reformed design of sagittal femoral condylar geometry based on TRIZ (Theory of Inventive Problem Solving) was proposed. Firstly, according to the development history of sagittal femoral condylar geometry and evolution theory of TRIZ, future state of the evolution line of femoral condylar geometry in sagittal plane was predicted. And then, solving principles of technical conflicts were used to propose improved solution of femoral condylar geometry in sagittal plane. The result obtained shows that reformed femoral condylar geometry can improve motion smoothness, low long-term wear rate and increase survival lifetime of artificial knee joint.

Keywords: *Artificial knee joint, sagittal plane, femoral condylar geometry, TRIZ*

1. INTRODUCTION

When people suffer from severe arthritis on their natural knee joint, the implementation of artificial knee replacement can achieve the optimal effect and make sufferers rehabilitate their moving ability to the farthest extent. At present, it is usual that two types of artificial knee joint are used clinically: the condylar prosthesis and the hinged knee prosthesis. The condylar prosthesis, which can be applied in wide range, not only can be easily replaced when the implantation fails but also can realize the best physiological simulation of human being's natural knee. The hinged knee prosthesis is usually used in the situation where the natural knee suffers from severe pathological changes. It is difficult to be overhauled or replaced when the failure of implantation, and cannot simulate the multiple-kinematics mechanism of natural knee perfectly. Thus, the condylar prosthesis occupies a important position in the replacement (Wang, 2004). When the knee joint motions, the location of the condylar prosthesis contact point directly affects the lever arm of the quadriceps, which determines the force necessary to be generated for a given external moment (Otis et al., 1986). When abnormality on the contact points between articular surface of femoral prosthesis and tibial bearing member occurs, the lever arm of the quadriceps will make the passive movement of artificial knee joint produce unreasonable slide. That can impair the normal functions of artificial knee joint such as unsteady movement, the increase of long-term abrasion, and so forth (Warren et al., 1994). Various studies have been carried on the improvement of femoral prosthesis, such as the melioration of unsteady movements and decrease of long-term abrasion, and so on. During this process, the number of radius of sagittal femoral condylar geometry increased gradually (Bercovy, 2005; Biegun et al., 2003; Colleran et al., 1999), which effectively improves the range of the extension and flexion of artificial knee joint. However, such devisal can only warrant the first derivative continuity, which is tangent continuity, between the adjacent piecewise curves of femoral prosthesis in sagittal plane. This will lead to two consequences: one is that the unsteady movement of artificial knee joint will definitely appear on the abrupt contact points of radii of the adjacent piecewise curves; the other is that the abrasion will increase gradually with the time extension of the implantation of artificial knee joint. In there, polyethylene wear of the articular surface is a well-known complication of artificial knee joint (Feng et al., 1994; Huang et al., 1999; Kennedy et al., 2003). Tibiofemoral articular geometry plays an important role in the process of polyethylene wear of the articular surface. According to TRIZ (Theory of Inventive Problem Solving) solving principles of technical conflicts, several authors (Hsu et al., 2006) designed the new artificial knee joint, which transform the pattern of articular surface matching between femoral prosthesis and tibial component from convexity-concave to concave-convexity. It is helpful to avoid the circumstance where the abrasion particles, produced after long-term movement of artificial knee joint, deposit on the concave articular surface of tibial component, and decrease the long-term abrasion of artificial knee joint dramatically. Nevertheless, tangent continuity between the adjacent piecewise curves in sagittal plane still was its design concept of femoral prosthesis. So, the further improvement of curve shape of femoral prosthesis in sagittal plane becomes the key of enhancing the quality of artificial knee joint.

For the purpose of solving the problem of long-term abrasion due to unsteady movement, a new method for reformed design of sagittal femoral condylar geometry was put forward in this article. It was based on evolution theory and solving principles of technical conflicts on TRIZ. Specifically, it can guarantee the second derivative continuity, which is curvature continuity, between the adjacent piecewise curves of femoral prosthesis in sagittal plane. This can eliminate the aberrance owing to the abrupt contact points of radii of the adjacent piecewise curves when the relative movement between tibiofemoral articular surfaces, make the artificial joint knee move steadily, decrease the long-term abrasion, and prolong the service life.

