Published in final edited form as:

J Hand Surg Am. 2018 March ; 43(3): 248–259. doi:10.1016/j.jhsa.2018.01.002.

The Teleology of the Thumb: on Purpose and Design

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Abstract

The Andrew J. Weiland Medal is presented by the American Society for Surgery of the Hand to a mid-career researcher dedicated to advancing patient care in the field of hand surgery. The Weiland Medal for 2017 was presented to the author at the annual meeting of the American Society for Surgery of the Hand. The purpose of this article is to present current evidence on how biomechanics and morphology influence the pathophysiology of thumb carpometacarpal joint (CMC) osteoarthritis.

Keywords

thumb; osteoarthritis; carpometacarpal; trapeziometacarpal; kinematics; functional tasks

Evolutionary development of the brain has afforded the accomplishment and possibility of the human hand (1–6). In turn, the hand and thumb serve the human brain – the actuator and receiver to perform simple activities of daily living, and, to the artist or athlete, highly coordinated movement. The teleology of the trapeziometacarpal joint - the thumb carpometacarpal (CMC) joint - represents the inextricable relationship of function to form. The CMC's unique saddle shape represents a complex design that accommodates similarly complex demands: mobility to produce precision pinch and firm grasp, and stability to manipulate or position an object. (7,8). The paradox of motion arguably drives the design.

The conventional wisdom regarding the etiology of CMC joint osteoarthritis implicates ligamentous laxity, postmenopausal hormonal imbalance, and the wear and tear of daily life. Despite being the most common site for surgical treatment in the hand (9), controversy exists regarding the varying roles of these factors as primary, secondary, or interrelated contributors (3,6,10,11). Compelling research on systemic osteoarthritis suggests a more intricate balance of joint homeostasis, with pathomechanics considered the driving force to up-regulate inflammatory markers and injure the surrounding soft tissue structures of the joint itself (12–14). With the premise of osteoarthritis as an organ system gone awry, we will

review current evidence that thumb CMC joint OA reflects its teleology – its purpose and design.

As to Purpose – Biomechanics

The thumb ray, in the neutral state, is out of plane to the rest of the hand but opposes the fingers, ever ready for digital communication. Three tasks representing the breadth of thumb CMC stability, mobility, and demands in opposition include lateral key pinch, grasp, and torsional grip such as a jar twist (6,10). In pinch, the thumb pad engages another finger, and in grasp, acts in concert with the fingers to close around an object. Fine motor intrinsic muscles stabilize the joint for key pinch. Grasp - prehension - typically requires forceful isometric load to accommodate a larger spherical or cylindrical shape, actively engaging intrinsic and extrinsic muscles. Opening a jar adds a torsional or shear load to the grasp position. The CMC joint carries extraordinary load in these routine tasks, and cadaveric biomechanical studies indicate that grasp produces a ten-fold increase in stress at the CMC joint compared to pinch (15).

What is the *in vivo* evidence of force generation and motion, supporting laboratory studies? The answer lies in analyzing the interdependent joint motion of the trunk and extremities, as well as discrete motion at the CMC joint. The hand is the terminus of coordinated, integrated movement of the upper extremity. Like the early hominins, good trunk and leg support, freeing a mobile shoulder, permits three-dimensional, spherical opportunity for the hand. This linkage creates powerful mechanical coupling for hand manipulation.

Examining abnormal motion best elucidates normal coordinated function. We have examined the hand, upper limb, and trunk in purposeful motion of reach and grasp of an object; as well as pinch, grasp, and jar opening with marker-based kinematic analysis (16–18). Like with abnormal gait, an errant golf swing (19), or the contracted space of a spastic upper limb (16,17), compensatory motion that is phasic in nature can be quantified. In each study, subjects with abnormal motion took longer to complete a task, used substitutions, and had compromised efficiency. For hand tasks, typical substitutions include shoulder abduction with elbow flexion to improve mechanical advantage. The adducted, arthritic thumb dynamically compensates with increased metacarpophalangeal (MP) abduction and extension (18). Our quantification of complex interactive hand and thumb motion in both normal and abnormal states provide target zones for emulating functional activity. We propose that this serves as a basis for creating training tools for rehabilitation, both in the non-operative and peri-operative setting.

