Biomechanical Role of the Transverse Carpal Ligament in Carpal Tunnel Compliance

Zong-Ming Li, PhD^{1,2,3} Tamara L. Marquardt, BS¹ Peter J. Evans, MD, PhD² William H. Seitz Jr., MD²

¹ Hand Research Laboratory, Department of Biomedical Engineering, Cleveland Clinic, Cleveland, Ohio

² Hand Research Laboratory, Department of Orthopaedic Surgery, Cleveland Clinic, Cleveland, Ohio

³ Hand Research Laboratory, Department of Physical Medicine and Rehabilitation, Cleveland Clinic, Cleveland, Ohio

Address for correspondence Zong-Ming Li, PhD, Cleveland Clinic, 9500 Euclid Avenue, ND20, Cleveland, OH 44195 (e-mail: liz4@ccf.org).

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Abstract

The transverse carpal ligament (TCL) is a significant constituent of the wrist structure and forms the volar boundary of the carpal tunnel. It serves biomechanical and physiological functions, acting as a pulley for the flexor tendons, anchoring the thenar and hypothenar muscles, stabilizing the bony structure, and providing wrist proprioception. This article mainly describes and reviews our recent studies regarding the biomechanical role of the TCL in the compliant characteristics of the carpal tunnel. First, force applied to the TCL from within the carpal tunnel increased arch height and area due to arch width narrowing from the migration of the bony insertion sites of the TCL. The experimental findings were accounted for by a geometric model that elucidated the relationships among arch width, height, and area. Second, carpal arch deformation showed that the carpal tunnel was more flexible at the proximal level than at the distal level and was more compliant in the inward direction than in the outward direction. The hamate-capitate joint had larger angular rotations than the capitate-trapezoid and trapezoid-trapezium joints for their contributions to changes of the carpal arch width. Lastly, pressure application inside the intact and released carpal tunnels led to increased carpal tunnel cross-sectional areas, which were mainly attributable to the expansion of the carpal arch formed by the TCL. Transection of the TCL led to an increase of carpal arch compliance that was nine times greater than that of the intact carpal tunnel. The carpal tunnel, while regarded as a stabile structure, demonstrates compliant properties that help to accommodate biomechanical and physiological variants such as changes in carpal tunnel pressure.

Keywords

- ligament
- carpal
- pressure
- wrist
- surgery

Carpal Tunnel Structure

The carpal tunnel is a fibro-osseous structure formed by the carpal bones interconnected by numerous ligaments. The eight irregularly shaped carpal bones are intricately arranged with the intercarpal ligaments to establish the medial, lateral, and dorsal boundaries of the tunnel. The proximal row of the carpal bones consists of the pisiform, triquetrum, lunate, and scaphoid, while the distal row comprises the hamate, capi-

tate, trapezoid, and trapezium. The volar aspect of the carpal tunnel is spanned by the transverse carpal ligament (TCL). This band of fibrous tissue inserts radially into the scaphoid tuberosity and trapezoid ridge, and ulnarly into the pisiform and the hook of the hamate. The thenar and hypothenar muscles are an integral part of the carpal tunnel structure, because the TCL serves as attachment sites for these hand muscles,^{1,2} and contraction of these muscles causes biomechanical interactions with the carpal tunnel via the TCL.³

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Within the carpal tunnel, the space is occupied by the median nerve, nine tendons of the extrinsic flexors of the thumb and fingers, and other connective tissues (e.g., bursae, synovium). The sophisticated anatomical configuration of the carpal tunnel results in complex biomechanical properties of the tunnel structure and also renders it vulnerable to pathomechanics.

Biomechanics of the Carpal Tunnel

Carpal tunnel mechanics and pathomechanics are clinically relevant in the management of many hand and wrist disorders, including carpal tunnel syndrome. Compression of the median nerve in the carpal tunnel is attributable to many deleterious mechanical factors such as forceful use of the hand and fingers,^{4,5} awkward postures of the wrist,^{6,7} volume increases in the carpal tunnel contents,^{8–12} muscle intrusion,^{11,13} elevated pressure within the tunnel,^{6,14,15} and hypertrophy or stiffening of the TCL.^{16,17} Attempts have been made to elucidate the mechanisms of these mechanical factors and their relationships and to utilize the knowledge of carpal tunnel biomechanics to help decompress the median nerve.

