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Development and evaluation of thoracic spine modeling techniques

Sherry Thaxton, Ph.D.
Texas Tech University

Jeff Woldstad, Ph.D.
University of Nebraska- Lincoln

Presentation outline

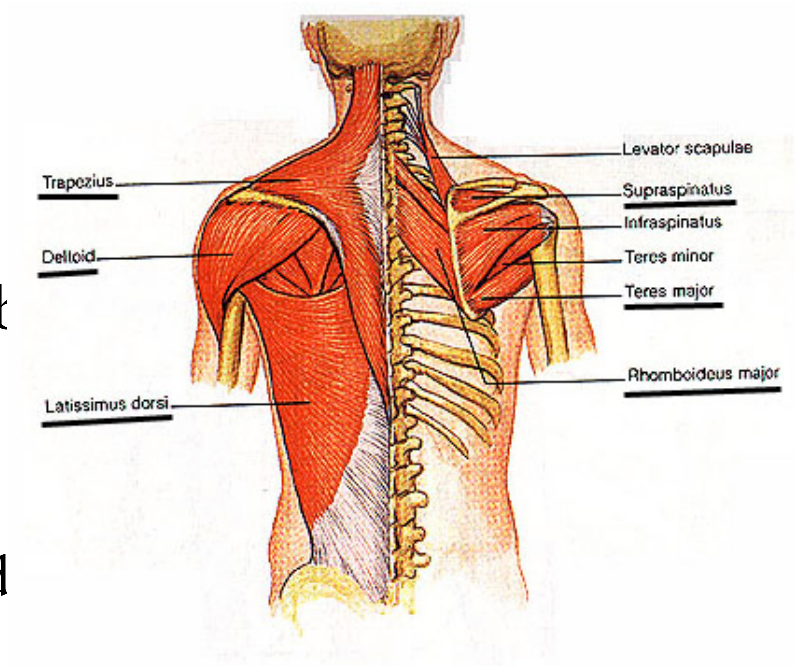
- Introduction
  - Why thoracic spine modeling?
  - How are muscle forces modeled in the spine?
  - Research goals and objectives
- Model development
- Experimental methods
- Results
- Discussion
- Conclusions
- References

Background-
Why thoracic spine modeling?

- Applications of thoracic spine muscle models include the development of targeted exercises for the prevention of bone mass loss

- Majority of back muscle modeling to date focuses on lumbar region

- Number of muscles exceeds the numb of equilibrium equations available
  - Simplify the anatomical model
  - Assign force values based on recorded EMG values
  - Use linear or nonlinear optimization routines



Background- Applications

Bone is deposited where it is needed and resorbed where it is not needed, as determined by mechanical demands on the bone (Wolff's Law)

- Astrand & Rodahl, 1986; Burr & Martin, 1992; Chaffin et al., 1999; Farfan, 1995; Gross & Bain, 1993)

Loss of bone mass during spaceflight represents one of the most serious health threats to astronauts during long duration flights

- Anderson & Cohn, 1985; Lang et al., 2004; LeBlanc et al., 1996; Rambaut et al., 1975

NASA is currently planning manned missions to the moon with extended stays, and future manned missions to Mars will last up to three years in duration

- *The Vision for Space Exploration*, 2004

Background-
Optimization-based modeling

- Optimization models seek to minimize or maximize (optimize) an objective function, subject to constraints
- Example: Running errands after work
  - Need to run errands
    - *Grocery store, bank, gas station*
  - Goal (objective)
    - *Minimize number of miles driven*
  - Constraints
    - *Need to visit the bank before 6:00*
    - *Want to go to the grocery store last so the milk doesn't spoil*
  - Solution
    - *Consider alternative routes and timing*
    - *"Optimal" route may depend on the algorithm used*

Background-
Optimization-based modeling

▪Optimization-based modeling of the spine

- Objective
  - *Minimize maximum stress of muscles*
  - *Minimize compression of vertebrae*
- Constraints
  - *Muscles must balance out the moment at the vertebrae created by external forces (weight of body, forces at hands)*
  - *Muscles can only act in tension*
  - *Force of a given muscle can only vary by certain amount across levels of the spine*
- Results of optimization
  - *Predicted muscle forces, given a set of external conditions*

