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Research Article

Trapeziometacarpal Joint Laxity in Pre- and Post-Menopausal Females by Dynamic Ultrasound

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Abstract

The trapeziometacarpal joint is critical for thumb functionality and a common site for osteoarthritis, especially in post-menopausal females. Joint laxity has been identified as a contributing factor to joint instability and osteoarthritis. The purpose of this study was to investigate the difference in trapeziometacarpal joint laxity between pre- and post-menopausal females using dynamic ultrasound imaging. The thumb was placed under traction at varying force levels with ultrasound evaluation of *in vivo* changes in joint distance. The subjects remained relaxed throughout the traction experiment. Joint distance change was calculated as the joint separation under traction with respect to no traction force. Joint laxity was quantified by the slope of the regression line of joint distance change as a function of traction force. Two-way ANOVAs showed that the joint distance changes were significantly affected by group ($p < 0.05$) and force level ($p < 0.001$). Joint laxity for the post-menopausal group (0.0709 ± 0.0202 mm/N) was 44.1% greater than the pre-menopausal group (0.0492 ± 0.0065 mm/N; $p < 0.05$). This increase in trapeziometacarpal joint laxity in the post-menopausal women suggests that menopause may affect the structural integrity of joint stabilizing tissues. This study highlights the application of dynamic ultrasound imaging to assess joint integrity of the trapeziometacarpal joint and sets the stage for future research on the pathomechanics of trapeziometacarpal joint osteoarthritis.

Keywords: Thumb; Trapeziometacarpal joint; Ultrasound imaging; Laxity; Menopause

Introduction

The trapeziometacarpal (TMC) is a key component of thumb functionality. While its unique saddle-shape allows for a wide range of motion, the shallow joint articular surfaces provide minimal intrinsic bony stability, placing a higher demand on the surrounding soft tissues for static and dynamic stability [1]. Previous studies have demonstrated joint stress in the TMC during daily activities (e.g., pinch and grasp) greater than that seen in the tibiofemoral joint during walking or climbing stairs [2,3]. Therefore, TMC joint laxity resulting from the compromise of surrounding soft tissue stabilizers exposes the articular surfaces to even greater stress and can lead to cartilage degradation and, ultimately, to osteoarthritis.

Joint hypermobility, or laxity, is one factor to consider in the development of TMC osteoarthritis, especially in association with the higher prevalence of TMC joint osteoarthritis among post-menopausal females. Hand hypermobility has been shown to be more prevalent in females and is also associated with more severe radiographic TMC osteoarthritis [4]. Additionally, relaxin, a

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hormone known to promote collagen degradation and joint laxity, has been shown to have increased serum levels in females aged 40-59 compared to their male counterparts [5] and has demonstrated increased receptor expression in the ligaments surrounding the TMC joint [6,7]. No significant difference was found in TMC joint mobility between healthy individuals and those with TMC osteoarthritis during functional tasks such as key pinch, jar grasp, and jar twist, however [8].

The Beighton Score is the standard tool for epidemiological screening and clinical diagnosis of generalized joint hypermobility [4,9], but a method to measure localized TMC joint laxity is needed [10]. TMC joint laxity has been assessed using radiograph stress views [11,12] and computed tomography (CT) scanning and quantification [8,13,14], but radiography and CT scans typically offer static imaging information. Ultrasound not only offers an accessible, non-invasive, and cost-effective point-of-care imaging modality that does not expose the patient to radiation, but also allows for the dynamic evaluation of the joint behavior of a joint in motion. Ultrasound imaging has been used to measure laxity in other joints, including the knee or shoulder [15-17].

In this study, we describe a novel methodology employing dynamic ultrasound imaging to analyze TMC joint laxity. Using an *in vivo* imaging modality and coordinate tracking, we quantified joint distance changes due to traction forces. Joint laxity was quantified by the slope of the regression line for the amount of distance changes as a function of distraction forces. Additionally, we examined joint laxity in pre-menopausal and post-menopausal females, a population of interest for TMC osteoarthritis. We hypothesized that joint laxity of post-menopausal women would be greater than that in pre-menopausal women.

Methods

Subjects

Thirty-two healthy females were recruited for the study. The exclusion criteria include neuromuscular disorders, diagnoses of arthritis and other inflammatory of the hand or thumb, thumb hypermobility, body mass index (BMI) greater than 30 kg/m^2, or non-naturally occurring menopause (e.g. surgical removal of reproductive structures). We recruited two groups based on menopausal status: pre-menopausal (n = 16; age, 28.7 ± 7.7 years; BMI, 23.5 ± 4.1 kg/m^2) and post-menopausal (n = 16, age, 64.4 ± 7.4 years; BMI, 25.5 ± 3.9 kg/m^2). Participants answered Menopause Rating Scale (post-menopausal women only) and the Functional Index of Hand Osteoarthritis to confirm their eligibility. Each participant provided informed written consent prior to study participation. The study was approved by the University of Arizona Institutional Review Board.