In an attempt to increase the carpal tunnel cross-sectional area, Li et al applied palmarly directed force onto the TCL from within the tunnel.¹⁸ The force application caused the TCL to form a larger arch, with increases in arch height and in tunnel cross-sectional area. Interestingly, the increased carpal arch area was due to arch width narrowing from the migration of the bony insertion sites of the TCL, and was not caused by elongation of the TCL. Subsequently, a geometric model of the carpal tunnel was developed to reveal the relationships among arch width, arch height, arch area, and TCL length. The model showed that increases in the carpal arch area were especially sensitive to narrowing of the carpal arch width,¹⁸ explaining the experimental finding that carpal arch area increases are effectively attainable by decreases of the arch width although the TCL length remains unchanged.

To understand the deformability of the carpal tunnel, Xiu et al studied the force-deformation relationship of the carpal arch width while inward and outward forces were applied to the TCL insertion sites.¹⁹ It was found that carpal tunnel compliance was location- and direction-dependent; the carpal tunnel was more flexible at the proximal level than at the distal level and was more compliant under inward force application than under outward force application. The difference in compliance in the inward and outward directions is likely due to the direction-dependent stabilizing role of the TCL as well as the other intercarpal ligaments.^{20–22} The role of the intercarpal ligaments in stabilizing the bony arch was also shown by Garcia-Elias et al, who applied compressive force to the carpal tunnel in the dorsal-palmar direction to quantify the rigidity of the tunnel with and without an intact TCL.²³ In contrast to the compliance in the radio-ulnar direction,¹⁹ the carpal tunnel stiffness in the dorsal-palmar direction²³ was not affected by transecting the TCL because of the other intercarpal ligaments in the tunnel structure. An investigation into the relative mobility of the intercarpal joints within

the distal carpal row by Gabra et al showed that the hamate-capitate joint had larger angular rotations than the capitate-trapezoid and trapezoid-trapezium joints²⁰; this is consistent with the concept that the scaphotrapezotrapezoid joint (STT) complex is relatively rigid, tightly held together by intercarpal ligaments. Furthermore, manipulating the carpal arch width caused complex, three-dimensional motion patterns of the carpal bones, which results from peculiar bony arrangement, elaborate ligamentous constraints, and oblique orientation of the carpal arch width.

Pressure Induced Morphological Changes of the Carpal Tunnel

The structural change of the carpal tunnel in response to pressure is another clinically meaningful phenomenon of carpal tunnel mechanics. There is a well-established association between carpal tunnel pressure and carpal tunnel syndrome. The pressure within the carpal tunnel is relatively low in a normal physiological state: less than 15 mm Hg when the wrist is at its anatomical neutral position.^{6,14,15} However, the carpal tunnel pressure in patients with carpal tunnel syndrome is known to be consistently elevated, and it is not uncommon to exceed even 200 mm Hg.^{6,15} Such an elevation of pressure may be attributable to the relatively inflexible carpal tunnel structure compounded by space-occupying factors such as fluid retention, edema, muscle intrusion, or tissue hypertrophy. Yet, it has been shown that carpal tunnel syndrome is associated with greater palmar bowing of the TCL.^{24–27} For example, Uchiyama et al showed a linear correlation between carpal tunnel area and TCL palmar bowing for the patients with carpal tunnel syndrome, but not for controls.²⁴ Mesgarzadeh et al used a bowing ratio (i.e., TCL palmar deviation divided by carpal arch width) to quantify the amount of bowing and found that carpal tunnel syndrome patients had a bowing ratio of 18.1% in comparison to a 5.8% ratio for controls.²⁷ Together, the pressure elevation and carpal arch change associated with carpal tunnel syndrome suggests that the tunnel exhibit some degree of compliance.