Research focus and objectives

Formulation of an optimization-based model of the thoracic spine

- Validate muscle force predictions against EMG data
- Compare multiple model formulations in order to select the best-performing parameters

Model development

Objective function

- Sum of Cubed Intensities (SCI)
  - *Nonlinear formulation that seeks to minimize the sum of cubed muscle intensities across all muscles at a vertebral level*
- Minimum Intensity-Compression (MIC)
  - *Two-step linear formulation that first minimizes maximum intensity, then minimizes compression*

Strategies to model thoracic region

- Include a representation of the rib cage and sternum to off-load muscles
- Ignore bones- model only muscles

Multi-level model consideration

- Differences in muscle force predictions between adjacent vertebral levels

Experimental methods-
Subjects and Equipment

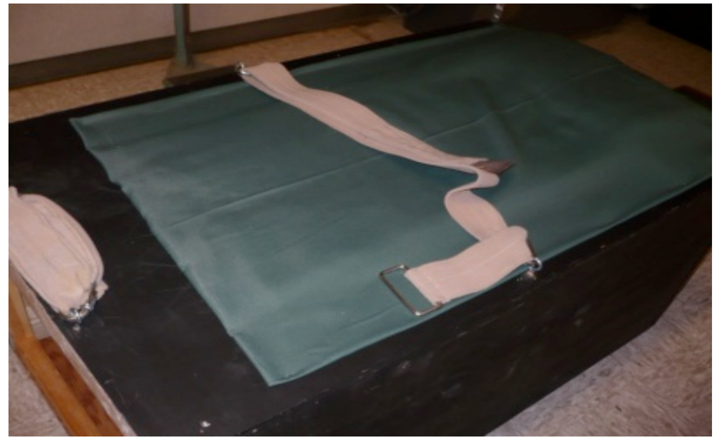
Subjects

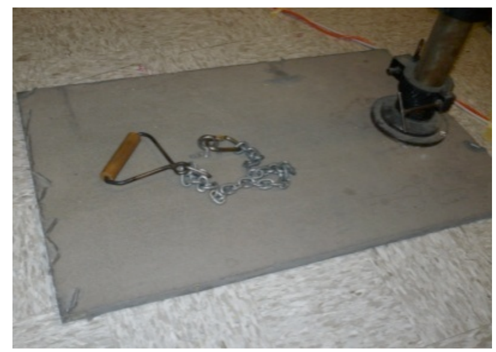
- 6 male, 6 female
- Age ranged from 23 to 32 years
- No recent history of low back pain/injury or hernia

Equipment

- Optical motion capture system
- EMG system
- Weights
- Testing rigs
- Anthropometer
- Scale