We have analyzed the functional tasks of key pinch, cylindrical grasp, and jar twist (Figure 1) in asymptomatic, healthy subjects without radiographic disease, compared to those with early symptomatic arthritis (modified Eaton 0/1(20)). The cylindrical grasp demonstrated weakness in the early OA population when adjusting for age, sex, and handedness. Standard gross grasp dynamometer measurements in these subjects showed no difference in comparison to asymptomatic controls (21). In addition, key, tripod, and tip pinch diminished in the early OA population compared to controls, with key pinch the most robust predictor of

OA (22). This suggests sensitive measurements exist for early, symptomatic disease, which may complement and refine non-operative joint protection and strengthening protocols.

The discrete and complex nature of the CMC joint poses a challenge to define during purposeful, coordinated motion. Micro-motion at a discrete joint may be analyzed with computed tomography (CT), with markerless motion analysis protocols adopted from large joint (hip and knee) kinematic analysis, as well as the wrist dart-thrower's motion (23,24). Our 10-year longitudinal, multi-institutional investigation of the thumb CMC joint examines age, sex, and radiographic disease and CT kinematics of the 3 functional tasks performed at 80% effort as measured by positioning jigs with an embedded load cell (Figure 1). Defining neutral with a thumb splint adjusted for subject's hand size, we have measured position based on segmented joint morphology for neutral, extension, flexion, abduction, and adduction, as well as loaded and unloaded pinch, jar twist, and grasp (25).

Analysis of the asymptomatic, disease-free subjects has revealed surprising results. Isometric loading of the CMC joint in 46 asymptomatic subjects (22 men and 24 women), with no radiographic OA and matched in two age cohorts (age 18–25 and age 40–75), revealed motion patterns unique to the 3 tasks. This motion, however, did not differ between men and women of either age cohort (26). Motion patterns differed with age, although not consistently across tasks (Figure 2). The directions of coupled CMC joint motion included flexion, internal rotation, and volar translation during key pinch (Figure 3A); external rotation, abduction, ulnar, distal, and volar translation during jar grasp (Fig. 3B); and proximal translation during jar twist (Fig. 3C) (26). Furthermore, internal rotation and ulnar translation were coupled with flexion (27), indicating a potentially stabilizing screw-home mechanism, as proposed by Edmonds's cadaveric descriptive study (28). This complex coupled motion, in concert with rotation, recalls the stabilizing effect of knee extension (29).

Joint congruency, considered a mark of a stable joint in a ball-and-socket articulation, is more difficult to interpret in the normal CMC joint. Based on joint position and polar histograms of curvature (Figure 3), we found that the joint was most congruent in the neutral position, that congruency differed between the tasks, but that there was no statistical difference between men and women in how the joint was positioned (25). This analysis included 68 asymptomatic subjects, again age-matched (16 men, 17 women, ages 18–25, and 16 men, 19 women, ages 45–75). In contrast, 87 subjects with modified Eaton stage 1 and 2 arthritis (20), age 45–75 (39 men ave. age 60, 48 women ave. age 52), joint congruency was consistently lower in all positions (25–27).

Joint stability assessment produced more surprising results. Stability was measured by metacarpal translation during the various tasks, with the most translation found in key pinch compared to other tasks. This did not differ between men and women or between asymptomatic (44 subjects) and early arthritic (modified Eaton 1 – 76 subjects) individuals (30). Beighton hypermobility scores (31) did not correlate with translation, although scores trended towards lowering with increasing age. As noted, weaker key pinch most correlated with early symptomatic arthritis independent of age, sex, and body mass index (BMI) (21,22).

