Evaluation of Shear Stress of the Human Temporomandibular Joint Disc

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The aim of this study was to determine the shear stress of the human postmortem temporomandibular joint (TMJ) disc. Correlation of shear stress with age or with the region of the disc was determined. Nine discs were removed unilaterally from postmortem humans, ages 36 to 76 years. Discs were sectioned into lateral (eight), central (eight), and medial (eight) specimens. Each specimen was attached by cyanoacrylate adhesive to a servohydraulic test system apparatus within 48 hours of retrieval. Shear properties were measured under quasistatic conditions with a linear increase of displacement until the specimen failed to maintain maximum resistance to the applied force. The shear moduli were analyzed by means of the Wilcoxon's signed ranks test. The results showed that values of shear moduli on peripheral portions (lateral and medial) were significantly higher than on central portions ($P = 0.0013$). The correlation between the shear moduli of TMJ discs and age showed a regression slope for shear moduli of $-0.326 + 0.031 \times age$ ($r = 0.769$; $P < 0.01$). Peripheral portions (lateral and medial) have a higher shear moduli and are stiffer than the central portions of discs and shear moduli or stiffness of TMJ discs increase with age.

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Rotary and translatory movements of the human temporomandibular joint (TMJ) and knee joint apply forces to the disc as well as its attachment.[1–8] Such forces cause shear stress within the disc and are potentially very destructive. Stress can decrease shear resistance and can lead to deterioration and stiffening of the TMJ disc. Under these conditions, the potential for TMJ dysfunction is increased.

Previous studies proposed that clicking and other similar intracapsular sounds may be caused by an abnormal stiffness of the TMJ disc.[9–12] Stiffness is the result of a change in shear properties. Shear resistance is decreased as shear modulus is increased, and breakage of the disc can occur. Clinically, the disc would become dysfunctional, and a perforation could be initiated within the joint.[13–17] This is an example of how signs and symptoms of TMJ dysfunction might be caused by changes in shear properties. Thus, greater modulus of shear stress indicates not only decreased resistance to breakage, but greater stiffness of this disc as well.[18]

An evaluation of TMJ disc shear stress could therefore lead to a better understanding of the physical properties of the human TMJ disc. Various portions of the human TMJ are being replaced by artificial materials.[19–22] To replace the disc with a biologically

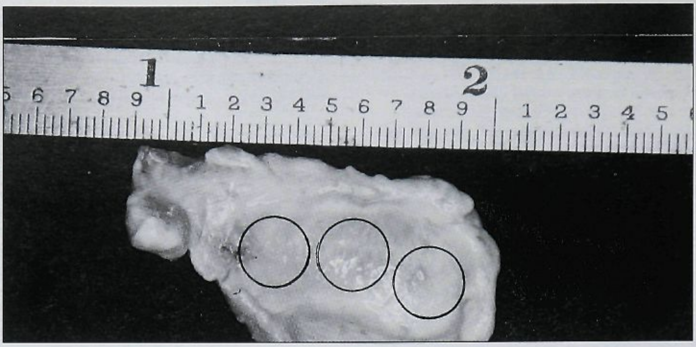

Fig 1 Three cylindrical specimens, each 6.5 mm in diameter, were removed from the disc. One punch specimen each was taken from the lateral, central, and medial portions of the disc.

compatible substance that replicates the physical characteristics of the human TMJ disc,[23] knowledge of shear properties is needed.

This study was undertaken to evaluate shear stress moduli that exist in the human TMJ disc so as to better understand how it can become dysfunctional and which of its properties must be reproduced in an artificial disc. Correlation of shear moduli with age also was determined.

Materials and Methods

Nine gross anatomically normal looking TMJ discs were removed via a cranial approach from seven male and two female humans within 24 hours of death. Appropriate consent was obtained. Age at death ranged from 36 to 76 years. Discs were immediately placed in isotonic bacteriostatic saline and stored at 4°C. Shear stress moduli were determined less than 48 hours after death.

