Joules, Genes, and Behaviors: Degeneration of The Human TMJ

Jeffrey C. Nickel, DMD, MSc, PhD
Associate Professor
University of Missouri-Kansas City
Department of Orthodontics and Dentofacial Orthopedics
Introduction

• Degenerative joint disease occurs 15-20 years earlier in the TMJ than knees and hips
• Osseous changes (DJD) are late stage events
• What happens before the inflammatory cytokines are detectable in the joint?
Introduction

Mechanical fatigue failure of TMJ tissues

• Initiating event leading to an inflammatory response

• Mechanical fatigue depends on:
  – TMJ loads
  – Energy density
  – Event frequency
Magnitudes of TMJ loads

Individual-specific craniomandibular mechanics

• Validation of numerical model accuracy (Trainor et al., 1995)
  – 3D Craniomandibular anatomy
  – Objective
    • Minimization of joint loads
    • Minimization of muscle effort
  – Tested with *in vivo* data
Validation of Model Accuracy: Subjects

- Recruited 49 women and 44 men
- Classified into 4 diagnostic groups using RDC and MR imaging
  - +Pain/+Disc Displacement (n= 27)
  - +Pain/-Disc Displacement (n= 15)
  - -Pain/+Disc Displacement (n= 19)
  - -Pain/-Disc Displacement (n= 17)
Subjects

• Diagnostic group determination
  – RDC-calibrated
    • Medical radiologist
      – CT scan
      – MRI

• Geo-files
  – Lateral & PA cephalograms
Validation of Model Accuracy: Biting Experiments
Conclusions

Numerical model predictions of muscle activities were good, with absolute errors 9-14%.
Objective: Test Hypothesis

TMJ loads during static biting:

Subjects with (+) TMJ disc displacement > Subjects without (-) TMJ disc displacement
Application: Biting Tasks

- Model
- Geo-file, eminence shape
- Objective: MME
- Predicted
  - Muscle forces
  - TMJ loads (IL, CL)
- 3 biting positions
- 13 biting angles

ANCOVA: sex, position, angle
Application: Biting Tasks

- Example
  - Left molar

Bite Force
(100 Units)
Application: Biting Tasks

- Example
  - Left molar

Bite Force (100 Units)
Application: Biting Tasks

- Example
  - Left molar

Bite Force (100 Units)
Application: Biting Tasks

- Example
  - Left molar
Group Differences: [+DD]–[-DD]

Canine Incisor Molar Biting Position

Difference in TMJ Load (% of Bite Force)

- Ipsilateral TMJ Load
- Contralateral TMJ Load

* indicates significant difference.
Group Differences: [+DD]–[-DD]

- Difference in TMJ Load (% of BF)
- Ipsilateral TMJ
- Contralateral TMJ

Biting Angle

1 2 3 4 5 6 7 8 9 10 11 12 13
Group Differences: [+DD]–[-DD]
Summary

• +DD group had joint loads 40-60% higher compared to −DD subjects
• During normal daily function, +DD subjects mechanically challenge their TMJs
Introduction

Mechanical fatigue failure of TMJ tissues

- Initiating event leading to an inflammatory response
- Mechanical fatigue depends on:
  - TMJ loads
  - Energy density
  - Event frequency
Introduction

Energy density (mJ/mm3)

• Concentration of mechanical work

• \( ED = \frac{\text{Work}}{\text{Tissue Volume}} = \frac{F_{\text{traction}} \cdot \Delta D}{\text{tissue volume}} \)
Surface Tractional Force: Plowing

- Mow et al., 1993 (*J Biomech Eng*)
- TMJ Stress-field translation
Objectives

Test the hypotheses that during jaw closing movements, energy densities in the TMJ disc were:

1) Higher in women compared to men
2) Higher in subjects with disc displacement compared to subjects with intact TMJs
Subjects: 32 adults