Experimental methods- Equipment



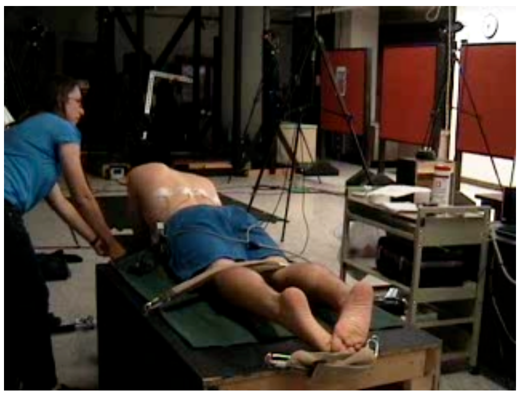


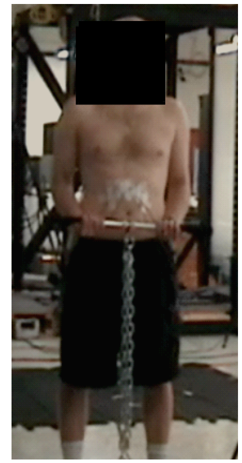
Experimental methods- Procedures

Each subject attended one session of approximately three hours in length

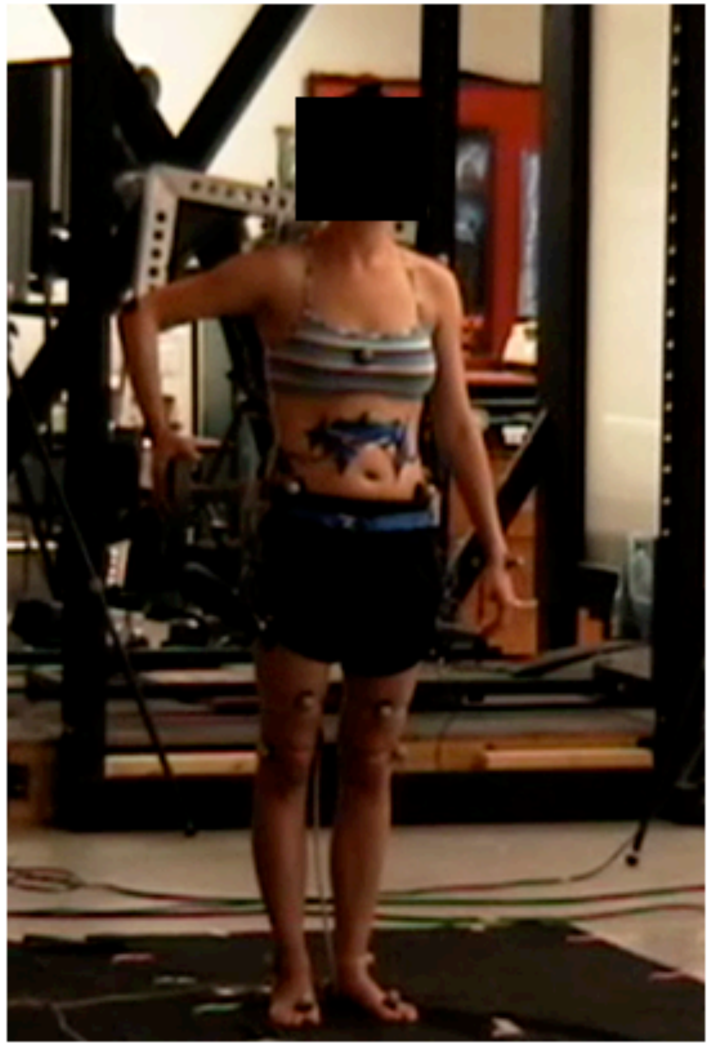
- Briefed about test protocol
- Signed appropriate release forms and health questionnaire
- EMG preparation
- Maximal voluntary contractions (pre-test)
- Motion tracking preparation
- Functional testing
- Anthropometric data collection
- Maximal voluntary contractions (post-test)

Experimental methods-
MVC and resting procedures





Experimental methods-
Symmetric and asymmetric static lifts



Results-
Model processing methods

EMG data

- High-pass and low-pass filtered, RMS
- Average taken for timeframe
- Normalized using minimum and maximum values

Optical motion tracking data

- Average taken for 10 frames from each trial

Resultant moments and forces

- Calculated at vertebral levels T8 through T12 using Mathematica program
- Based on body segment center locations, segment mass estimates, and forces at the hands

Muscle force predictions

- Calculated with Mathematica program using MIC and SCI models, with and without rib cage representation, with delta values of 10 N/cm^2 and 10,000 N/cm^2

Results-
Data analysis performed

Did model predictions align with EMG data?