Based on the *in vivo* biomechanics of purposeful movement, we have thus far challenged the concept that women have intrinsic laxity that makes them more susceptible to wearing out the CMC joint. Where else can we look?

As to Design - Morphology

Further analysis of anatomy and pathoanatomy contribute to inferred function in normal and pathologic shape. The biaxial “saddlejoint” described by Gray as an “articulation by reciprocal reception” (32) bears morphology like no other: the first metacarpal-trapezial surface is largely convex in the volar-dorsal plane and concave in the radial-ulnar plane, with a curved complement, although more loosely so, on the metacarpal surface (Figure 4). Furthermore, the radial side is elongated, and extra-articular protuberances for ligaments and draping muscles preclude a perfect double saddle (6,33).

Osteology

The CMC joint lacks the stable bony configuration of a ball-and-socket joint such as the hip, and its loosely reciprocal, eccentric configuration lends to differential joint congruity that supports the screw-home mechanism of the knee (6, 25,28–30). In contrast to previous reports (34–36), we found no difference in the shape of the trapezium and 1st metacarpal between men and women in 50 healthy, age-matched, asymptomatic subjects. With shape modeling analysis, the only difference encountered between men and women was size (37). We additionally identified older healthy subjects, compared to healthy young subjects, as having higher curvature in concave and lower curvature in convex directions of the trapezial and metacarpal reciprocating surfaces (38). Subjects with early OA (modified Eaton 1/2 (20, 39–41)) had significantly different metacarpal and trapezial articular shapes from healthy subjects of the same age. These findings suggest that aging and OA affect the articular shape of the CMC joint, but challenge current concepts that inherent sex differences based on shape are responsible for the higher incidence of CMC OA in women (42).

Furthermore, utilizing our standardized CT segmentation technique, we identified decreasing subchondral bone distance, indicating cartilage wear, in early OA subjects with absent or minimal x-ray changes (modified Eaton 0/1 (20) (Figure 5). A change in center of pressure - the “centroid” - occurs with each loaded and unloaded position in women (42). The larger joint space area, representing diminished cartilage distance, was also encountered in older asymptomatic female subjects without radiographic arthritis (Figure 6). This suggests that joint space narrowing precedes radiographic arthritis in women, supporting the concept of female predisposition to develop OA (42). Our preliminary analysis of progression in the early OA cohort magnifies this effect, with half of subjects progressing one modified Eaton stage by 3 years.

At the other end of the spectrum from our *in vivo* early OA cohort, we have also focused on advanced arthritis. The accessible population are surgical patients, by definition a symptomatic population with end-stage clinical disease, regardless of radiographic staging. With micro-CT, we have identified that the volar ulnar trabecular bone in 16 explanted trapezia has greater trabecular number and connectivity compared to 13 trapezia without arthritis (43). This increase in bone density suggests preferential loading in the volar ulnar

quadrant, supporting the concept of concentrated force loading with degeneration. In addition, surgically excised trapezia display 3 reproducible patterns of wear: 1) retained saddle configuration with minimal osteophyte formation; 2) reversal of the volar-dorsal convexity into one large concave “dish” with extensive rimming osteophytes, especially beneath the abductor pollicis longus (APL) radially and the flexor carpi radialis (FCR) ulnarly; and 3) a volar concave neo-facet encountered in the corresponding region of the volar metacarpal beak, similar to a glacier “cirque” (Figure 7) (44). Whereas a retained saddle typically represents “early” or “mild” radiographic disease, no correlation exists between “advanced” severity and modified Eaton 3/4 (20). Whether this patterning represents a degenerative continuum or a divergent pathway is unclear. We favor the divergent pattern prediction, given radiographic heterogeneity and surgical findings.