A stainless-steel tissue punch was used to remove three cylindrical specimens, each 6.5 mm in diameter and 1 to 4 mm thick, from each disc. One punch specimen was taken from the lateral portion of the disc, one from the central portion, and one from the medial portion (Fig 1). Three of the discs were not large enough to yield three separate 6.5-mm pieces of tissue; thus, six discs yielded three portions each and three discs yielded two portions each. Eight specimens were obtained from lateral portions, eight from medial portions, and eight from central portions. Twenty-four total specimens were tested.

Within 48 hours of retrieval, each specimen was attached by cyanoacrylate adhesive to the axiotorsional apparatus of a servohydraulic test system (MTS 858, MTS Systems, Minneapolis, MN) (Fig 2, a to c). Shear properties were measured under quasistatic conditions with displacement control at the rate of 2 mm/100 seconds (Fig 2, d). Linear increase of displacement was applied until the specimen failed to maintain maximum resistance to the applied shear force (Fig 2, e and f). At that point, the modulus of shear stress (N/mm^2) was determined (Fig 3).

Statistical Analysis

The group means for shear moduli of the central and peripheral (lateral and medial) portions of the TMJ discs were analyzed by means of Wilcoxon's signed ranks test. Spearman's rank correlation coefficient was used to analyze the correlation of shear moduli of discs with age. The regression of shear modulus versus age was examined by means of linear regression.

Results

Generally, TMJ discs appeared as biconcave avascular fibrous dense connective tissues with a mediolateral width ranging from 16 to 22 mm and an anteroposterior dimension of 9 to 10 mm. The central portions of the discs were 1 to 1.5 mm thick. In contrast, the medial and lateral portions of the

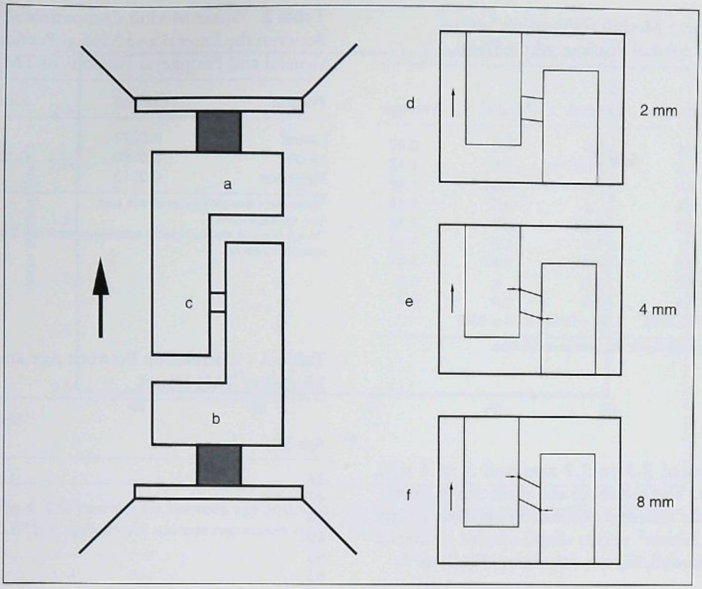

Fig 2 Schematic diagram of shear stress apparatus attached to an axiotorsional servohydraulic system used to apply shear force to TMJ disc specimens: *(a)* simulation of mandibular bone; *(b)* simulation of temporal bone; *(c)* TMJ disc specimen attached by cyanoacrylate adhesive 2 to 5 mm thick × 6.5 mm in diameter; *(d)* movement 2 mm/100 seconds; *(e)*, *(f)* movement until the specimen detaches from the apparatus.