- Contingency tables
- Correlation analysis
- Categorized graphs
- ANOVA for reduced set of data

Results-
Contingency table and correlation analyses

- Contingency table analysis
  - Each value of chi-square statistic greatly exceeded the critical point
  - Not a good fit between model and predictions
- Correlation analysis
  - Correlation coefficients indicated lack of strong linear relationship between EMG and model predictions

Results-
Categorized graphs

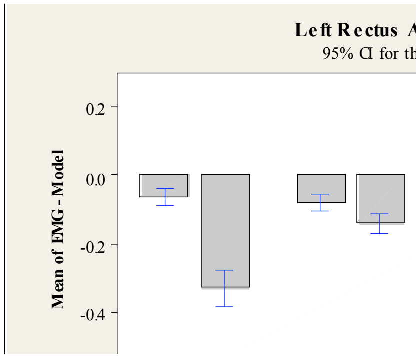
Bar graphs of mean difference between EMG and model predictions created

- Included 95 percent confidence intervals for the mean
- Created based on groupings of model parameters as well as test parameters
- Plotted for each muscle modeled

Results-
Categorized graphs

Models tended to err on the side of over-predicting muscle activity

- Difference exceeded 50 percent in some cases



Results- Categorized graphs

- Symmetric lifts appeared to be predicted more closely than asymmetric lifts for many cases
- Low force lifts appeared to be predicted more closely than high force lifts for many cases
- Reduced dataset was selected for further analysis including only symmetric lifts of low force

Major Discussion Points

- Lift symmetry
  - Symmetric lifts were considered to be predicted better based on an overall trend, though there were several exceptions
    - Attributable to increased coactivation, larger moment arms
- Weight of lift
  - Model over-estimations seemed to worsen for anterior muscles during heavy lifts
    - May be partially attributable to differences in subject strength
- Exclusion of these factors for ANOVA simplifies analysis
  - Results now must be taken into context (applicable for lower weight, symmetric lifts)

Major Discussion Points

- Subject gender
  - ANOVA results indicated better predictions for male subjects
    - *Male subjects may have matched male database better than female subjects matched female database*
    - *Male subjects may have been lifting a lower percentage of maximum capacity*
- Objective function
  - Linear model tended to predict better than nonlinear model
  - Linear model is also simpler to implement
- Rib cage implementation
  - Models without the rib cage had better results
  - Modifications to rib cage representation may change this
    - *More accurate geometric and materials properties*
    - *Inclusion of rib cage as an objective function*
  - Over-prediction trend indicates that it could be helpful to allocate more force to rib cage
- Limitation of force difference between vertebral levels
  - Inclusion of this constraint resulted in indeterminate results for many trials
  - When this constraint impacted results, it was usually beneficial

Conclusions

- Traditional modeling methods used for the lumbar spine were adapted for use in the thoracic region
  - Modifications to include rib cage anatomy and predictions for multiple vertebral levels
- Compared model predictions to EMG in order to determine which formulations yielded the best agreement
  - Linear objective function, without rib cage, without limitations between vertebral levels
- Allowed for exploration of new modeling strategies and analysis of parameter interactions

Future Work

- Improved accuracy of predictions may be obtained through:
  - More accurate representations of muscles and bones
    - *Internal geometry*
    - *Physiological properties*
    - *Alternate rib cage mechanisms*
  - Better standardization of postures between maximal and sub-maximal lifting trials

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Questions?

Backup slides

Model development-
Muscles modeled

T8	Erector Spinae	Latissumus Dorsi	Major Pectoral	Trapezius		
T9	Erector Spinae	Latissumus Dorsi	Major Pectoral	Trapezius		
T10	Erector Spinae	Latissumus Dorsi			Rectus Abdominis	
T11	Erector Spinae	Latissumus Dorsi			Rectus Abdominis	External Oblique
T12	Erector Spinae	Latissumus Dorsi			Rectus Abdominis	External Oblique

- Selected based on:
  - Precedence from previous research
  - Accessibility for EMG data collection
  - Relevance to thoracic movement
  - Availability of geometric data in literature

MIC model not including rib cage

Objective 1:

$$Minimize\ I_{max}$$

Objective 2:

$$Minimize \sum_{i=1}^{n} \|f_i\| \tau_i^z$$

Constraints:

