# SIMULATED ARTICULAR SURFACE SHAPES FOR THE THUMB CARPOMETACARPAL JOINT

**Mari S. Truman**
ArthroMotion
Warsaw, Indiana

**Anne Hollister**
Department of Surgery
Rancho Los Amigos Medical Center
Downey, California

**ABSTRACT**

A computer aided design (CAD) technique is used to create a *series* of surfaces for a thumb carpometacarpal (cmc) joint based upon its kinematic mechanism. Conics are incorporated in the torroidal shape to facilitate efficient modeling of complex articular cartilage anatomy. The resulting surfaces are compared to determine the relationship between the revolute orientation and surface shape. The simulation techniques and the effect of the conic variations on range of motion and stability are discussed and compared to preliminary results for other fixed axis joints.

**INTRODUCTION**

The interacting surfaces of the offset-fixed axes (Hollister et al, 1992) of the saddle shaped cmc joint can be modeled as skewed torroids(Truman et al, 1994). Conics were incorporated in the torroidal shape to simulate a series of anthropomorphic surface shapes. Curve analysis and kinematic studies were performed with the solid models to quantify the accuracy and validity of the simulations. The techniques and resulting articular surfaces geometries will be used in future analyses to discern the potential to minimize material stresses within the cartilage, bone, and potential joint prostheses.

**MATERIALS AND METHODS**

Computer aided design (CAD) and computer aided engineering (CAE) analysis were used to design and analyze solid models of the articulating surfaces. A Hewlett Packard Apollo 9000 Series 715/50 workstation, with HP-UX 9.01 through 9.05 UNIX software (Hewlett Packard Van Nuys, Ca) and Structural Dynamics Research Corporation's (SDRC) (Cincinnati, OH) IDEAS Master Series (versions 1.0 through 2.0) CAD and CAE software were used to develop the joint surfaces. The surfaces are nonuniform rational Bezier splines (NURB) surface patches bounded by curves generated from surfaces of revolution or swept surfaces (Truman et al, 1995). The sweeping path for all anatomic models included a conic with an increasing radius about the trapezial axis from the center of the joint to the volar aspect of the trapezium. Varying conics in NURB spline form replace constant radii arcs in the swept surface technique to facilitate efficient modeling and subsequent analyses of complex articular cartilage anatomy. (Figure 1). Using this method, natural joint surface curvatures are incorporated with the kinematic definition to reproduce cartilaginous surface shapes with surface fit and curvature characteristics nearly identical to natural human specimens. A saddle shaped patch of the torroidal surface with the desired range of motion is selected. Closed section geometries are used during all modeling steps to create solid parts. Curve analysis, and evaluation of congruency were performed with the solid models using the methods of Atesian et al (1992). Various standard CAD/CAE software subroutines were used to position the models and measure interference, liftoff and volume between articular surfaces in the pinch position and for extreme ROM positions.

Point and surface curvature (gaussian, max, min, mean, rms), surface areas, surface area increase due to curvature variation, effective dorso-radial saddle depth on the trapezium, typical trapezial cross section curvature plots, “congruency” in pinch, and volume between surfaces in pinch position (unloaded) were recorded for 8 simulated trapezial and 4 simulated metacarpal surfaces (4 pairs).

## RESULTS

Curve and curvature analyses showed similar patterns to those reported for normal bones with circular curves in the middle of the saddle and ellipsoidal curves at the periphery(Figures 2 & 3). Congruity of the joint varies with position, the most congruous position being in flexion abduction. The configuration space for the joint shows all three anatomic rotations and displacements for the metacarpal on the trapezium. When comparing bones surfaces shapes, either physically or in the CAD environment, the regions of high bone congruency and inherent stability were always associated with peak load positions.

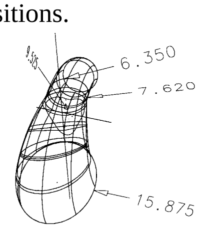


Figure 1. Wireframe of varying conic torroidal surface (units mm).

