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Morphological and positional changes of the carpal arch and median nerve during wrist compression

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ABSTRACT

Background: The carpal tunnel is a fibro-osseous structure containing the median nerve and flexor tendons. Its cross-sectional area has been shown to increase during compressive force application to the carpal bones in modeling and in vitro studies. The purpose of this study was to investigate the morphological and positional changes of the carpal arch and median nerve while in vivo compressive force was applied in the radioulnar direction across the wrist.

Methods: Ultrasound images of the carpal tunnel and its contents were captured for 11 healthy, female volunteers at the distal tunnel level prior to force application and during force application of 10 and 20 N.

Findings: With applied force, the carpal arch width significantly decreased, while the carpal arch height and area significantly increased ($P < 0.001$). The median nerve shape became more rounded as the compressive force magnitude increased, reflected by decreases in the nerve's flattening ratio and increases in its circularity ($P < 0.001$). The applied force also resulted in nerve displacement in the radial-volar direction.

Interpretation: This study demonstrates that noninvasively applying radioulnar compressive force across the wrist may potentially provide relief of median nerve compression to patients suffering from carpal tunnel syndrome.

1. Introduction

The carpal tunnel is a fibro-osseous structure within the wrist bounded by the inter-connected carpal bones and the transverse carpal ligament (TCL). The tunnel serves as a passageway for the digital flexor tendons and the median nerve. The delicate nature of the median nerve lends itself susceptible to compression within the carpal tunnel; prolonged compression of this nerve may lead to the median nerve neuropathy known as carpal tunnel syndrome.

When subjected to stress, the median nerve may displace or undergo morphological changes to minimize its insult within the carpal tunnel (Wang et al., 2014a). Previously, the deformation and displacement of the median nerve have been investigated in response to wrist and finger motion in patients with carpal tunnel syndrome (van Doesburg and Henderson, 2012; van Doesburg et al., 2012; Wang et al., 2014b; Yoshii et al., 2013) as well as in asymptomatic volunteers (van Doesburg et al., 2010; Wang et al., 2014a; Yoshii et al., 2009). These aforementioned studies have shown that the median nerve displaces in three dimensions and its shape often changes to better accommodate the space that is unoccupied by the other tunnel contents.

The amount of space available for the median nerve, and the additional carpal tunnel contents, is furnished by the boundaries of the carpal tunnel. The morphology of the carpal tunnel boundary has been shown to change with varying wrist postures (Garcia-Elias et al., 1992) and after the surgical intervention of carpal tunnel release (Gartsman et al., 1986; Richman et al., 1989; Viegas et al., 1992). These structural changes are likely related to the soft tissue components of the carpal tunnel boundary which provides the carpal tunnel with some degree of compliance (Garcia-Elias et al., 1992; Li et al., 2011, 2013; Tung et al., 2010; Xiu et al., 2010). Recent studies support that the cross-sectional area of the carpal tunnel can be increased by narrowing the carpal arch width (CAW), i.e., distance between the trapezium and hook of hamate (Kim et al., 2013; Li et al., 2009, 2011, 2013). Geometric modeling (Li et al., 2009) and in vitro (Li et al., 2009, 2013) studies have shown that CAW narrowing is associated with palmar bowing of the TCL which increases the height and cross-sectional area of the carpal arch. These changes may provide additional space within the carpal tunnel for its contents; however, such previous studies have not investigated the impact of CAW narrowing on the tunnel contents. Additionally, the in vitro strategy of force application to achieve CAW narrowing involved directly applying invasive force to the carpal bones or transverse carpal ligament (Li et al., 2013; Xiu

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et al., 2010). Non-invasive, in vivo narrowing of the CAW by applying external transverse force across the wrist has not been explored.

Therefore, the purpose of this study was to investigate the in vivo morphological and positional changes of the carpal arch and the median nerve during transverse, compressive force application across the wrist. It was hypothesized that force applied across the wrist would result in a decrease of the CAW, accompanied by an increase in the carpal arch height and area. It was also hypothesized that the median nerve shape would become rounder and the nerve would displace in the volar direction due to the additional space created within the carpal arch.

2. Methods

2.1. Human subjects

Twelve healthy, right-handed female volunteers were enrolled in this study; however, one participant was excluded because not all of this study's anatomical landmarks of interest could be identified within the same ultrasound imaging plane ($n = 11$, 24.8 (SD 5.5) years old). The participants had no history of injury, surgical intervention, or musculoskeletal/neuromuscular disorders affecting the right hand or wrist. The study was approved by the institutional review board and written informed consent was obtained from each volunteer prior to study participation.

2.2. Compression system

A custom system was developed to non-invasively apply transverse compression across the wrist at the distal level of the carpal tunnel (Fig. 1). The system included 1) a height adjustable support for the hand, wrist, and forearm, 2) two six degrees-of-freedom alignment mounts, 3) two pneumatic actuators (Bimba Manufacturing, Monee, IL, USA), 4) two end effectors, 5) an air pressure regulator (VBM Medical, Noblesville, IN, USA), 6) plastic tubing, and 7) a digital pressure gage. Each actuator was rigidly attached to an alignment mount and an end effector was securely fastened to each actuator's extension rod. The end effectors consisted of concave pieces of thermoplastic that were molded to comfortably fit the curvature of the hand/wrist. Before molding each thermoplastic piece, it had a cross-sectional area of 9.6 cm^2 and was 0.3 cm thick. For added comfort, a thin piece of foam (0.3 cm thick) was added to the surface of the end effectors that made contact with the wrist. The plastic tubing was used to connect the pressure regulator, digital pressure gage, and actuators. The pressure regulator generated and controlled the desired force magnitude according to a calibration performed that related the regulator pressure to the amount of force applied by the actuators.