Trapezia with scaphotrapezial and other facet involvement (modified Eaton stage 4) display variable changes to the 1st metacarpal surface that defies a concept of disease progression as a continuum, and the inadequacy of radiographic staging (41,45,46). Ascribing “early” vs “late” arthritis to radiographic disease, whether Kellgren-Lawrence (47) or Eaton (20,39–41,45) is likely a misnomer. Reproducible, measurable radiographic classifications may better characterize disease progression or divergence. The pronated anteroposterior Robert view visualizes the metacarpal-trapezium surface in radioulnar (RU) profile (48). The Thumb Osteoarthritis Index (ThOA) measuring this RU width to the height, correlates to the extent of cartilage eburnation and is highly reproducible. Measurements >1.55 corresponded to significant degeneration and Eaton 3/4 staging (Figure 8) (20). This represents a reliable measure of dysmorphology (Figure 9) and provides the opportunity for further correlation with clinical and subjective measurements, and can inform treatment decisions.

Ligaments

Ligaments confer stability, especially in loose joints with eccentric surfaces such as the shoulder and thumb CMC. The anterior oblique ligament (AOL) has been implicated as an important stabilizer and the focus of reconstructive procedures (9,39,40,49–51). Recent studies have identified the dorsal ligament complex as more robust in gross dimensions, in collagen structure, in cellularity, and in innervation (33,52). The dorsal complex comprised of the dorsal radial ligament (DRL), posterior oblique ligament (POL), and a dorsal central ligament (DCL) are found consistently to resist dorsal translation and antagonistic tensioning (33) in non-arthritic specimens (Figure 10). Furthermore, with dual immunofluorescent staining techniques, the ligaments demonstrate a variety of mechanoreceptors including Pacini and Raffini nerve fibers (33,53,54) independent of free nerve endings (55). These findings support the role of dorsal structures as contributors to proprioception and dynamic stability. In contrast, the volar structures including the variable superficial and deep anterior oblique ligament (AOL) and ulnar collateral ligament (UCL) are smaller in caliber and have fewer mechanoreceptors, suggesting structures that are more capsular in nature rather than representing a stabilizing presence (Figure 11) (33,56).

Examining the role of ligaments *in vivo* supports this phenomenon. The anatomic locations of the AOL and DRL of 44 healthy (nonarthritic) subjects were computationally represented based on literature references (33,49,56,57). The role of ligament recruitment during the 3

functional tasks was assessed; with the assumption that ligaments do not strain more than 10% physiologically, we concluded that the AOL is likely slack during much of functional movement (58). In contrast, the DRL appears to be taut in positions of CMC joint abduction and flexion, suggesting a supportive role in the healthy state.

The role ligaments play in arthritis as contributors or bystanders is, to date, unknown, but current evidence suggests ligaments and their associated structures, undergo dysplasia and degenerate in symptomatic subjects. AOL deterioration is reported (3,50), and we have identified the presence of an unknown population of mechanoreceptors in both DRL and AOL in surgically removed trapezia (59,60). Furthermore, the synovium intimal to both the AOL and DRL have a high presence of nociceptive histologic markers in surgical specimens (59–61). What is lacking from our current understanding is whether those who have “burnt out” disease – and advanced radiographic changes – represent a subset of individuals. Do they progress to a Charcot equivalent, with destruction of nociceptive, mechanoreceptors, and other proprioceptive feedback? Does an active inflammatory phase initiate the disruption of joint homeostasis (12)? Such processes remain to be identified, as part of the quest of musculoskeletal science to eradicate OA.

Muscles

Muscles contribute to proprioception, normal function, and weaken with joint degeneration. The opponens pollicis is intimal to the AOL as visualized arthroscopically (57), and may indeed be a more important dynamic stabilizer of the volar complex. The first dorsal interosseous (FDI) dorso-ulnarly, and the opponens pollicis volar-radially, appear to play critical roles in stabilization both biomechanically (62), and in dynamic stability in rehabilitation (63). Preliminary work using ultrasonography (Figure 12) to measure cross-sectional area of the thenar muscles and the FDI, demonstrates atrophy of the opponens and insertional component of the FDI in subjects with CMC OA (64), supporting this complementary stabilizing effect; or alternatively, early degeneration and contribution to OA development. Future examination of the role of mechanoreceptors in muscle, specifically Golgi tendon bodies (65), may represent the next step in identifying active roles of supporting muscles as both contributors and bystanders to OA.

