AWARD NUMBER: W81XWH-13-2-0043

TITLE: Lumbar Spine Musculoskeletal Physiology and Biomechanics During Simulated Military Operations

PRINCIPAL INVESTIGATOR: Dr. Samuel R. Ward PT, PhD

CONTRACTING ORGANIZATION: University of California, San Diego
La Jolla, CA 92093

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PREPARED FOR: U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland  21702-5012

DISTRIBUTION STATEMENT: Approved for Public Release;
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The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision unless so designated by other documentation.
This study evaluated the relationship between 3D geometry of the lumbar spine, under different loading conditions and positions, and the pathophysiology of the intervertebral disc and lumbar trunk muscles. 43 Marines were scanned using upright MRI in operationally relevant loading conditions with minimum load, 39 of these Marines were also scanned in a high-resolution MRI scanner to muscle and disc pathophysiological assessment. Significant decreases in lumbar lordosis were found through all levels except L1-L2 when sitting. When prone on elbows, the only increase in lumbar lordosis was found at L5-S1. A caudal increase in fat fraction of the multifidus was observed, with no significant increase in the erector spine. No significant correlations were found between disc injury and muscle pathophysiology.
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</table>
1. **INTRODUCTION:** The weights of loads carried into battle pose an injury and performance problem for the US Marines. Marine Corps assault loads range from 44kg for the rifleman to 61kg for the squad leader. These are well in excess of the recommended assault load of 22.7kg; 30% of body weight. Two things are clear: (1) Marines routinely carry more weight than the recommended limit, and (2) the Veterans Administration shows an increasing trend in disabilities related to lower back injury as a result of carrying excessive loads in operational environments. We have implemented new MRI technologies enabling quantification of lumbar spine kinematics under simulated march conditions. From these investigations, we have observed a large number (37.5%) of Marines with some evidence of disc pathology. However, it is unclear if these disc changes, or the expected concomitant muscle changes, are related to kinematic changes in the lumbar spine. Further, it is not known whether pre-existing disc pathology predicts future injury and service life in U.S. Marines. Our central hypothesis is that lumbar disc and muscle degeneration alters the kinematic response of the lumbar spine to functional positions and loads, predisposing individuals to injury.

2. **KEYWORDS:** Spine, Lumbar, Kinematics, Muscle Architecture, Low Back Pain, Position

3. **ACCOMPLISHMENTS:**

   ▪ **What were the major goals of the project?**
   ▪ **Major Goal 1:** To compare lumbar spine kinematics in simulated operational conditions in Marines with measurable lumbar disc pathology
     ▪ Task 1-Approved IRB Protocols
       ▪ Local IRB Approvals
         ▪ Due: 01 August 2013
         ▪ Completed: 100%
       ▪ HRPO Approvals
         ▪ Due: 01 August 2013
         ▪ Completed: 100%
     ▪ Task 2-Subject battalions identified and coordinated
       ▪ Subjects 1-33 recruited, consented and scheduled
         ▪ Due: 01 February 2014
         ▪ Completed: 100%
       ▪ Subjects 34-66 recruited, consented and scheduled
         ▪ Due: 01 August 2014
         ▪ Completed: 81%
       ▪ Subjects 67-100 recruited, consented and scheduled
         ▪ Due: 01 Jan 2015
         ▪ Completed: 0%
     ▪ Task 3-Data Collection/Analysis
Major Goal 2: To quantify changes in lumbar spine muscle architecture in Marines with measurable lumbar disc pathology.

- **Task 1-Approved IRB Protocols**
  - Local IRB Approvals
    - Due: 01 August 2013
    - Completed: 100%
  - HRPO Approvals
    - Due: 01 August 2013
    - Completed: 100%

- **Task 2-Subject battalions identified and coordinated**
  - Subjects 1-33 recruited, consented and scheduled
    - Due: 01 February 2014
    - Completed: 100%
  - Subjects 34-66 recruited, consented and scheduled
    - Due: 01 August 2014
    - Completed: 18%
  - Subjects 67-100 recruited, consented and scheduled
    - Due: 01 Jan 2015
    - Completed: 0%

- **Task 3-Data Collection/Analysis**
  - Supine data acquisition
    - Due: 01 December 2015
    - Completed: 39%
  - Supine data analysis
    - Due: 01 February 2016
    - Completed: 39%