Experimental set-up

Each participant was asked to sit at a testing table, with the left hand supinated and immobilized in a custom brace which was attached to a metal base (Figure 1). The brace served two functions: isolating the thumb from the other four fingers to standardize placement of the ultrasound probe, and securing the current hand position for traction. The thumb was inserted into a finger trap which was attached to a metal cable, and the metal cable went across a pulley to hang sand weights for loading. The pulley position was adjusted to assure that the finger trap was aligned along the longitudinal axis of the thumb at its natural angle to minimize rotation during imaging. Next, an 18L6 HD probe (Acuson S2000, Siemens Medical Solutions USA, Mountain View, CA) was mounted into a 3D printed probe holder fastened to a position- adjustable arm. The ultrasound probe was placed lengthwise over the TMC joint, thereby allowing the volar trapezium and first metacarpal to appear simultaneously in the ultrasound images. Refined small adjustment of the probe position was made to obtain clear images of the trapezium and first metacarpal. Afterward, the current probe position was secured by locking the positioning arm. The ultrasound system was set for optimal two-dimensional B-mode imaging at a frequency of 17 MHz, a gain of 12 dB, and an image depth of 2 cm.

Experimental procedures

Traction force to the thumb was implemented by hanging sand weights to the free end of the pulley. Four levels of weights (3N, 6N, 9N, 12N), each repeated three times (12 trials total), were applied in randomized order. Within each trial, dynamic ultrasound video was recorded for 10 seconds, with approximately 2 seconds of unload and 8 seconds

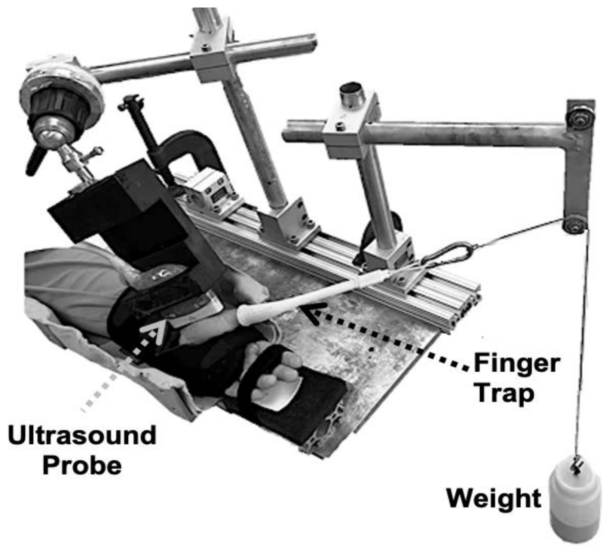

Figure 1: Experimental setup for ultrasound imaging of the TMC joint during weight induced traction.

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of load. At the end of each trial, the load was removed. A 60-second rest was given between consecutive trials. During data collection, the subject was asked to remain relaxed. The images were collected at 30 frames per second.

Ultrasound video processing

On ultrasound imaging, the bony surfaces of the trapezium and fist metacarpal were hyperechoic, with a hypoechoic shadow beneath the surfaces; the gap between the two bones was hypoechoic (i.e., lower grayscale values), creating distinct patterns to identify the two bones and the TMC joint. As the force was loaded, we visualized the TMC joint space widening, ensuring the probe position captured the joint motion throughout the entire loading period. For data processing, one prominent point close to the bony surface of the metacarpal and another on the trapezium were manually selected from the first frame of the ultrasound video, and automatically tracked in the following frames by a Lucas-Kanade algorithm [18]. The joint distance change under traction was determined by the difference between the distance between the metacarpal/trapezium points of the loaded joint and that of the unloaded joint. Linear regression of the joint distance changes as a function of force was obtained by setting the intercept as 0. The slope of the regression line was used to quantify joint laxity. The average joint distance change of the 3 trials per force was used for analysis.

Statistical analysis

Two-way repeated measures analyses of variance (ANOVAs) were used to examine the dependence of joint distance changes on the menopause status and traction force levels (group x force). Tukey post-hoc tests were performed to examine all pairwise comparisons. The group difference in joint laxity was assessed by a student t-test. The significance level was set as 0.05. Sigmaplot 14.0 (Inpixon, Palo Alto, CA) was used for statistical analysis.

Results

Ultrasound images showed that the joint separated with application of the traction force, and this separation became more pronounced as traction force increased for both pre- and post-menopausal (Figure 2). This is further illustrated in Figure 3 showing joint distance changes at different traction forces for a representative subject.