The Thumb – an Organ

Throughout this evaluation of the CMC joint – its existence, its function, and its deterioration – the purpose and design remain intimately connected, an organ unto itself. The CMC joint contains features of all types of joints in the human body enabling the spectrum of demands: mobility, stability, and demands in opposition. A synergy of collaboration in our discipline and across the musculoskeletal landscape will provide better clues to deciphering the puzzle of the human thumb. Analysis of our longitudinal study subjects may yield information linking advanced disease to divergent patterns of wear and to further elucidation of the predilection of women to this disease. Eight subjects have recently advanced symptomatically and radiographically to withdraw from the study after 4.5 years evaluation, and will have explanted trapezia analyzed to correlate to functional CT data.

Improved characterization of inflammatory markers across joint disease will provide opportunities for further discovery. Furthermore, sophisticated “big data” cross-sectional analyses examining multiple variables of sex, ethnicity, health, genetics, concomitant arthritis and bone health, as well as occupation and vocation, will, no doubt, provide insight into etiology and predisposition. Collaborative investigations and prospective, multicenter patient-reported outcomes (66–68) will provide more sensitive information about functional status and disability. The characterization of disease progression in wear patterns, predisposition, patient-reported outcomes, and timing will refine how we inform patients. The opportunity to predict OA type based on plain radiographs, prescribe techniques to prevent or delay its progression, or implant prosthetics that emulate complex coordinated movement are potentially within, well, our grasp. The next decades promise to improve our knowledge and treatment of this common and debilitating disease.

Acknowledgments

This body of work represents collaboration and funding across multiple disciplines and individuals. Primary clinical and research collaborators include Joseph J Crisco PhD, Elisabet Hagert MD PhD, Susanne Rein MD PhD, Jessica Rose PhD, and Arnold-Peter Weiss MD; with Eni Halilaj PhD, Deborah Kenney MS, OTR, and Douglas Moore MS playing critical roles in our research teams. Mentors Robert A Chase MD and Vincent R Hentz MD inspire the many projects and subject. A multitude of medical students, residents, fellows, and other research collaborators have contributed to this work.

ASSH/AFSH Funding

- 2000 Bunnell Traveling Fellowship
- 2009 Basic Science award (Christopher Got, PI): “Utilization of Computed Tomography to evaluate the mechanics of the first CMC joint during dynamic loading”
- 2011 Resident & Fellow Fast Track Grant (Cameron Barr, PI): “Trapezium Trabecular Microstructure Using Flat-Panel Volume CT: A Feasibility Study”
- 2017 Andrew J. Weiland Medal, American Foundation for Surgery of the Hand

NIH Funding

- 1999–2001, 2008–2010 Small Business Innovation Research SBIR)/NBIB #1 R43 EB003067-01 and 02AL “A 3-D Interactive Atlas of the Human Thumb Carpometacarpal (CMC) Joint”
- 2011–2016, NIH-R01, Skeletal Biology Structure and Regeneration Study Section (NIH/SBSR) 1R01AR059185-01A1: “Thumb CMC Biomechanics and Early OA Progression”
- 2016–2021, NIH-R01, Skeletal Biology Structure and Regeneration Study Section (NIH/SBSR) 1R01AR059185-01A2 - renewal: “Thumb CMC Biomechanics and Early OA Progression.”

Additional funding

- 2005–2007 Packard Foundation Grant, “Development of an Upper Limb Motion Index”
- 2010–2011 OREF/RJOS/DePuy Career Development Award “Thumb CMC Joint in Women: Anatomy and Function in Symptomatic and Early Arthritis Subjects”
- 2014 ABJS Nicolas Andry Award, “The Puzzle of the Thumb: Mobility, Stability, and Demands in Opposition”
- 2010–2017 Williams Foundation support for research and personnel

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Figure 1.