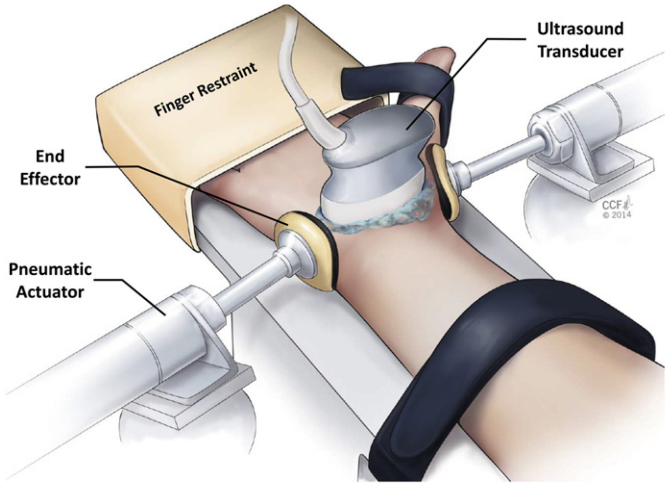

Fig. 1. Experimental setup for in vivo wrist compression and ultrasound imaging.

2.3. Experimental procedures

Each participant lay supine on a testing bed. Their right arm was abducted 30° and placed on the height adjustable support of the compression system so that their palm faced up. Their four fingers were stabilized in the extended position and secured using a restraint; their thumb was naturally abducted and held with a Velcro® strap. Additionally, the forearm was stabilized using a Velcro® strap (Fig. 1). To guide the alignment of the end effectors, an ultrasound system (Acuson S2000, Siemens Medical Solutions USA, Mountain View, CA, USA) with an 18L6 HD linear array transducer (Siemens Medical Solutions USA, Mountain View, CA, USA) was used to identify the axial imaging plane that clearly contained the hook of hamate and ridge of trapezium, corresponding to the distal level of the carpal tunnel. The position of the ultrasound transducer was outlined for each subject using a skin marking pen. Then, the actuators were adjusted so that the line of action of the end effectors coincided with the determined imaging plane, and the center of the end effectors were positioned at the mid-point between the volar and dorsal surface of the wrist.

Transverse, compressive forces of 10 N and 20 N were applied to the wrist at the distal level of the carpal tunnel for each study volunteer. The air pressure regulator supplied a single air pressure through bifurcated tubes to simultaneously actuate the two end effectors, applying the specified force magnitude to both the radial and ulnar aspects of the wrist. Each force level was applied four times, for a total of eight trials in a randomized order. At the beginning of each trial, the ultrasound transducer was oriented perpendicularly to the palm of the participant with an axial imaging plane that provided visualization of the hook of hamate, ridge of trapezium, median nerve, and the thenar muscles' ulnar point (TUP) (Shen and Li, 2012). Then, three ultrasound images were captured without force application (unloaded, 0 N condition). Next, the pressure regulator generated and maintained the desired, predetermined force output for 3 min. After 3 min of continuous force application, three additional ultrasound images were obtained of the carpal tunnel following the above described procedure. After collecting the loaded ultrasound images, the compressive force was released for that trial. Between consecutive trials, participants removed their arm from the compression system and were given a 5-minute resting period. Throughout imaging, the ultrasound system was operated in two-dimensional B-mode, with tissue harmonic imaging at an imaging frequency of 8 MHz and an image depth of 2.5 cm.

2.4. Data analyses

One trial for each of the 10 N and 20 N force conditions was used for analyses for each participant; the remaining trials were used as backup. For each trial, the three unloaded images and the three loaded images were examined by a single investigator (TLM) who has received musculoskeletal ultrasound training. The examiner was blinded to the magnitude of the compressive force for each image. The *ImageJ* (US National Institutes of Health, Bethesda, MD, USA) point tool was used to determine the coordinates of the most volar point of the hook of hamate and the ridge of trapezium on each image. Similarly, the TUP was identified and its coordinates were recorded. The multipoint selection tool in *ImageJ* was used to trace the median nerve within its hyperechoic border. The nerve tracing provided quantification of the median nerve's shape descriptors, including the nerve perimeter, area, flattening ratio ($\frac{major\ axis}{minor\ axis}$ of fit ellipse), and circularity ($4\pi * \frac{area}{perimeter^2}$). The flattening ratio and circularity of the median nerve provided an indication of the nerve's roundness. For both parameters, a value of 1.0 indicates a perfect circle. A flattening ratio greater than 1.0 or a circularity of less than 1.0 reflects a more elliptical cross-sectional shape. Additionally, the coordinates of the median nerve centroid were found.

All of the coordinates obtained from *ImageJ* were transformed to an anatomical coordinate system using a custom *MATLAB* (MathWorks,