Metacarpophalangeal Joint Replacement

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Abstract

Patients with congenital hand defects or severe trauma have few options for recovering normal function. Current metacarpophalangeal (MCP) joint replacements rely on ligaments to stabilize the implant. Several design alternatives for the joint between the proximal phalange and the metacarpal that do not rely on ligamentous support have been designed and the most promising has been pursued. The design has been tested for range of motion and ability to bear loads everyday activities. The test results have been analyzed and improvements have been suggested.

Background

Anatomy and Terminology

- MCP joint falls between the proximal phalange and the metacarpal
- Collateral ligaments connect the metacarpal to the proximal phalange
- The volar plate prevents hyperextension of the finger

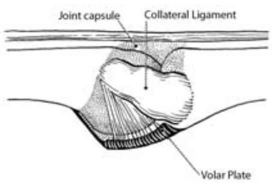

Figure A[1]. Collateral ligaments and volar plate.

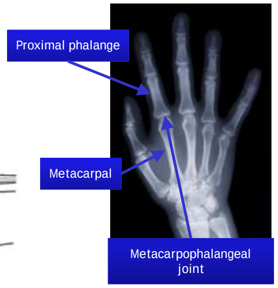

Figure B[2]. Location of MCP joint, proximal phalange, and metacarpal.

Competition

- Silicone implant
  - Micromotion due to inability to osteointegrate
- Semi-constrained implant
  - Does not prevent dislocation under tensile loads

Figures C[3] (top) and D: Silicone implant and semi-constrained implant

Problem Statement

Figure E. Example of congenital hand defect (symbrachydactyly).

- Patients who suffer congenital defects or severe trauma lack collateral ligaments and a volar plate
- Desired joint replacement should not require collateral ligaments for joint stability

Design Criteria

Client Requirements	Design Specifications
Functional range of motion	20^{o} extension to 90^{o} flexion [4] 40^{o} abduction and adduction at 0^{o} flexion [4]
Lifespan of at least 10 years	Withstands ~310 million cycles at varying movement angles [5]
Withstand physiological loading	70 N pinch grip [6] 464 N power grip [7]
Appropriate mode of failure	Lowest factor of safety at the articulating surface
Biocompatible	Uses materials that are FDA-approved
Osteointegratable	Stems coated with surface treatment

Final Design (Interlocking Groove)

Materials implemented:
- Metacarpal component-
  - Cobalt chrome (CoCr) plasma sprayed and coated in hydroxyapatite
- Phalangeal components-
  - Ultra-high molecular weight polyethylene (UHMWPE)
  - CoCr plasma sprayed and coated in hydroxyapatite
  - CoCr pin connection

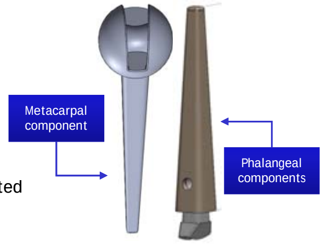

Figure F. SolidWorks model of final design.

Features of design:
- Interlocking groove controls range of motion
  - 45^{o} extension to 90^{o} flexion
  - 10^{o} adduction/abduction at 0^{o} flexion
  - 1^{o} adduction/abduction at 90^{o} flexion
- Insertion at 45^{o} hyperextension
- Narrowing groove to model abduction and adduction
- Hyperbolic paraboloid geometry on articulating surface

Analysis of External Forces

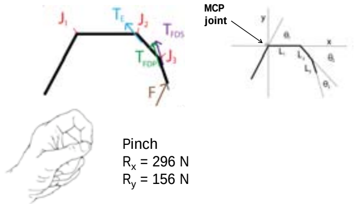

Figure G[8]. Pinch free body diagram.

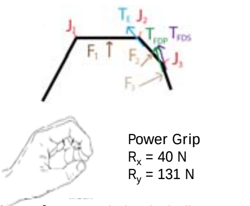

Figure H[8]. Power grip free body diagram.

- Large variation in predicted internal forces in literature
- Simplifying assumptions were required for free body diagrams
- Tendon forces are similar for pinch and power grip
- For pinch, joint reaction forces are within the literature range [9]
- For power grip, joint reaction forces are smaller than literature values [6]

Testing

Finite Element Analysis

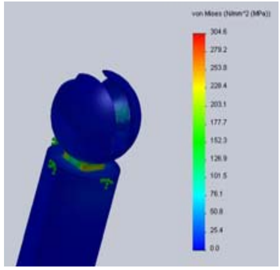

Figure I. Metacarpal component in power grip loading.

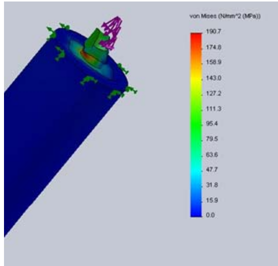

Figure J. Phalangeal component in power grip loading.

Figure K. Cross section showing potting of the metacarpal component.

Limitations of Current Design

- UHMWPE component cannot withstand physiological loading
- Center of rotation for adduction/abduction is not anatomically correct
- Requires modifications where the stem meets the articulating feature

Future Work

- Modify design to address limitations
- Optimize dimensions using FEA testing
- Analyze failure modes
- Implant into cadaver hand
  - Determine ease of implantation
  - Confirm range of motion
- Begin wear testing

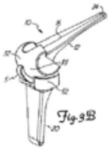

Figure L[10]. Patented MCP joint replacement.

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References

1. Kleinert, HE. Sunil, TM. Use of volar plate for reconstructing the radial collateral ligament after metacarpophalangeal arthroplasty of fingers in rheumatoid arthritis: Surgical technique. The Journal of Hand Surgery, 30(2): 390-393, March 2005
2. Spectrum data. "X-Ray Scanning & Film Digitisation." 2009. http://www.spectrumdata.com.au/service.aspx?sid=39.
3. Small Bone Innovations. "Surgical Technique." 2008. http://www.totalsmallbone.com/us/pdfs/MKT%2010610%20Rev%20B.pdf
4. Pylios, T., et al. "Biomechanics of the normal and diseased MCP Joint: Implications on the design of joint replacement implants. J Mechanics in Medicine and Biology, 7(2): 163-174, 2007.
5. Fowler, NK et al. "Long-term measurement of metacarpophalangeal joint motion in normal and rheumatoid hand." IMechE, 215(H): 549-553, 2001.
6. Beevers, D. J. et al. "Design of a non-constrained, non-cemented, modular, metacarpophalangeal prosthesis." IMechE, 209: 185-195, 1995.
7. Irwin, CB. Radwin, RG. A new method for estimating biomechanical loading in grip. Proceedings of the Human Factors and Ergonomics Society 47th Annual Meeting 1126-1130, 2003.
8. Chao, E. Y. et al. "Three-dimensional Force Analysis of Finger Joints in Selected Isometric Hand Functions." J. Biomechanics, 9: 387-396, 1976.
9. Dennerlein, JT et al. "Tensions of the flexor digitorum superficialis are higher than a current model predicts." J. Biomechanics, 31(4): 295-301, 1998.
10. Lippincott III, Albert L. "Constrained Prosthesis for Replacement of Joints between Long Bones in the Hand." Patent 5,938,700. 17 August 1999.