2. METHODS

2.1 The evolution theory and solving principles of technical conflicts on TRIZ

The evolution theory of TRIZ is mainly concerned about the evolvement tendency of technology on structure, that is, laws of technology evolvement, or patterns of evolvement and lines of technology evolvement. This theory can not only predict the development of technology, but also demonstrate the possible structural state of the product based on forecast results, thus it plays a guiding role in product innovation. The solving principles of technical conflicts in TRIZ, a core to invention, make use of the 40 inventive principles to solve those conflicts and make the technology system progress from lowclass form to advanced form along evolution lines, eventually realize the product innovation (Mann, 2002).

In 1990s, Boris Zlotin, expert of TRIZ in USA, developed the evolution theory of TRIZ into eight directed evolution patterns as below (Zlotin et al., 2001):

Pattern 1: Stages of evolution includes: birth, development, maturity and quit;

Pattern 2: Evolution toward increased ideality;
Pattern 3: Non-uniform development of system elements leads to the advent of conflict;
Pattern 4: Evolution toward increased dynamism and controllability;
Pattern 5: Evolution toward increased use of fields through integration;
Pattern 6: Evolution with matching and mismatching elements;
Pattern 7: Evolution toward micro-levels;
Pattern 8: Evolution toward decreased human involvement

These eight evolution patterns result in different evolution lines. In common, a system evolves from its primitive state along pattern 1 and pattern 2, and continues to evolve along the other six patterns after reaching certain level while each pattern has respectively several evolution lines. The process of innovation design usually includes following steps: Analysis-researching the evolution course of assembly in a given technology system and predicting the evolution line of assembly according to patents, papers and other information; Conflict resolving-in terms of the predicted evolution line of assembly, utilize the inventive principle to solve conflicts happened while assembly were progressing from lowclass phase to advanced phase along evolution lines, get innovated assembly and realize the innovation of technology system eventually.

2.2 Reformed design of sagittal femoral condylar geometry using TRIZ

Analysis of data. In terms of the history of artificial knee replacement (Wang, 2004), we summarized the evolution mode of sagittal femoral condylar geometry showed in Figure 1. Here, C and C_i (i=0,1,2) are respectively the curvature center of segments on sagittal femoral condylar geometry.

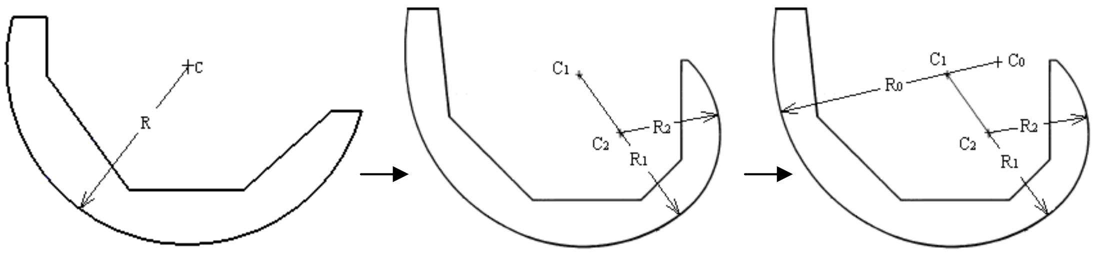


Figure 1. The evolution mode of femoral condylar geometry in sagittal plane.

From Figure 1, the sagittal femoral condylar geometry evolved from the single radius, then to two-segment radius, and now to three-segment radius even the multiple-segment radius. Combined with the monograph about the theory of directed evolution (Zlotin et al., 2001), we put forward the evolution line of sagittal femoral condylar geometry, and predicted the future state of that evolved along the evolution line displayed in Figure 2.