Age
- Mean: 34 ± 12 years
- Range: 21-60 years

Classified using
- Research diagnostic criteria
- MR and CT imaging

<table>
<thead>
<tr>
<th>Diagnostic Group</th>
<th>Females</th>
<th>Males</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>-Disc Displacement/-Pain</td>
<td>7</td>
<td>7</td>
<td>14</td>
</tr>
<tr>
<td>+Disc Displacement/±Pain</td>
<td>13</td>
<td>8</td>
<td>21</td>
</tr>
</tbody>
</table>
Methods

Subjects provided
- Informed consent
- Anatomic data via images
  - Cephalometric x-ray (PA, lateral)
  - Magnetic resonance
- Kinematic data via jaw tracking
  - 10 symmetric jaw opening/closing movements

Numerical Modeling:
\( F_{\text{normal}} \)

Dynamic stereometry
Methods

ED = W/Q

- \( W = F_{\text{traction}} \cdot \Delta D \)
  - \( \Delta D = \) stress-field translation

- \( Q = \) volume of disc tissue under stress-field
Methods

\[ W = F_{\text{traction}} \times \Delta D \]

- \( F_{\text{traction}} = F_{\text{normal}} \times a \times \left(-0.5[\left(\frac{x-x_0}{b}\right)^2 + \left(\frac{y-y_0}{c}\right)^2]\right) \)

- \( y = \) velocity of stress-field translation
- \( x = \) aspect ratio \( \bullet \) compressive strain
- \( a, b, c, x_0, y_0 = \) constants

Nickel et al., Orthod Craniofac Res, 2009
Measuring TMJ Disc Plowing Forces
Tractional Coefficient = \( \frac{F_{\text{Traction}}}{F_{\text{Normal}}} \)
$R^2 = 0.85$
Methods

\[ W = F_{\text{traction}} \bullet \Delta D \]

- \( F_{\text{traction}} = F_{\text{normal}} \bullet a (-0.5[({x-x_0}/b)^2+({y-y_0}/c)^2]) \)
- \( y = \text{velocity of stress-field translation} \)
- \( x = \text{aspect ratio} \bullet \text{compressive strain}^3 \)
- \( a, b, c, x_0, y_0 = \text{constants} \)

Nickel et al., Orthod Craniofac Res, 2009
Methods

Numerical modeling: $F_{\text{normal}}$

– Based on:
  • 3D anatomy of each subject
  • Objective function
    – Minimization of muscle effort
  • Validation tests: 8-15% error (91 subjects)
    – 20 N load on mandibular canine
    – contralateral TMJ load ($F_{\text{normal}}$)
Methods

Dynamic stereometry

• Individual-specific
  – Anatomy: MRI
  – Kinematics: Jaw tracking
Methods

Dynamic stereometry

- Anatomy: MRI
- Kinematics: Jaw tracking
- Variables for ED calculations
  - $y = \text{velocity of stress-field translation}$
  - $x = \text{aspect ratio} \cdot (\text{compressive strain})^3$
  - $\Delta D = \text{stress-field translation}$
  - $Q = \text{volume of disc tissue}$
Data & Statistical Analyses

• ED = W/Q
  – Determined for jaw closing phase
  – Averaged over 10 cycles/subject

• ANOVA: Sex, diagnostic group

• Regression analysis: Single variable contributions

• Significance: $\alpha = 0.05$
Results

Mean Energy Density/Cycle (mJ/mm³)

- Females -DD: 3.8 ± 1.6
- Males -DD: 1.9 ± 1.6
- Females +DD: 6.4 ± 1.3
- Males +DD: 2.5 ± 1.5

