PROSTHETIC JOINT REPLACEMENT USING SURFACES OF REVOLUTION FOR TWO OFFSET AXES OF ROTATION

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ABSTRACT

Recent evidence suggests that many human joints move about one or more offset-fixed axes of rotation. The articulating portions of current prosthetic joints are frequently surfaces of revolution for axes of rotation perpendicular to the bones and to each other. A new technique is described using mathematically derived surfaces of revolution for two offset-fixed axes of rotation to create prosthetic joint replacements. These resulting articular surfaces restore the normal joint kinematics and thus the balance of muscle and external forces.

In our work, a single mathematical representation for all model elements is used...double precision non-uniform rational B-splines (NURB or NURBS). The skewed torroid-like surfaces are created using two methods, revolved or swept NURB surfaces. The software and modeling methods allow integration of multiple shape, fit, and structural analyses (including finite element solutions) during early design phases, setting the stage for full appreciation of concurrent engineering benefits.

INTRODUCTION

It is very important that a prosthetic joint replacement restores normal joint kinematics. The location and orientation of the axes of rotation determine how the bones move about each other. The mechanical advantage of the muscles and external forces are determined by their distance from and angle of application relative to the axes of rotation of the joints. Changing the location, nature or number of the joint's axes of rotation changes the spacial motion, the mechanics and the joint reaction forces for a given external load, effecting not only the resurfaced joint but the remaining joints in the extremity. Allowing more degrees of freedom in the prosthesis than are found in the natural joint usually results in a shortage of local motors (muscles) to control the joint position and the application of force. This, in turn, fatigues the soft tissue and cancellous bone near the joint replacement.

We have developed a new method of using the surfaces of revolution for two offset fixed axes of rotation, a skewed torus, to create articular surfaces for prosthetic joint replacement. From these surfaces full joint models are created, and analyzed for articular contact areas, kinematics, shape with respect to normal healthy articular surface anatomy, potential lift-off or impingement at extreme ranges of normal motion, and finally mechanical strength.

Design processes are often iterative in nature. When analysis or test results indicate that model alterations are required to meet initial design objectives, changes are implemented and the components are re-evaluated. By using a modeling method and CAD software flexible enough to allow completion of several analyses during the initial design phases, we can minimize the risk for late changes. Late design changes need to be prevented because they exponentially increase project costs in terms of time and dollars. *Surfaces which can be used in thumb cmc joint and tibio-femoral knee joint creation are shown as examples.* **(Figures 1 & 2)**

MATERIALS AND METHODS

Computer aided design (CAD) and engineering analysis (CAE) software, is used to create solid models of the implant surfaces (and subsequently of each component of the joint implant) whose surfaces are NURB surface patches bounded by curves. The mathematical description for creation of NURB surfaces of revolution and NURB swept surfaces have been previously published. The software we used, SDRC IDEAS Master Series, integrates the solid modeling mathematics with finite element modeling (FEM) and analyses (FEA). In CAD systems which utilize non-rational Bezier splines and rational formulae for arcs and curves, a similar process can be used to create the joint surface geometries, however, the mathematics will be altered.

RESULTS - SKEWED TORROIDAL SURFACE CREATION

Preliminary construction geometry requirements vary with CAD systems. At least two methods can be used for skewed torroidal surface or solids creation. One requires creation of a portion of a circular arc to be used as a sweeping curve path. The other requires creation of the axis of revolution and planer projections of the 3-D curves. In most CAD software, "simple" surfaces of revolution must be created from geometry which lies in the same plane as the axis of revolution. Thus the surface shape "revolved" is a shape which is essentially a projection (NURB curve) of the desired 3-space curve onto the required plane.

STEP 1. Insert points at origin of the first axis and the second axis of rotation. Construct both axes. To visualize the torroidal shape to be created, build a circle composed of at least two arcs whose origin is on the first axis, and passes through the second axis near the center of the bone curvature shape for the second axis. One of these arcs (or an in-plane offset of this arc) can later be used as a swept surface path. This circle must be perpendicular to the first axis.

