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Narrowing carpal arch width to increase cross-sectional area of carpal tunnel — a

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ABSTRACT

Background: Carpal tunnel morphology plays an essential role in the etiology and treatment of carpal tunnel syndrome. The purpose of this study was to observe the morphological changes of the carpal tunnel as a result of carpal arch width narrowing. It was hypothesized that carpal arch width narrowing would result in increased height and area of the carpal arch.
Methods: The carpal arch width of eight cadaveric hands was narrowed by a custom apparatus and cross-sectional ultrasound images were acquired. The carpal arch height and area were quantified as the carpal arch width was narrowed. Correlation and regression analyses were performed for the carpal arch height and area with respect to the carpal arch width.
Findings: The carpal tunnel became more convex as the carpal arch width was narrowed. The initial carpal arch width, height, and area were 25.7 (SD 1.9) mm, 4.1 (SD 0.6) mm, and 68.5 (SD 14.0) mm^2, respectively. The carpal arch height and area negatively correlated with the carpal arch width, with correlation coefficients of −0.974 (SD 0.018) and −0.925 (SD 0.034), respectively. Linear regression analyses showed a 1 mm narrowing of the carpal arch width resulted in proportional increases of 0.40 (SD 0.14) mm in the carpal arch height and 4.0 (SD 2.2) mm^2 in the carpal arch area.
Interpretation: This study demonstrates that carpal arch width narrowing leads to increased carpal arch height and area, a potential mechanism to reduce the mechanical insult to the median nerve and relieve symptoms associated with carpal tunnel syndrome.

1. Introduction

The carpal tunnel is a unique fibro-osseous structure formed by the transverse carpal ligament at the palmar side and by the carpal bones at the dorsal, the radial and the ulnar aspects. Within the tunnel, the nine flexor tendons and the median nerve traverse through the confined space. Many etiological factors may contribute to the compression of the median nerve in the tunnel, leading to the prevalent hand disorder called carpal tunnel syndrome (Moore, 2002). Routinely, carpal tunnel release is performed, whereby the transverse carpal ligament is transected in a surgical procedure to decompress the median nerve and relieve the symptoms of carpal tunnel syndrome. However, surgical release of the ligament compromises biomechanical integrity of the carpal tunnel, causing a number of post-operative complications such as weakness of grip strength, pillar pain and recurrence of symptoms (Fuss and Wagner, 1996; Kline and Moore, 1992). Many non-operative procedures for the intervention of carpal tunnel system have been attempted, but their long-term efficacy is lacking (Huisstede et al., 2010).

Carpal tunnel morphology plays an essential role in the etiology and treatment of carpal tunnel syndrome (Bekkelund and Pierre-Jerome, 2003; Kato et al., 1994). The morphological characteristics of the tunnel have been extensively studied using a variety of techniques including (i) radiography (Cobb et al., 1993; Gartsman et al., 1986; Viegas et al., 1992), (ii) computed tomography (Bleecker et al., 1985; Flores et al., 2009; Jessurun et al., 1987), (iii) magnetic resonance imaging (Allmann et al., 1997; Mesgarzadeh et al., 1989a; Mogk and Keir, 2007; Tsujii et al., 2009), (iv) ultrasonography (Altinok and Karakas, 2004; Kamolz et al., 2001; Lee et al., 2005; Sarria et al., 2000), (v) plastination (Sora and Genser-Strobl, 2005) and (vi) molding (Pacek et al., 2010; Richman et al., 1987). Among the morphological parameters, a small cross-sectional area of the carpal tunnel (i.e., tunnel stenosis) has been considered to be a predisposing factor for idiopathic carpal tunnel syndrome because a small carpal tunnel provides less space for its contents (Bekkelund and Pierre-Jerome, 2003; Bleecker et al., 1985; Cobb et al., 1997; Dekel et al., 1980). As an anatomical structure with a soft tissue component, the carpal tunnel has some degree of compliance as shown in human and animal in vitro studies (Li et al., 2011; Tung et al., 2010). Clinical studies have shown that individuals with carpal tunnel syndrome have increased palmar bowing of the

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transverse carpal ligament (Allmann et al., 1997; Buchberger et al., 1992; Mesgarzadeh et al., 1989b; Tsujii et al., 2009; Uchiyama et al., 2005), presumably due to elevated carpal tunnel pressure (Gelberman et al., 1981; Goss and Agee, 2010). Carpal tunnel release surgery is known to increase carpal tunnel cross-sectional area and volume (Ablove et al., 1994; Brooks et al., 2003; Kato et al., 1994; Richman et al., 1989), which is correlated with a decrease in carpal tunnel pressure after the surgery (Gelberman et al., 1981; Okutsu et al., 1989). In a cadaveric study, the pressure–morphology relationship for a released carpal tunnel revealed a nine times greater compliance than that of a carpal tunnel with an intact transverse carpal ligament (Kim et al., 2013). This helps explain the reduction of carpal tunnel pressure and relief of symptoms for patients after carpal tunnel release surgery. Carpal tunnel release also leads to a change in the carpal arch width (CAW), measured between the trapezium and the hook of the hamate (Gartsman et al., 1986; Viegas et al., 1992). The CAW was also shown to vary when the wrist was flexed or extended from the neutral position (Garcia-Elias et al., 1992).