*p<0.05
*p<0.04
# Results: Linear Regression

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>SD</th>
<th>Variable vs. ED: Pearson r</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta D ) (mm)</td>
<td>0.04</td>
<td>0.01</td>
<td>0.70</td>
<td>0.012</td>
</tr>
<tr>
<td>( y ) (mm/s)</td>
<td>6.66</td>
<td>2.80</td>
<td>0.72</td>
<td>0.009</td>
</tr>
<tr>
<td>( Q ) (mm(^3))</td>
<td>225.9</td>
<td>70.8</td>
<td>-0.45</td>
<td>Not significant</td>
</tr>
<tr>
<td>( a/h ) (aspect ratio)</td>
<td>1.53</td>
<td>0.71</td>
<td>0.52</td>
<td>Not significant</td>
</tr>
<tr>
<td>( F_{\text{traction}}/F_{\text{normal}} )</td>
<td>0.003</td>
<td>0.001</td>
<td>0.74</td>
<td>0.006</td>
</tr>
<tr>
<td>( F_{\text{normal}} ) (N)</td>
<td>14.9</td>
<td>2.9</td>
<td>0.38</td>
<td>Not significant</td>
</tr>
</tbody>
</table>
Discussion

Mechanical fatigue failure

• Anderst & Tashman, 2010

Dog knee menisci

 – Healthy stress-field velocity
   • = 50 mm/s

 – ACL transection
   • = 2.5X ↑velocity

WJ Anderst and S Tashman, J Biomechanics 43:994-997, 2010
Gallo et al., 2000, 2006

- Healthy TMJs moving @ 1 Hz
  - Open-close average velocity = 40 ± 19 mm/s
  - Laterotrusion: 1.5X ↑ work
Summary

Mechanical fatigue failure

• Women impose more mechanical work per volume of TMJ disc cartilage compared to men
Introduction

Mechanical fatigue failure of TMJ tissues

- Initiating event leading to an inflammatory response
- Mechanical fatigue depends on:
  - TMJ loads
  - Energy density
  - Event frequency
Introduction

Intensity and frequency of mechanical loading of the mandible in humans?

• Polysomnography
  – Rossetti et al., 2008 (J Orofac Pain: 30 pain, 30 healthy)
  – Rosetti et al., 2008 (Cranio: 14 TMD, 12 healthy)
  – Rompre et al., 2007 (J Dent Res: 100 sleep bruxism, 43 nonbruxers)
  – Raphael et al., 2012 (J Am Dent Assoc: 124 TMD-Bruxers, 46 Healthy)

• Ambulatory (Sleep State) Recording
  – Van Selms et al. 2008 (J Oral Rehab: 8 Pain)
  – Baba et al., (J Orofac Pain: 103 healthy)

• Ambulatory (Awake-state) Recording
  – Michelotti et al., 2005
  – Farella et al., 2005)
Introduction

The issues we want to address:

• Muscle activities were expressed as %MVC
• Scarcity of data comparing day and night muscle activities in TMD/Healthy subjects
Introduction: Duty Factor

Used to describe how much a muscle is active over a prescribed period of time

- Van Wessel et al. Exp Brain Res 2005
  - Rabbit:
    13% duty factor (at 5% RMS_{maximum})
Objectives

• Test whether or not duty factors can be measured in:
  – ±Disc Displacement
  – ±Pain subjects

• Test for diagnostic group differences in Masseter and Temporalis muscle DFs
Materials and Methods: Subjects

- 50 subjects
- IRB oversight
- RDC and MRI
  - -DD/-Pain, n=11 (8 ♀, 3 ♂)
    • Average 30.6 years
  - +DD/-Pain, n=11 (7 ♀, 4 ♂)
    • Average 38.1 years
  - +DD/+Pain, n=28 (16 ♀, 12 ♂)
    • 33.3 years
Materials and Methods: Field Recording of Muscle Activities

Two-channel EMG recorder
- Sampling frequency
  2 kHz/channel
- Amplified 5000x
- Data storage: 512 MB SD card
Materials and Methods: Field Recording of Muscle Activities

- Trained subjects
- Unilateral recordings of masseter and temporalis muscle activities
- Subjects repeated unacceptable recordings (i.e. ≤5 hrs)
Materials and Methods: Laboratory Calibrations

Duplicate laboratory calibrations

- Pre-calibrated bite force (N) transducer
- Unilateral loads on right and left first molar teeth
- Bilateral surface EMG measured muscle activity
Materials and Methods: Laboratory Calibrations