(From left to right) The three positions of lateral key pinch, cylindrical grasp, and jar twist for functional and kinematic assessment, measured with infrared motion capture markers and computed tomography (CT) markerless registration. The load cell measuring force is embedded in the positioning jigs. *Image reproduced from Luker 2014 (18).*

Figure 2. Average CMC motion with load applied for A-key pinch (flexion, internal rotation, and volar translation), B-jar grasp (flexion, abduction, volar and ulnar translation), and C-jar twist (varied motion). *Image reproduced from Halilaj 2014 (26).*

Figure 3.

a) The trapezium and metacarpal bones from segmented surface CT scans, b) Congruency represented by topography, and c) polar coordinate systems of the 3D histograms. *Image reproduced from Halilaj 2014 (25).*

Figure 4.

Surface topography of the reciprocal saddle configuration of the trapezium (left) and 1st metacarpal (right), demonstrating quadrants as reported by Ateshian (35). [*] represents the volar beak of the metacarpal and the position of maximal congruence of the volar beak on the trapezium. *Image © S Hegmann, with permission*

Figure 5. Modified Eaton staging with Stage 0 (left) representing absence of radiographic findings, and Stage 1 (right) representing no joint space narrowing but evidence of subchondral sclerosis (20). Compare to Eaton stage 1, which is a normal radiograph or slightly widened articular surfaces (39,40). *Image © A Ladd, with permission*

Figure 6.

A healthy (left) and an arthritic (right) CMC joint, where the color intensity represents bone-to-bone distance between the trapezium (TPM) and the metacarpal (MC1), in a resting key pinch position. The joint is closer (narrower joint space) in OA subjects than in healthy controls. The joint space area is defined as the area where the bone-to-bone distance is less than or equal to 1.5 mm (yellow). The joint space centroid (black) is the distance-weighted centroid of the joint space area. *Image reproduced from Halilaj 2015 (42).*

Figure 7.

A–C: Micro-CT of 3 arthritic surgical specimens examined in the volar-dorsal plane (from left to right of each specimen). A- retained saddle shape with convex configuration, B- dish-shape, with reversal of the convexity, C-cirque shape, with neo-facet with volar reversal of the convexity. The black circle represents artifact from pin/tap used as a joystick for extraction. *Image © A Ladd, with permission (43)*

Figure 8.

The Thumb Osteoarthritis Index obtained from the Robert's pronated AP radiograph, obtained from the horizontal distal width of the trapezium divided by the height. Left represents a normal image, right a trapezium with severe dysplasia. Image © A Ladd, with permission (20)

Figure 9.
Severe dysplasia in the excised trapezium and radiograph depicted in Figure 8. *Image © A Ladd, with permission (20)*

Figure 10.

The dorsal deltoid ligament complex of a left thumb: dorsal radial ligament (DRL), dorsal central ligament (DCL), and posterior oblique ligament (POL). The abductor pollicis longus (APL) is also shown. *Image © A Ladd, with permission (33)*

Figure 11.

The volar ligaments of a left thumb: anterior oblique ligament (AOL) draping radially over the metacarpal volar beak, and the ulnar collateral ligament (UCL). A typical window is encountered between the two; typically the opponens pollicis is firmly invested to the capsule. The abductor pollicis longus (APL) and the flexor carpi radialis groove (FCRg) of the trapezium are also shown. *Image © A Ladd, with permission (33)*

Figure 12.

Ultrasound imaging of abductor pollicis brevis (APB) and opponens (OPP) muscles with probe in the short axis of the thenar eminence in a healthy subject. The opponens is deep to the APB and normal in muscular volume; in severe OA subjects it is atrophic. The flexor pollicis longus (FPL) tendon and 1st metacarpal (First MC) are also identified (64)