- **What was accomplished under these goals?**
  - 43 Marines (mean age = 26.8 ± 6.4 years, height = 1.78 ± 0.07 meters, weight = 82.04 ± 9.85 kg, BMI = 25.90 ± 2.86 kg/m²) were scanned in an upright MRI machine in their normal standing position (StU;
no load), standing with body armor (11.3 kg) (StL), sitting with body armor (SiL), and prone on elbows with body armor (PL) positions. Digital seed points were manually placed on the corners and the posterior elements of each vertebra using OsiriX. The location of the seed points were imported into Matlab and used to define an endplate-based joint coordinate system applied to the superior and inferior endplate of each vertebra. This method is detailed in Berry DB et al., “An endplate-based joint coordinate system for measuring kinematics in normal and abnormally-shaped lumbar vertebrae.” J Appl Biomech; 31(6):499-503. 2015.

Figure 1: T2-weighted mid-sagittal magnetic resonance images of the lumbar spine (top) and photographs of Marines in the MRI scanner (bottom). Volunteers were scanned standing unloaded (A, E), standing with body armor (B, F), sitting with body armor (C, G) and prone on elbows with body armor (D, H).
Figure 2: Distribution of Pfirrmann graded intervertebral discs by level. Disc degeneration increases caudally through the lumbar spine. 33/43 (77%) of Marines spines were classified as degenerated based on having a Pfirrmann grade >2 at L5-S1.
Figure 3: Global measures of lumbar spine posture. Top: angle with respect to horizontal. Middle: Sacral Slope. Bottom: Cobb angle. Statistical significant difference between measurements (p>0.05) indicated by line. Marines with disc degeneration at L5-S1 were found to have less whole lumbar range of motion, (difference between Cobb angle sitting and prone on elbows) then healthy controls (9°).
Figure 4: Local measures of lumbar spine posture. Intervertebral angles from L1-L2 (top) to L5-S1 (bottom) are shown. Statistical significant difference between measurements (p>0.05) indicated by line.
Supine 3T MRI images were acquired from 39 Marines. Psoas, Quadratus Laborum and Erector Spinae muscles, and the Intervertebral disc were manually segmented using OsiriX. Physiologic measurements were made based on segmented tissues and structural anatomic scans. Average T2 value of the intervertebral disc was proportional to Pfirrmann grade. No significant differences were found between volume, fat fraction, T2, or DTI in any of the muscles in subjects with disc degeneration. A positive correlation was found between subjects height and weight compared to muscle volume.

Figure 5. (Left) Axial anatomical image of paraspinal and trunk muscles delineated per manual segmentation, and (right) Anterior view of three-dimensional reconstruction of paraspinal and trunk muscles: ES+M (yellow), PS (green), and QL (blue).
Figure 6. Tractography of multifidus muscle from diffusion tensor imaging (A), shown in red. Erector spinae volumes are shown in blue (B).

Figure 7: Volume of the lumbar trunk muscles at each vertebral level. The volume of the erector spinae was greater at upper lumbar levels (L1-L3), and the volume of the multifidus was greatest in the lower lumbar spine (L4-S1). Psoas and quadratus lumborum volume increase caudally.
12 Marines (mean±SD age, 23.41±4.71 years; age range 19–35 years; height, 177.8±5.41 cm; weight, 76.77±11.32 kg; body mass index, 24.15±2.19 kg/m²) were scanned in an upright MRI machine standing unloaded and while carrying 22, 33 and 45kg of load distributed both 50%-50% and 20%-80% anteriorly and posteriorly (AP), respectively. Postural measurements were made as described above.

Figure 8: Fat fraction of the erector spinae and multifidus muscles at each vertebral level. The erector spinae has elevated fat fraction compared to the multifidus. Erector Spine fat fraction increases caudally while multifidus fat fraction remains the same across lumbar levels.

- 12 Marines (mean±SD age, 23.41±4.71 years; age range 19–35 years; height, 177.8±5.41 cm; weight, 76.77±11.32 kg; body mass index, 24.15±2.19 kg/m²) were scanned in an upright MRI machine standing unloaded and while carrying 22, 33 and 45kg of load distributed both 50%-50% and 20%-80% anteriorly and posteriorly (AP), respectively. Postural measurements were made as described above.