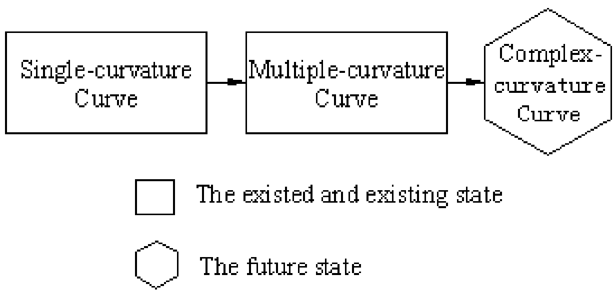


Figure 2. The evolution line of femoral condylar geometry in sagittal plane.

At the forepart of the history of artificial knee replacement, surgeons tried using muscle, fat or other tissues to realize knee arthroplasty. Nevertheless, the real development of artificial knee joint started from the replacement of Co-Cr-Mo femoral unicondylar prosthesis, and at that time the sagittal femoral condylar geometry was mainly composed of single-curvature curves and could only perform the flexion within the range of 90^0 (Wang, 2004). Accordingly, the evolution line of this geometry started from the single-curvature curve.

The evolution line showed in Figure 3 accorded with the directed evolution pattern 2 brought forward by Boris Zlotin. In order to increase the bending range of artificial knee joint and transmit the external load effectively, it needed to simulate the rollback effect with multiple-curvature centers, that is, a combination of backward rolling and sliding of the distal femur along the proximal tibia as the knee flexes (Wang, 2004). The segment number of the sagittal femoral condylar geometry was continuously increasing, also it represented such an inequation: $R_0>R_1>R_2$, which made artificial knee joint better simulate the rollback effect of natural knee joint, increased the bending angle of knee joint persistently and transmitted the external load reasonably.

Utilized the inventive principle to solve conflicts. As shown in figure 2, we found that the evolution process of sagittal femoral condylar geometry was divided into two stages, as following:

The first stage: The sagittal femoral condylar geometry evolved from single-curvature curve to multiple-curvature curve.

The second stage: The sagittal femoral condylar geometry evolves from multiple-curvature curve to complex-curvature curve

From the evolution mode showed in Figure 1 and the evolution line in Figure 2, it is known that sagittal femoral condylar geometry is at the stage of multiple-curvature curve presently. The future state of this evolution line offers a springboard for the innovation of sagittal femoral condylar geometry, namely, the designer can take complex-curvature curve to ameliorate the design of sagittal femoral condylar geometry.

Comparing to single-curvature curve, in order to increase the bending angle, decrease the internal stress and pressure, and make artificial knee joint better simulate the functions of natural knee joint, it needs to increase the segment number of sagittal femoral condylar geometry. However, tangent continuity between the adjacent piecewise curves is still the present technology. And then, the force on the contacting point of relative movement between tibiofemoral articular surfaces will produce a break due to the abrupt radius of the adjacent piecewise curves. Following increase of the segment number of curve, the abrupt forced contacting point between tibiofemoral articular surfaces manifolds, thus, it will debase the long-term stability, increase the long-dated abrasion and shorten the lifetime of artificial knee joint. We used 39 general engineering parameters of TRIZ to describe these limitations as one technical conflict, as below:

Characteristics to be improved: Adaptability

Characteristic that is getting worse: Force

From the conflict matrix, we found that the following three inventive principles have greatest relevance for this technical conflict.

1) Principle 15. Dynamics

2) Principle 17. Another dimension

3) Principle 20. Continuity of useful action

The principle 15 suggests changing the relative position among the segments of sagittal femoral condylar geometry and dividing sagittal femoral condylar geometry into parts capable of movement relative to each other. Through this way, the principle 15 can solve the technical conflict between the increase of number of the segment curve and the decrease of stability of artificial knee joint.

The principle 17 suggests increasing the dimension of the segments of sagittal femoral condylar geometry, for example: changing one-dimensional curves into two-dimensional curves; changing two-dimensional curves into three-dimensional curves. Through this way, the principle 17 can solve this technical conflict.