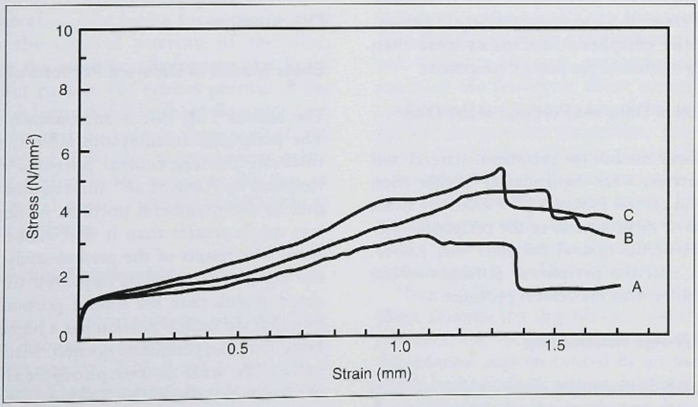

Fig 3 Shear stress (N/mm^2) plotted against strain: *(A)* central portion, *(B)* medial portion, and *(C)* lateral portion.

Table 1 Shear Moduli (N/mm^2) in Lateral, Central, and Medial Portions of the Discs

Disc/ age (y)	Lateral	Central	Medial	Average
1/36	1.4	0.5	1.0	0.97
2/43	1.3	1.06	1.1	1.15
3/58	2.0	0.6	1.86	1.48
4/60	1.7	x	0.6	1.15
5/65	3.2	0.89	2.9	2.33
6/65	1.1	1.1	1.6	1.27
7/67	1.6	1.2	1.47	1.42
8/68	2.0	1.0	x	1.5
9/76	x	2.0	3.4	2.7
Mean	1.79 ± 0.65	1.04 ± 0.46	1.74 ± 0.96	

x = no specimen available for this portion of this disc.

discs measured 2.5 to 3.5 mm and 3 to 4 mm, respectively. The results of the shear stress experiments for the different portions of specimens were plotted as N/mm^2 versus displacement of strain. The shear moduli, G, was calculated (Fig 3) as[24]:

$$G = \frac{\tau \text{ (shear stress at the maximum detachment force)}}{\gamma \text{ (shear strain)}}$$

in N/mm^2. The shear stress moduli of all specimens are shown in Table 1. There was no statistically significant difference between lateral and medial shear moduli (Table 2). Therefore, data for the lateral and medial tissue specimens were combined and treated as one (peripheral) group. Moduli of the peripheral specimens were then compared to moduli of the central specimens.

Shear Moduli of Different Portions of the Disc

Values of shear moduli on peripheral (lateral and medial) portions were significantly higher than were those on central portions ($P = 0.0013$) (Table 2). The ratio of shear moduli of the peripheral portions to that of the central portions was 1.69:1. This means that the peripheral portions of the discs were stiffer than the central portions.

Shear Moduli–Age Relationship

The correlation between the shear moduli of TMJ discs and age was significant ($r = 0.769$; $P < 0.05$) (Table 3 and Fig 4). The shear moduli of the TMJ discs increased with age, an indication that disc stiffness increased with age.

Table 2 Shear Moduli Comparisons* (*P* Values) Between the Lateral and Medial Portions and the Central and Peripheral Portions of TMJ Discs**

Portion	Central	Lateral
Lateral	0.0277	
Medial	0.0180	0.1763 (ns)
Peripheral	0.0013	

*Wilcoxon's two-tailed signed rank test.
ns = nonsignificant.
**n = 9 discs (6 discs yielded 3 specimens each and 3 discs yielded 2 specimens each).

Table 3 Correlation Between Age and Shear Moduli of TMJ Discs*

Age (y)	Shear moduli (N/mm^2)
36	0.97
43	1.15
58	1.48
60	1.15
65	2.33
65	1.27
67	1.42
68	1.5
76	2.7

*Spearman's rank correlation coefficient.
Shear stress regression equation slope: $-0.326 + 0.031 \times$ age.
$r = 0.769$; $P < 0.05$.