Two-way ANOVAs showed that the joint distance changes were significantly affected by group ($p < 0.05$) and force level ($p < 0.001$). There was no statistical interaction between the factors of group and force ($p = 0.509$). Individual comparisons showed that the joint distance changes for the 9 N and 12 N forces were significantly greater in the post-menopausal group than the pre-menopausal group ($p < 0.05$) (Figure 4). The joint distance changes for the two groups were not significantly different for the 3 N force ($p = 0.139$) and 6 N force ($p = 0.089$). Regression analysis showed that joint laxity for the post-menopausal group was significantly greater than the pre-menopausal group ($p < 0.05$). Joint laxity in pre- and post-menopausal groups were 0.0492 ± 0.0065 mm/N and 0.0709 ± 0.0202 mm/N, respectively (Figure 5), an average increase of 44.1%.

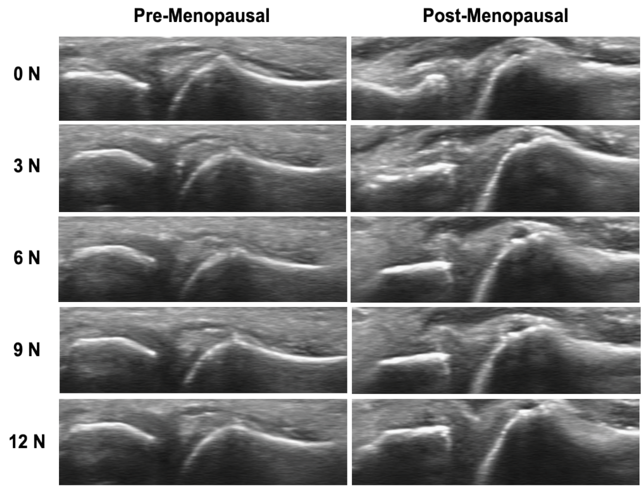

Figure 2: Representative ultrasound images of TMC joint under different traction forces for pre- and post-menopausal groups.

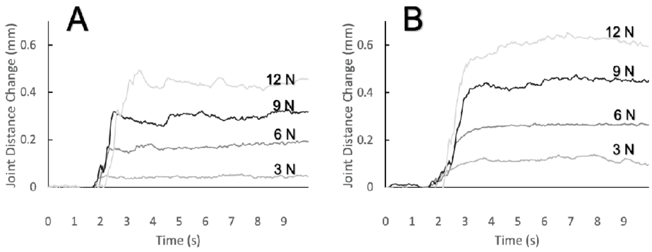

Figure 3: Representative joint distance changes under different traction forces for (A) pre-menopausal and (B) post-menopausal groups.

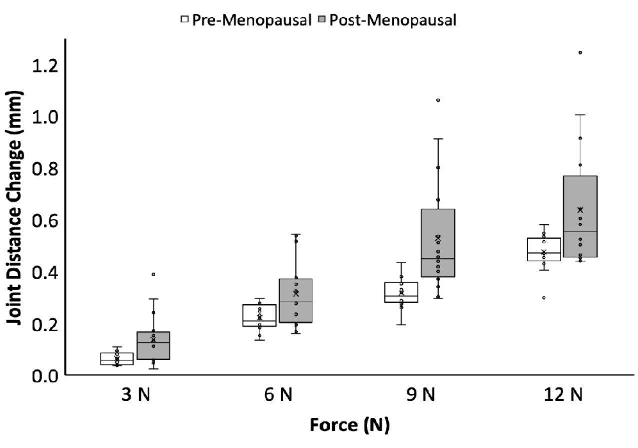

Figure 4: Joint distance changes under different traction forces for pre- and post-menopausal groups

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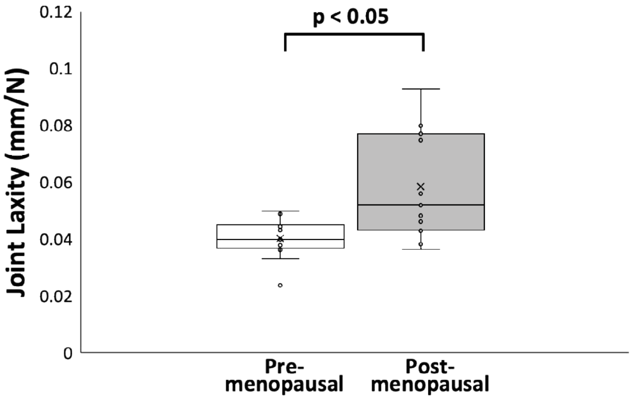

Figure 5: Joint laxity in pre- and post-menopausal groups.

Discussion

The TMC joint is critical to thumb function, facilitating the movement required in many daily activities. It is also one of the more common sites for hand osteoarthritis, especially in post-menopausal females. The mechanics and pathomechanics of the TMC joint remain unclear, however. In this study, we investigated joint laxity using dynamic ultrasound and found that post-menopausal females have greater joint laxity than pre-menopausal females.