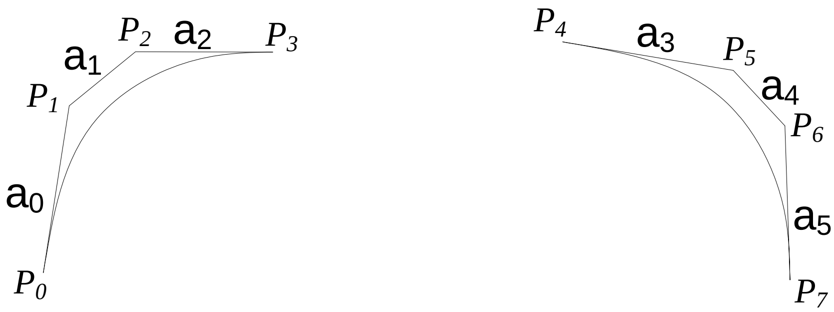
The principle 20 suggests eliminating the break state in the movement process of artificial knee joint for warranting the movement stability of the system. Through this way, the principle 20 can solve this technical conflict.

According to comparative analysis, the principle 20 can be used best to resolve this technical conflict. Specifically, it proposed a method which can ensure curvature continuity between the adjacent piecewise curves of femoral prosthesis in sagittal plane, that is, the complex value of curvature is equal to one another on the ends of the adjacent piecewise curves, then it could solve the technical conflict between the increase of number of the segment curve and the decrease of stability of artificial knee joint. In the case, it not only eliminated the phenomenon where the radius break in the relative movement between tibiofemoral articular surfaces leads to the position abnormality of the contacting point, but also warranted the stability of movement of artificial knee joint, the decrease of long-dated abrasion and the extension of the service life.

The formula where curvatures of endpoints at the segment curve are equal to each other is as below (Hosaka, 1992):

$$-\frac{\mathbf{n}\cdot\mathbf{a}_1}{|\mathbf{a}_2|^2} = \frac{\mathbf{n}\cdot\mathbf{a}_4}{|\mathbf{a}_3|^2} \tag{1}$$

Meaning of the parameters in the equation 1 are shown in Figure 3, $\mathbf{a}_\mathbf{i}$ denotes the position vector of the controlling polygon, while P_i (i=0,1,2......5)and P_j（j=i+1）all denote the endpoints of the control polygon, that is, $\mathbf{a}_\mathbf{i}$ is equal to the position vector of $\mathbf{p}_\mathbf{i}\mathbf{p}_\mathbf{j}$. The left side of equation 1 is the curvature of the rightmost endpoint on the left curve, while the right side of the equation 1 is the curvature of the leftmost endpoint on the right curve. Here, $\mathbf{n}$ denotes the unit normal vector of the endpoint P_3 at the segment curve, $\mathbf{a}_\mathbf{1}$ represents the second position vector counting from the rightmost endpoint at the control polygon of left-side curve, and $\mathbf{a}_2$ is the first position vector counting from the rightmost endpoint at the control polygon of left-side curve as showed in Figure 3 (a). While in Figure 3 (b), $\mathbf{a}_3$ denotes the first position vector counting from the leftmost endpoint at the control polygon of right-side curve, and $\mathbf{a}_4$ is the second position vector counting from the leftmost endpoint at the control polygon of the right-side curve.



(a) The control polygon of left-side curve (b) The control polygon of right-side curve

Figure 3. The control polygon of curve.

3. RESULTS

According to the inventive principle 20 and equation 1, we inferred the curve shape of complex curvature value of femoral prosthesis in sagittal plane showed in Figure 4.