Discussion

Shear Moduli of Different Portions of the Disc

The human TMJ disc is anatomically biconcave.[25] The peripheral (medial and lateral) portions are thickest, and the central portions are thinnest. Research by Teng et al[24] showed that tensile stiffness in the peripheral portions of dog TMJ discs was much greater than it was in the middle portions. The results of the present study showed that the peripheral portions appeared to have higher shear moduli than the central portions, an indication that the central portion has a higher shear resistance than the peripheral portion. Mechanical properties, as well as morphologically different thicknesses, allow the TMJ disc to perform a "biofeedback" effect. When pressure from the osseous components of the TMJ compresses the disc, a rotary movement of the disc forces the thicker portions away from the opposing bone and

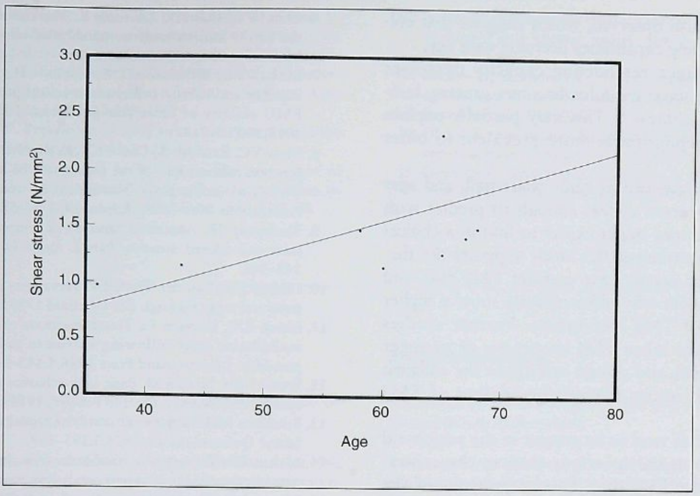

Fig 4 The correlation between age and shear moduli of TMJ discs (shear moduli = –0.326 + 0.031 × age) shows a linear regression ($r = 0.769$; $P < 0.05$).

brings the thinner portion between the bones. In contrast, when pressure between the bony parts is released and the space is widened, the disc rotates so that the thicker part of the disc will fill the space. In a joint that is functioning normally, the condylar surface is located on the thinner central portion of the disc. Therefore, the biting force exerts itself mainly on the central portion of the disc. Nevertheless, the mechanical property of a lower shear modulus enables the central portion of the disc to bear a larger force without damage, even though the central portion is thinner than the peripheral portion. If the disc increases shear modulus, through dysfunctional stress on the disc or aging, the central portion will be more likely to deteriorate or perforate.

Shear Moduli–Age Relationship

The prevalence in clinical subjects of some craniomandibular disorder symptoms has been reported to increase with age.[26–31] Bibb et al[26] and Serfaty et al[28] showed that TMJ symptoms in elderly populations were not associated with impaired general health.[26,28] In contrast, Agerberg and Bergenholtz[29] and Rieder et al[31] reported that crepitation and TMJ noise occurred more frequently in older age groups. The findings of these studies concur with those from previous studies with regard to reports of crepitation or a decrease in jaw opening with increased age.[29–31]

The TMJ disc is composed of dense fibrous tissue containing primarily collagen fibers. Collagen fibers are integrated with cells and intercellular substances, such as collagen, proteoglycan/glycosaminoglycan, elastin, and so forth, in a single tissue. Collagen fibers in connective tissue provide much of the tensile or shear strength, and glycosaminoglycan components of the matrix account for the compressive properties. The vessels and nerves are distributed only in the peridiscal capsular and synovial tissues. Because it is avascular, the disc body is difficult to heal after injury. Fibroblast cells also decrease with age. Therefore, disc collagen fibers fail to regenerate from mechanical damage more frequently in older populations.

Nimni[32] reported that as people age, collagen fibers undergo less degradation, and the amount of fibrous tissue increases. This decrease in collagen degradation may be caused by an increase in the number of crosslinks present. Increased crosslinking of collagen chains with age has been also reported.[18,33] Furthermore, Olczyk's study[34] demonstrated that collagen solubility decreases with age. An increase with age in collagen's aldehyde content was also observed, which suggests that collagen remodeling capabilities decrease with age.

While collagen remodeling capacity decreases with age, the shear modulus becomes greater, indicating more stiffness.[35] This may partially explain why TMJ crepitation is more prevalent in older patients.