• Bilateral surface electrodes
• Masseter and temporalis muscle activities (µVolts)
• Static and dynamic (0.5-2.0 Hz) bite-forces
Materials and Methods: Laboratory Calibrations

- EMG vs bite-force data to produce a linear regression for each subject
- Subject-specific threshold muscle activity for a 20 N bite-force
  - $(\text{RMS}_{20 \text{N}}, \mu\text{V})$

\[
y = 0.6886x + 11.586 \\
R^2 = 0.8347
\]
Materials and Methods: Data Analysis

- EMG signals analyzed in two stages
- Used 128 ms windows for analysis
- Stage 1 processing:
  - Added the number of windows \( \geq \% \) RMS20 N for the 5 thresholds of \( \geq 5\% \) to \( \geq 80\% \) RMS20 N
  - Calculated duty factors for the 5 thresholds by the equation:
    \[
    (\#\text{Windows}) \times \left( \frac{128 \text{ ms}}{\text{window}} \right) \times \left( \frac{\text{Duration of Recording}}{\text{Duration of Recording}} \right)
    \]
Stage 2 processing:

- 128 ms windows
  - Threshold criteria for each $\geq \%RMS20$ N, according to 6 duration criteria of $\geq 1$ s to $\geq 20$ s
- Determined the effect of duration criteria on duty factors by the equation:

\[
(\#\text{Contiguous Windows}) \times \left( \frac{128 \text{ ms}}{\text{window}} \right) \times \left( \frac{\text{Duration of Recording}}{\text{x}} \right)
\]
Materials and Methods: Data Analysis

ANOVA and Tukey-Kramer post hoc tests for independent variable effects

- Diagnostic group (+DD +P; +DD −P; −DD −P)
- Awake- or sleep-state
- Muscle (masseter, temporalis)
- Threshold criteria
- Duration criteria
Results

- 50 subjects produced 284 recordings
- Awake-state records: 6.9 ± 2.3 hrs
- Night records: 7.6 ± 1.9 hrs
- Significant differences: Masseter*Threshold
• Masseter DF = Temporalis DF
Temporali
s

Mass DF > Temporalis DF

Masseter

Temporali
s

Masseter
Masseter Duty Factors: Awake

* P< 0.05

Masseter Awake Duty Factor (%)

Threshold Magnitude (% RMS_{20N})

[Graph showing data with different conditions and statistical significance]
Masseter Duty Factors: Night

* $P < 0.05$

** $P < 0.01$
Temporalis Duty Factors: Awake

Threshold Magnitude (% RMS_{20N})
Temporalis Duty Factors: Night

![Graph showing Temporalis Night Duty Factor (%) against Threshold Magnitude (% RMS$_{20N}$) with bars for +P+DD, -P+DD, and -P-DD categories. The graph visually represents the duty factor distribution across different threshold magnitudes.]
Group Differences in Muscle Activities

- Muscle duty factors can be measured in TMD diagnostic subgroups
- Subjects with pain exhibit more low level masseter muscle activity
- No differences amongst groups for bruxing type muscle effort
Overall Summary and Conclusions

Mechanical fatigue failure of TMJ tissues depends on:

- TMJ loads
- Energy density
- Event frequency
Summary

Mechanical fatigue failure of TMJ tissues depends on:

- TMJ loads
  - Diagnostic group differences
  - +DD joint loads are > 40% higher
Summary

Mechanical fatigue failure of TMJ tissues depends on:

– Energy density
  • Women impose more mechanical work per unit volume of cartilage
Summary

Mechanical fatigue failure of TMJ tissues depends on:

- Event frequency
- Pain is associated with low grade chronic masseter muscle activity
Future Work

Multi-domain model of TMJ degeneration

- Mechanics
  - Energy density
- Frequency
  - Behavior
- Genes
  - Inflammation
  - Pain
- Cell Metabolism
Acknowledgments

This study funded by NIH R01-DE16417

Thank you to the subjects who participated

Kim Theesen,
Graphic Artist
Make an Investment . . . to continue your Commitment to the Specialty