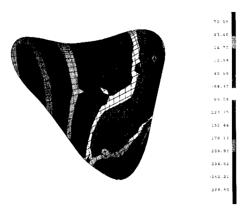

Figure 2. Typical trapezial surface gaussian curve study output (units 1/m).

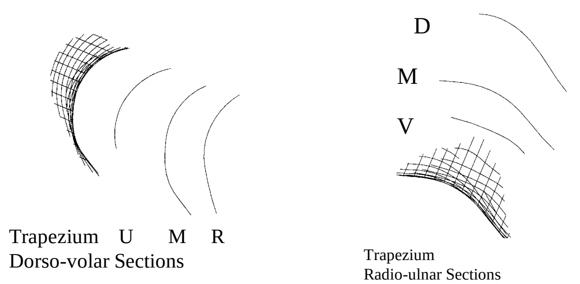


**Figure 3**. Curvature analysis of the metacarpal and trapezial surfaces after Atesian et al (1992). The centers of the surfaces shapes have circular curves whilst the outer portions are ellipsoidal. This is similar to the pattern seen in human specimens.

## DISCUSSION

We have modeled the surfaces of several fixed axis joints including the wrist, metacarpo-phalangeal(mp), proximal-interphalangeal (pip), knee tibio-femoral and knee patello-femoral joints. Full surface congruency is NOT found in most human joints. The competing requirements for stability (motion control), motion, nutrition, and lubrication result in a compromise surface shape. Several common findings will be discussed.

Pelligrini et al, (1991) focused on the role of the soft tissue stabilizers of the cmc joint. In numerous publications Grood has documented the role of ligamentous, meniscal and capsular structures in stabilizing the knee (e.g. Grood et al, 1988). **Our work in the cmc joint complements these efforts and the efforts of North et al (1983), and Atesian et al (1992) by focusing on the role of cartilaginous and bony surface shape in joint kinematics and mechanics**. Ligaments and other soft tissues are stabilizers which help to keep the surfaces in close approximation so that the shapes of the joint components and respective motors can maintain control of the motion envelope. In positions which require high force transmission, bone surface shapes provide inherent stability to the joint. CAD/CAE assisted modeling and analyses of joint surfaces is a new and promising tool for understanding joint structure and function.

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1) Motion is restricted by surface shape in positions where stability is required.
2) Surface shapes reduce shear and torsion on bone and other stabilizers.
3) Articular surface shapes are asymmetric.
4) Torroidal surfaces can be used to reconstruct diseased articular surfaces.
5) More complex varying conic swept surfaces are required to duplicate cartilaginous anatomy. Simple torroidal surfaces do not fully represent the motion envelope of most human joints.
6) Joint surfaces have the highest contact surface area (highest congruency under load) in positions requiring high force transmission.
7) There are common joint shape variations which are predisposed to functional problems such as dislocation or degenerative problems such as osteoarthritis.

8) Bone asymmetry aids other stabilizers in resisting joint dislocation.

The extended thumb is inherently less stable than the flexed thumb. The dorsal portion of the thumb surface matches the kinematic torroidal surface shape exactly. However, when the joint is rotated to full flexion, the shape changes to prevent continuous rotation about the FE axis, providing additional stability in high force activities. More adduction than abduction is allowed with respect to the neutral position. Further Abduction-or adduction motion in these positions results in joint interference on one side and lift off on the opposing side. The joint is self- centering under high loads. For the cmc joint, only a torroidal surface patch taken from a simple surface of revolution for the joint's revolute will allow full congruency in peak load positions. (Figure xxxx) However, the spacial motion envelope is sacrificed. The ROM is typically less restricted in the FE direction and more restricted in the AB-AD direction.

Biomechanics analyses which have taken into account the offset axes locations during setup and calibration (hand biomechanics workstation (xx) - and mechanical testing systems (knee simulator - Joel Bach (xx) have generated results with higher reproducibility and higher correlation to in-vivo performance than prior analyses. Hollerbach and Hollister (xx) have shown that Eulerean angle methods can not be used to accurately describe joint motion unless the coordinate reference frame is aligned with the joint's mechanism (axis of motion).

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).

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