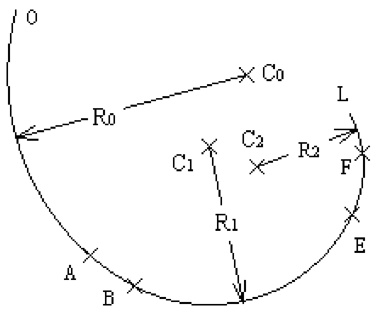
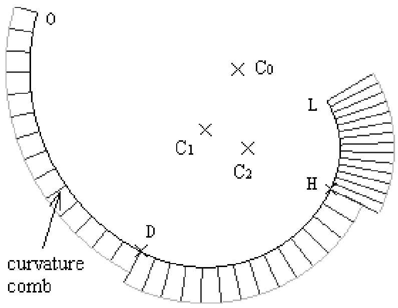


Figure 4. The curvature continuity curve of femoral condylar geometry in sagittal plane.

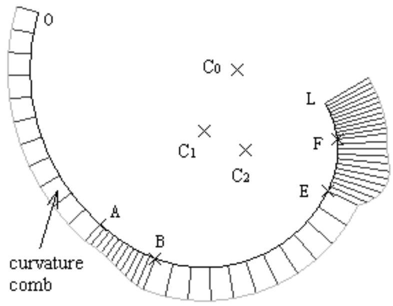
From Figure 4, it was seen that the radius of curve segment OA is R_0， while radius of BE is R_1 and radius of FL is R_2. It also showed that curve segment AB is a transition which ensures the curvature continuity when transiting from R_0 to R_1, and curve segment EF is a transition which ensures the curvature continuity when transiting from R_1 to R_2. Here, C_0, C_1 and C_2 are respectively the curvature center of OA，BE and FL.

4. DISCUSSION

Figure 5 denoted the sketch of comparative analysis between tangent continuity and curvature continuity of sagittal femoral condylar geometry.



(a) Tangent continuity



(b) Curvature continuity

Figure 5. The curvature analysis of femoral condylar geometry in sagittal plane.

From Figure 5 (a), it was known that on sagittal femoral condylar geometry, the curvatures of OD, DH and HL all kept constant, however, on the position of D and H, the endpoints of the segment curve, the shape of the curvature comb produced a break which made the phenomenon appear where the movement became unstable at the abrupt contact points of radii of the adjacent piecewise curves on artificial knee joint. Thus, along with the extension of the implanting time of knee prosthesis, the abrasion of artificial knee joint would become larger and larger. Here, C_0, C_1 and C_2 are respectively the curvature center of OD，DH and HL. In Figure 5 (b), we can see that the curve OL adds the transition curve segment AB and EF to itself, whose curvatures keep changing differing from the situation where the curvatures of OA, BE and FL all stay constant. The curvatures of the curve around the endpoint are equal to each other at the points of A, B, E and F, which can make the shape of curvature comb not produce any break and the radius of the curve equal to each other at A, B, E and F, consequently, it will eliminate the phenomenon where the movement becomes unstable at the abrupt contact points of radii of the adjacent piecewise curves on artificial knee joint, and finally decrease the long-term abrasion of artificial knee joint as well as prolong its life-span. Here, C_0, C_1 and C_2 are respectively the curvature center of OA，BE and FL.

5. CONCLUSIONS

This paper proposed a new method for reformed design of sagittal femoral condylar geometry based on TRIZ. On the foundation of analyzing the evolution history of sagittal femoral condylar geometry, we put forward the evolution line of sagittal femoral condylar geometry, predicted the future state of sagittal femoral condylar geometry developing along the evolution line, and resolved the technical conflict between the increase of the segment number of sagittal femoral condylar geometry in the course of evolution and the decrease of stability of artificial knee joint. Eventually, we got the ameliorated solution of sagittal femoral condylar geometry, in which curvature continuity appeared between the adjacent piecewise curves, and it eliminated the phenomenon where the movement became unstable at the abrupt contact points of radii of the adjacent piecewise curves on artificial knee joint, also decreased the long-term abrasion as well as prolonged the service life. In order to realize such design concept in the real products and produce the experiment result which accords with the physiological conditions, every kind of factors should be considered in the advanced research, such as the lubricating environment of the real inner artificial knee joint, the biomechanics characteristics of the parenchyma around the knee joint and so forth.

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