STEP 2. Create a second circle or a circular arc component with the desired surface radius. Orient the curve portion of the geometry so that the axis lies in the correct non-orthogonal position as described for the joint axis The origin location on this axis should allow near duplication of natural (healthy) joint shapes. This second curve geometry can be used as a portion of the open or closed curve section required for swept surfaces creation or it can be projected onto the appropriate plane and be used to create revolved surface geometries. To create solid parts closed section geometries with appropriate geometric constraints must be created. Several closed geometries can be used to create the articular surface desired as long as the circular arc or NURB curve shape of interest is a part of the section, and is appropriately positioned for the sweep or revolve tasks. Create the desired sweeping path or axis of revolution geometries. Only one of many possible paths and axes were created in *STEP 1*.

STEP 3. Once preliminary geometries are created and positioned the final surface or solid shape is generated using the standard sub-routines for swept surfaces or surfaces of revolution.

STEP 4. Variations of implant articular surface shapes are created and analyzed to evaluate the effects of specific parameters on the joint mechanics or kinematics.

DISCUSSION

The skewed torroidal surfaces can be used directly as the articular surface geometry (wrist, ankle, thumb cmc, hand and foot mp joints, or the knee). The surface creation and modification techniques allow design variation to account for material properties and other considerations in prosthetic design while preserving the mechanics necessary for function.

Current prostheses for joints which move about one or more fixed offset axes of rotation do not allow the surgeon to restore normal kinematics. Most are based on fixed axes of rotation which are perpendicular to the bones and to each other including those for the knee (hinged type), wrist, finger and toe (CMC, MP and PIP joints), ankle, elbow, and shoulder. Most "minimally constrained" prostheses allow multiaxial motion because one or more axes of rotation are either not present within the implant design, or are not fixed with respect to both articular components. Many current total knee designs are based on a changing horizontal axis of rotation. Prostheses for joints which move about one or more fixed offset axes of rotation must allow motion about these axes without adding detrimental torsional, shear and compressive stress concentrations to the living tissues surrounding the resurfaced joint or surrounding the other joints in the extremity.

Creation of total joint implants with axes of rotation identical to those found in healthy normal joints, and with skewed torroidal surface components, will give surgeons a tool which *will* allow them to restore normal kinematics to the effected limb.

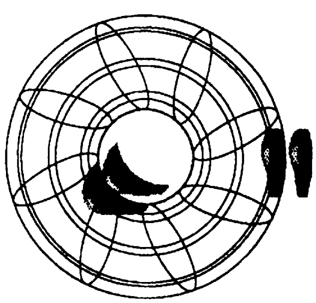

Figure 1 - skewed torriod for the cmc joint created with swept surfaces. The location of the axes determines the surface saddle shape.

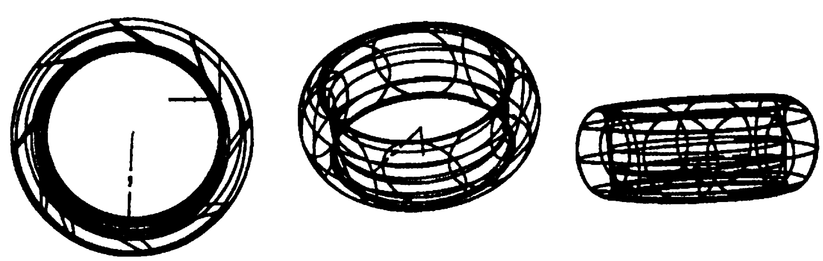

Figure 2 - skewed "flat" torriod for lateral condyle of an average knee: left - transverse view; middle - isometric view and right - AP (coronal) view. The knee 's flexion-extension axis is posterior to the lateral rotation axis.

These surfaces have been used in subsequent work to model joint prostheses. In this work, a thumb based cmc joint design has been created which meets the following objectives:

- The articular surface shapes and simplified surgical tools allow the surgeon to restore normal mechanics and kinematics of the joint.
- The prosthesis components transfer stresses to the cortical bone in a manner which prevents macromotion and hence minimizes wear debris at the bone-prosthesis interface.
- The prosthetic articular surface contact stresses and internal Von Mises stresses are well within acceptable performance levels for the materials used, minimizing the potential for articular surface wear debris and implant fatigue failure.

Full description of the development process including test methods and results can be discussed, and will be documented in full length papers.