Recent studies have suggested an alternative mechanism to increase the carpal tunnel area by narrowing the CAW (Kim et al., 2013; Li et al., 2009, 2011). When a force was applied from within the tunnel to the transverse carpal ligament in the palmar direction, the ligament insertion sites moved toward each other and the CAW was decreased (Li et al., 2009). This led to palmar bowing of the transverse carpal ligament and increases in the carpal arch height (CAH) and the carpal arch area (CAA). Additionally, it was shown that inter-carpal joint mobility provides flexibility for CAW narrowing (Gabra et al., 2012; Li et al., 2009), leading to carpal arch formation which benefits the carpal tunnel environment by accommodating physiological variations of pressure in the tunnel. Also, a study examining the morphological changes of the carpal tunnel in response to the carpal tunnel pressure showed that an increase in the tunnel pressure is associated with a decrease in the CAW and an increase in the tunnel circularity, contributing to an increase in the carpal tunnel area (Li et al., 2011). When the transverse carpal ligament was transected, the pressure increase inside the carpal tunnel led to a decrease in the CAW and separation of the transected edges of the ligament, jointly contributing to the increase of the cross-sectional area (Kim et al., 2013). A geometric model to examine the relationship among the morphological parameters also showed that an increase in the carpal arch area was sensitive to CAW narrowing as well as lengthening of the transverse carpal ligament (Li et al., 2009). Furthermore, the in vivo biomechanical interaction of the thenar muscles and the transverse carpal ligament induced by isometric tip pinch was shown to be associated with an increased palmar bowing, a decreased CAW and an increased CAA (Shen and Li, 2013).

While previous studies showed the association of the carpal arch width and the carpal tunnel cross-sectional area, there is no study that directly controlled CAW narrowing and observed its morphological effect, particularly in regard to palmar bowing and the carpal tunnel area. As such, the purpose of this study was to examine the changes in the carpal tunnel cross section as a result of CAW narrowing using a cadaveric model. The cross section of the carpal tunnel was recorded by ultrasound imaging while the CAW was manipulated. The carpal arch formed by the transverse carpal ligament was analyzed on the ultrasound images. It was hypothesized that CAW narrowing would lead to greater palmar bowing with increases in the CAH and the CAA.

2. Methods

2.1. Preparation of cadaveric specimens

Eight (n = 8) fresh frozen cadaveric hand specimens [7 male, 1 female; 7 left, 1 right; age 54.6 (SD 5.9) years] were used in this study. The specimens were thawed overnight at room temperature prior to experimentation. To prepare each specimen, the palmar skin from 15 mm proximal to the distal wrist crease to the mid-palm was excised, and the remaining fat and fascia tissue superficial to the transverse carpal ligament was removed. Then, the carpal tunnel was evacuated by removing the flexor tendons and the median nerve. The hamate and the trapezium bones were identified at the palmar side of the wrist and a wire-lockable socket head cap screw (McMaster-Carr, Aurora, OH, USA) was drilled into the hamate and the trapezium in the palmar to dorsal direction approximately 10 mm deep.

2.2. Apparatus for carpal arch narrowing

The narrowing of the CAW was implemented with a custom compressive apparatus (Fig. 1A). The apparatus consisted of a base, two point steel-tipped probes (McMaster-Carr, Aurora, OH, USA), and two orthopedic MiniRail fixators (Orthofix Holdings, Inc., Lewisville, TX, USA). The probes and the fixators were each attached to opposite sides of the base. The device provided positioning flexibility of the probes by translations and rotations.

2.3. Experimental procedures

Following specimen preparation, a water-filled pressure balloon attached to a tube was inserted into the evacuated carpal tunnel and centered with respect to the tunnel's longitudinal axis. The

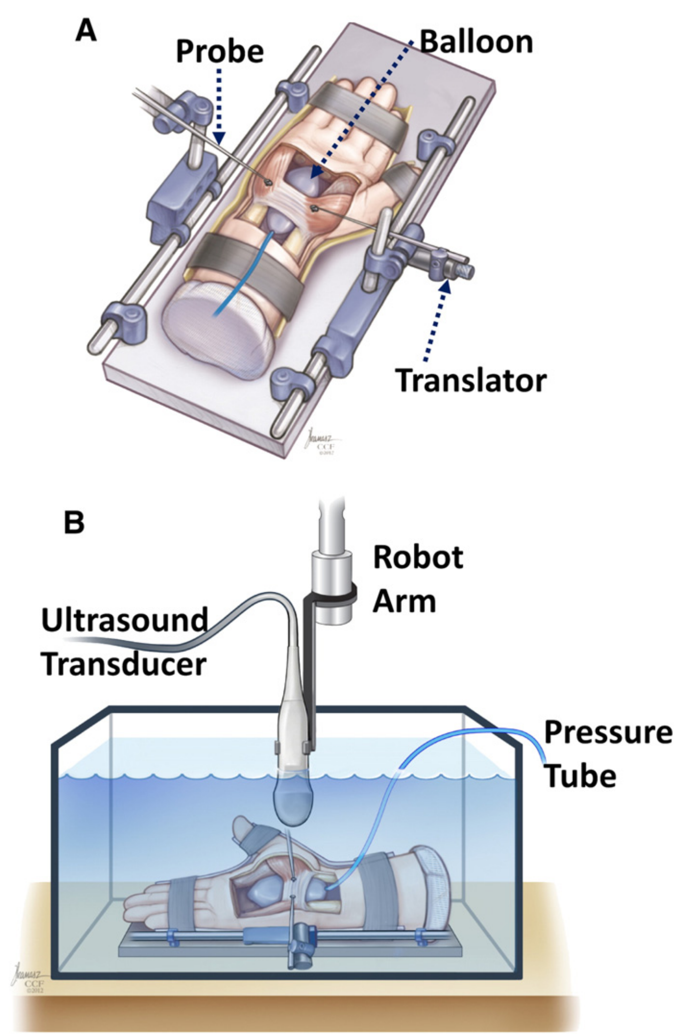

Fig. 1. Experimental setup for carpal arch width narrowing (A) and ultrasound imaging (B).