Subject to

$$\sum_{i=1}^{n} \|f_i\|(r_i \times \tau_i) + M^E = 0$$

$$f_i \geq 0$$

$$\left|\frac{f_i}{A_i} - \frac{f_{i+1}}{A_{i+1}}\right| \leq \delta$$

$$\frac{f_i}{A_i} \leq I_{max}$$

MIC model including rib cage

Objective 1:

$$Minimize\ I_{max}$$

Objective 2:

$$Minimize \sum_{i=1}^{n} \| f_i \| \tau_i^z$$

Constraints:

Subject to

$$\sum_{i=1}^{n} \| f_i \| (r_i \times \tau_i) + \sum_{j=1}^{m} \| f_j^B \| (r_j^B \times \tau_j^B) + M^E = 0$$

$$f_i \geq 0$$

$$\frac{f_i}{A_i} \leq I_{max}$$

$$\left| \frac{f_i}{A_i} - \frac{f_{i+1}}{A_{i+1}} \right| \leq \delta$$

$$\left| \frac{f_j^B}{A_j^B} \right| \geq p$$

SCI model not including rib cage

Objective:

$$\text{Minimize} \sum_{i=1}^{n} \left(\frac{f_i}{A_i}\right)^3$$

Constraints:

Subject to

$$\sum_{i=1}^{n} \|f_i\|(r_i \times \tau_i) + M^E = 0$$

$$f_i \geq 0$$

$$\left|\frac{f_l}{A_l} - \frac{f_{l+1}}{A_{l+1}}\right| \leq \delta$$

SCI model including rib cage

Objective:

$$\text{Minimize} \sum_{i=1}^{n} \left(\frac{f_i}{A_i}\right)^3$$

Constraints:

Subject to

$$\sum_{i=1}^{n} \|f_i\|(r_i \times \tau_i) + \sum_{j=1}^{m} \|f_j^B\|(r_j^B \times \tau_j^B) + M^E = 0$$

$$f_i \geq 0$$

$$\left|\frac{f_j^B}{A_j^B}\right| \geq p$$

EMG data processing

Amplification performed through hardware system, sampled at 2000 Hz

Filtering within Delsys software using second-order Butterworth

- High-pass filter with 30 Hz cut-off frequency
- Low-pass filter with 1000 Hz cut-off frequency

RMS values calculated

- Time constant window of 60 ms

Normalized against maximum voluntary contractions and resting EMG

Average value taken during duration of trial

- MVC trials- between seconds 2 and 6
- Lifting trials- between seconds 0.5 and 2.5

EMG data processing

$$EMG_{norm} = \frac{EMG_{test} - EMG_{resting}}{EMG_{MVC} - EMG_{resting}}$$

EMG_{norm} : normalized EMG

EMG_{test} : EMG data from lifting task

$EMG_{resting}$: minimum EMG value across all trials

EMG_{MVC} : maximum EMG value across all trials

Results-
ANOVA

- Performed for each muscle modeled
  - Five-way repeated measures
  - $\alpha = 0.05$
- Fixed effects:
  - Gender (male, female)
  - Model (MIC, SCI)
  - Delta (with, without)
  - Ribs (with, without)
- Random effect
  - Subject, nested within gender
- Dependent variable
  - Difference between percent of maximum as observed in normalized EMG data and the percent of maximum as predicted by model formulations
- Unbalanced ANOVA due to missing data points (indeterminate values from some model predictions)
- Performed using general linear model capabilities of Minitab

Results-
ANOVA significant effects

	LES	RES	LLD	RLD	LRA	RRA	LEO	REO
Gender								
Model	0.001			0.049		0.022	<0.001	<0.001
Ribs	<0.001						<0.001	<0.001
Delta								
Gender*Model	0.021		0.031		0.016			<0.001
Model*Ribs	<0.001					0.037		<0.001
Gender*Model							<0.001	
Gender*Ribs			0.015				0.003	0.002
Model*Delta						0.011	0.001	
Gender*Model*Delta						0.011	0.001	
Model*Ribs*Delta						0.011	0.003	
Gender*Model*Ribs								<0.001
Gender*Model*Ribs*Delta						0.011	0.005	