To understand the compliant nature of the carpal tunnel, Li et al performed a cadaveric experiment to examine the change in carpal tunnel area and shape in response to increasing pressure within the tunnel.²⁸ Controlled pressure (0–200 mm Hg) was applied to the carpal tunnel through a custom balloon device, and the resulting cross sections of the carpal tunnel were recorded using magnetic resonance imaging (MRI) (→Fig. 1). The technique used to apply pressure inside the tunnel by balloon inflation mimicked some pathomechanical phenomena associated with pressure elevation inside the carpal tunnel. The relationships between carpal tunnel pressure and carpal tunnel morphological parameters at the cross section of the hook of the hamate were derived.

The results showed that the carpal tunnel had considerable compliance to accommodate pressure variation inside the tunnel. Specifically, the cross-sectional area of the distal tunnel increased by 9% and 15% at 100 mm Hg and 200 mm Hg of tunnel pressure, respectively (→Fig. 2). This

Fig. 1 (a) MRI of the pressurized carpal tunnel (b) with a custom balloon device.

increase in carpal tunnel area was mainly attributed to the carpal arch formed by the TCL. For example, at carpal tunnel pressure of 200 mm Hg, the carpal arch area increased by 39% as opposed to the relatively small increase of 9% in the bony arch area. Furthermore, the circularity and aspect ratio of the tunnel's cross section were positively and negatively correlated with tunnel pressure, respectively. This means that as carpal tunnel pressure increased, the tunnel's cross section became more rounded. The aspect ratio changed from 2.05 at 0 mm Hg to 1.78 at 200 mm Hg. The change in cross-sectional shape explains the change in cross-sectional area even though the perimeter remained unchanged. Further analyses revealed that the compliance at the proximal tunnel (pisiform) level was greater than that at the distal tunnel level,²⁸ which is consistent with a previous study demonstrating that the carpal tunnel is less deformable at the distal than proximal level.¹⁹

Change of Structural Compliance after Carpal Tunnel Release

Although the carpal tunnel demonstrates some ability to accommodate pressure increases, the structural compliance of the intact carpal tunnel is limited. In the case of carpal tunnel syndrome, the TCL is viewed as an unfavorable mechanical constraint, and it is routinely transected during carpal tunnel release. Morphological changes to the carpal tunnel structure are known to occur as a result of transecting the TCL. MRI studies have shown that after carpal tunnel release there is an increase in carpal tunnel cross-sectional area and circularity, as well as tunnel volume.^{29–31} Notably, Kato et al reported that endoscopic carpal tunnel release caused a 33% increase in the cross-sectional area of the carpal

Fig. 2 Change in total carpal tunnel area with respect to carpal tunnel pressure.

tunnel and a 3.6 times increase in the carpal arch area.³² The change in the carpal arch width after carpal tunnel release remains controversial,³³ as some studies reported a widening of the carpal arch,^{34,35} while other studies found no width changes at postoperative follow-up.^{29,30} It is known that carpal tunnel release effectively reduces carpal tunnel pressure¹⁵; however, postoperative pressure may remain higher than normal and even surpass 100 mm Hg during hand activities.^{15,36} Therefore, it is expected that the compromised tunnel structure after carpal tunnel release exhibits different biomechanical properties, particularly in regard to its implications on carpal tunnel pressure.

To understand the compliance of the released carpal tunnel, Kim et al investigated the pressure-morphology relationship of the carpal tunnel after endoscopically releasing the TCL in cadaveric hands.³⁷ After the release, carpal tunnel pressure was increased by infusing water into the lumen of the tunnel until a pressure of 120 mm Hg was achieved (→ Fig. 3). While the pressure was increased, cross-sectional ultrasound images at the hamate hook level were simultaneously recorded. The imaging and pressure data were analyzed to determine the pressure-morphology relationship of the carpal arch.