The sample size of this study was small, and ages were not dispersed widely enough to predict with certainty what one might expect to find in a clinical situation. Nevertheless, this study supports the theory that older people have a stiffer TMJ disc, and may also explain why older patients show a higher prevalence of TMJ crepitation. Further studies should include more TMJ specimens of younger human subjects, and should investigate the collagen changes that occur around the healing of TMJ wounds.

Shear moduli tend to be greater in the peripheral (lateral and medial) portions than in the central portion of the TMJ disc. Lateral portions of the disc are therefore more stiff. Shear resistance is greater in the central portions, which are therefore more flexible. Because shear moduli of human TMJ discs increase with age, older discs become more stiff. The higher clinical prevalence of crepitation in older patients, especially when mandibular excursive movements cause the condyle to pressure the peripheral portions of the TMJ disc, may be explained by this increased disc stiffness with age.

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Resumen

Evaluación del estrés interno de resistencia del disco de la articulación temporomandibular humana

El propósito de este estudio fue el de determinar el est rés interno de resistencia del disco de la articulación temporomandibular (ATM) humana, post mortem. Se determinó la correlación del estrés interno de resistencia de acuerdo a la edad o a la región del disco. Se sacaron unilateralmente nueve discos humanos post mortem, cuyas edades oscilaban entre los 36 y los 76 años. Los discos fueron seccionados en especimenes laterales (ocho), centrales (ocho) y medios (ocho). Cada espécimen fue adherido con adhesivo de cianoacrilato a un aparato con un sistema de examen servohidraúlico con un sistema de recuperación de 48 horas. Se midieron las propiedades de resistencia bajo condiciones cuasiestáticas con un aumento linear de desplazamiento hasta que el espécimen no pudo mantener la resistencia máxima a la fuerz Òa aplicada. Los módulos de resistencia fueron analizados utilizando el examen de rangos de Wilcoxon. Los resultados demostraron que los valores de los módulos de resistencia sobre las porciones periféricas (lateral y media) fueron significativamente mayores que en las porciones centrales (P=0,0013). La correlación entre los módulos de resistencia de los discos de la ATM y la edad demostró que existía un declive de regresión para los módulos de resistencia de -0,326 +0,0313 en la edad (r=0,769; P<0,01). Las porciones periféricas (lateral y media) tienen unos módulos de resistencia mayores y son más rígidos que las porciones centrales de los discos. Además, los módulos de resistencia o rigidez de los discos de las ATM aumentan con la edad.

Zusammenfassung

Auswertung der Scherbeanspruchung des Diskus des menschlichen Kiefergelenk

Ziel dieser Untersuchung war es, die Scherbeanspruchung des Diskus des menschluchen Kiefergelenk festzustellen. Wechselbeziehungen zwischen Scherbeanspruchung und Alter, bzw. Teil des Diskus wurden festgestellt. Neun Disci wurden einseitig von Leichen (36 - 76 Jahre alt) entnommen.und in sektioniert. Die Disci wurden dreifach geteilt. Gewonnem wurden laterale (8), mittlere (8) und mediale (8) Untersuchungsstücke. Jedes Probestück wurde mit Akrylatad- häsiv an ein Hydroverstärkungdgerät befestigt. Sher Eigenschaften wurden umter quasi-statische Bedingungen gemessen bis das Probestück nicht weiter den maximalen Widerstand gegen den Druck auswies. Die Sher Moduli wurden mit dem Wicoxon Signed Ranks Test analysiert. Es zeigte sich, dass die Werte der Sher Moduli der peripherale Teile (laterale und mediale) grösser waren, als die der mittlere (P = 0,0013). Di Korrelation zwischen den Sher Moduli der Kiefergelenk Disci und Alter zeigte eine negative Neigung von -0,326 + 0,031 3 Äler (r = 0,769, P < 0,01). Peripherale Teile haben höhere Sher Moduli Werte und sind steifer als die mittlere Teile des Diskus und die Sher Moduli und Steifheit des Kiefergelenk Diskus werden mit Lebensdauer grösser.