Laxity has been described as a factor contributing to or preceding hypermobility, instability, and osteoarthritis throughout the musculoskeletal system [12,19,20]. With the known association between laxity and joint pathology, it has become an area of interest in TMC research, garnering increasing attention given the unique structure of the TMC joint and its reliance on soft tissue stabilizers. Previous studies have described how structural compromise of the surrounding ligaments and muscles may alter joint biomechanics, predisposing the TMC joint to degeneration by increasing joint contact force distribution, metacarpal base mobility, and overall shear forces [1,21]. Population studies have also demonstrated increased laxity or joint hypermobility (measured by the Beighton score) in the TMC joint in those with TMC osteoarthritis [4]. Furthermore, relaxin, a hormone known to increase joint laxity, has been shown to have higher serum concentrations and increased receptor expression in the stabilizing ligaments surrounding the TMC joint of post-menopause aged females [6,7]. These results suggest that joint laxity is a factor of clinical importance for the TMC joint and that the biomechanical implication of the increased TMC joint laxity after menopause requires further examination.

The Beighton score, one of the more common instruments employed to measure generalized joint hypermobility, has limitations and fails to identify laxity in specific joints [10], highlighting the need for a better method to evaluate localized laxity. This need, in addition to the scarcity of *in vivo* studies of TMC biomechanics, motivated us to use dynamic ultrasound imaging to examine joint laxity. Our use of *in vivo* ultrasound, thumb traction, and video analysis with bony tracking is a unique method of assessing TMC joint laxity. While ultrasound has been used in TMC osteoarthritis treatment [22], researchers have chosen CT [8] or stress view radiographs [11] to assess TMC instability or laxity. Although ultrasound may not provide imaging of three-dimensional bony structures, it offers many other advantages such as low cost, no exposure to radiation, wide availability, and most importantly, the ability to monitor the joint space change with biomechanical inputs. By fixing the probe in position throughout the trials, we attempted to minimize the operator-dependent variability that may arise with ultrasound imaging. Overall, ultrasound and coordinate tracking of bony structures is a precise, easily reproducible method to examine joint laxity within the carpometacarpal joint and can be easily replicated or expanded for use within other joints.

For our study, we quantified joint laxity as the slope of the regression line of the distance changes with respect to traction force. We hypothesized that the post-menopausal group would have greater joint laxity than the pre-menopausal group in healthy female subjects. Our results supported this hypothesis, showing not only a greater TMC laxity in the post-menopausal women but also greater increases in joint distance changes at 9 N and 12 N in comparison to pre-menopausal women. Even though a lower force did not achieve statistical significance, this may have been due to our sample size. A previous study reported that age was not found to have an effect on TMC joint instability in functional tasks, although it was suggested this may have resulted from compensatory co-contraction obscuring possible instability for older subjects [8]. Our study design attempted to minimize compensatory reactions by asking participants to remain relaxed throughout the exam. Grip strength also varies with gender, age, and presence of hand osteoarthritis [23,24], but our study does not have these confounding influences, providing a more reliable measurement of laxity. Our study has two other main differences from previous methodology, i.e., imaging modality and measuring techniques. While CT in combination provides multiplanar measurements, our Lucas-Kanade algorithm and use of dynamic ultrasound allowed us to monitor the movement of bony segment and find the joint distance.

Our findings suggest that joint laxity serves as a good indicator for quantifying the instability of the TMC joint and could be utilized as a joint stability parameter for future research into TMC biomechanics and TMC osteoarthritis in the post-menopausal population. The establishment of baseline values of joint laxity may be useful for examing changes in joint stability and determining the risk of developing TMC osteoarthritis in longitudinal cohort studies that span the peri- and post-menopausal time frames. Our findings of increased

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joint laxity in the post-menopausal group provide a possible biomechanical explanation for this population's increased prevalence of TMC osteoarthritis. Whether this difference also exists in post-menopausal individuals with diagnosed TMC osteoarthritis is yet to be determined, however. Additionally, the source of increased TMC joint laxity within the post-menopausal population could be due to a multitude of factors, including aging, differences in hormonal levels, and sex differences, and requires further evaluation. Although the specific cause has not been identified, our study demonstrates a biomechanical difference in joint laxity between pre- and post-menopausal females. This difference indicates that a change in the surrounding stabilizing tissues increases TMC joint laxity, which may render the joint more vulnerable to developing osteoarthritis. Overall, our study indicates the importance of joint laxity as a biomechanical factor of clinical importance and demonstrates that our methodology of ultrasound with coordinate tracking provides a precise and easily reproducible method for measuring joint laxity *in vivo*.

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