Fig. 3 Ultrasound imaging of the carpal tunnel cross section (denoted by A-A') while pressure was applied inside the tunnel.

Fig. 4 Carpal tunnel cross-sectional images showing the transected TCL (dotted line) at (a) 10 mm Hg and (b) 120 mm Hg (H = hamate, T = trapezium).

As carpal tunnel pressure increased, the TCL increasingly separated at its transected edges (► **Fig. 4**), and the carpal arch shape became more convex (► **Fig. 5**). The carpal arch area increased by $62.4 \pm 20.2 \text{ mm}^2$ when the pressure reached 120 mm Hg, relative to the carpal arch area at the baseline pressure of 10 mm Hg. The increased carpal arch area of the released carpal tunnel was due to increases in the carpal arch length and height. The carpal arch area increased linearly within a low-pressure range and plateaued around 70 mm Hg. This demonstrates that the released carpal arch is relatively compliant at low pressure and becomes less compliant as pressure increases and the tunnel expands. In the linear region (10–70 mm Hg) of the pressure-area plot, the compliance of the carpal arch quantified by the slope of the regression line was $0.89 \text{ mm}^2/\text{mm Hg}$ (► **Fig. 6**). When compared with the intact carpal arch within a similar pressure range,²⁸ the released carpal arch had a 9 times greater compliance (► **Fig. 6**). The increased compliance of the released carpal arch is expected because the leaflets of the TCL are more flexible to deform at the cutting edges. The dramatic increase in carpal arch compliance after carpal tunnel release helps explain the mechanisms of median nerve decompression in alleviating symptoms of carpal tunnel syndrome.

The TCL: Present and Future

The TCL has attracted extensive research attention for the past two decades, and considerable knowledge has been gained

Fig. 5 Representative outlines of the TCL volar boundary in response to pressure changes.

from basic science research and its clinical implications in hand and wrist surgery. The TCL is known to have functional significance in stabilizing the carpal tunnel structure,^{19,22,38} serving as a pulley for the flexor tendons,^{39,40} anchoring the thenar and hypothenar muscles for hand strength,^{2,3} as well as providing wrist proprioception.⁴¹ Although this article focuses on the TCL's biomechanical role in carpal tunnel compliance, the science of this ligament has progressively evolved with regard to its cellular mechanisms,⁴² histological composition,^{43,44} fiber architecture,^{44–46} neural anatomy,⁴¹ morphological characteristics,^{47–49} material properties,^{50–52} and structural mechanics.^{3,19,38,53–57}

Clinically, transecting the TCL has been shown to benefit patients by relieving symptoms of carpal tunnel syndrome. However, disrupting the tunnel structure may compromise other aspects of hand function; these implications remain to be further clarified. Alternative surgical techniques^{58–62} and nonsurgical strategies related to the TCL^{63–65} continue to be explored, each warranting rigorous scientific investigation to establish evidence-based interventions. Regarding the many etiological factors of carpal tunnel syndrome, TCL thickening and stiffening are suggested as possible mechanisms, causing pathomechanics for median nerve compression and carpal tunnel syndrome.¹⁶ Future studies are needed to elucidate the potential mechanobiological effects on the TCL resulting from repetitive hand use that involves biomechanical interactions among tissues (e.g.,

Fig. 6 Change in carpal arch area as a function of tunnel pressure for the intact (O) and released (*) carpal tunnels with dotted lines indicating respective linear regressions in the pressure range of 10–70 mm Hg.

TCL, flexor tendons, and thenar muscles). For carpal tunnel biomechanics and its relationship to the TCL, a validated computational model of the wrist with high-fidelity constitutive components is valuable to assist our understanding of pathomechanisms and to provide patient-specific simulation and surgical procedures. More research is needed to investigate wrist function in the in vivo, physiological environment with the aid of dynamic imaging modalities, such as ultrasound, fluoroscopy, computed tomography (CT), and MRI. Such advancement of knowledge will further improve clinical management of hand and wrist conditions.

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Conflict of Interest

None

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