Figure 9. Photographs of the load distribution system used for this study. The black cable seen in the pictures is from the MRI coil.
Figure 10: Lumbar spine flexion results for loads carried with equal anterior-posterior distribution (clear bars) and with posterior bias (solid bars) for 22kg (clear grey), 33kg (dark grey) and 45kg (black). The dashed line represents trunk flexion when standing without external load. Solid horizontal bars represent significant differences (p<0.05) between load magnitudes and configurations. Asterisks represent significant differences when compared to the standing unloaded position. A decrease in angle with respect to the horizontal indicates a subject is leaning forward. A significant effect of load and distribution was found. When load is evenly distributed, no change in forward leaning was observed. When load is distributed 20/80 anterior/posterior, subjects will lean more forward.
Figure 11. Cobb angle was measured in each position to assess lumbar lordosis. A.) Sagittal Cobb angle is measured from the superior endplate of L1 to the superior endplate of S1. B.) Sagittal Superior Cobb angle is measured from the superior endplate of L1 to the inferior endplate of L3. C.) Sagittal Inferior Cobb angle is measured from the superior endplate of L4 to the superior endplate of S1. As load increases, the superior lumbar spine increases lordosis when load is distributed 20/80. There is a decrease in lordosis in the inferior lumbar spine when load is distributed 20/80.

- **What opportunities for training and professional development has the project provided?**
  - Nothing to report
- **How were the results disseminated to communities of interest?**
  - Nothing to report
What do you plan to do during the next reporting period to accomplish the goals?

During the next reporting period, we intend on completing data analysis for supine MRI measures and preparing manuscripts on the following topics: 1. Kinematics of the lumbar spine of active duty Marines in simulated operational positions, 2. Pathophysiology assessed by MRI of the lumbar spine muscles in active duty Marines, 3. Technical note: Diffusion Tensor Imaging in the Lumbar Spine, diffusion measurements and tractography, 4. Comparison between lumbar spine kinematics and muscle physiology in Active Duty Marines.

4. IMPACT:

What was the impact on the development of the principal discipline(s) of the project?

The results of this study may inform a set of load carriage guidelines to be put in place, through changes in training practices, gear design and/or implementation of exercises to strengthen the musculature of the spine. Additionally, the results of this study will allow researchers to better relate the complex 3D geometry of the lumbar spine in subjects with different levels of lumbar disc and degeneration and muscle health. The role of idiopathic lumbar back pain on lumbar spine kinematics will also allow us to investigate differences in the shape of the lumbar spine between a wide range of positions.

What was the impact on other disciplines?

Nothing to report

What was the impact on technology transfer?

Nothing to report

What was the impact on society beyond science and technology?

The broad impact is that the load recommendations determined from this study can be applied to anyone who works with their spine under awkward or loaded positions.

5. CHANGES/PROBLEMS:

Changes in approach and reasons for change

Nothing to report

Actual or anticipated problems or delays and actions or plans to resolve them

One adverse event has occurred: one subject experiences peripheral nerve stimulation and claustrophobia in the supine scanner (19/02/2014). He was immediately removed from the scanner and calmed down. For this subject, kinematic but not anatomical supine data was acquired.

Changes that had a significant impact on expenditures

Nothing to report

Significant changes in use or care of human subjects, vertebrate animals, biohazards, and/or select agents

Nothing to report

Significant changes in use or care of human subjects

Nothing to report
• Significant changes in use or care of vertebrate animals.
  • Nothing to report
• Significant changes in use of biohazards and/or select agents
  • Nothing to report

6. PRODUCTS:
• Publications, conference papers, and presentations
  • Journal publications.
  • Books or other non-periodical, one-time publications.
    • Nothing to report
  • Other publications, conference papers, and presentations.
  • Website(s) or other Internet site(s)
    • Nothing to report
  • Technologies or techniques
    • Nothing to report
  • Inventions, patent applications, and/or licenses
    • Nothing to report
  • Other Products
    • Nothing to report.

7. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS
• What individuals have worked on the project?
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<tr>
<th>Name:</th>
<th>David Berry</th>
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<td>Graduate Student</td>
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<td>Mr. Berry has participated in upright MRI data collection, data analysis and interpretation of results</td>
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<tr>
<td>Name:</td>
<td>Ana Rodriguez-Soto</td>
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<td>Funding Support:</td>
<td>UC MEXUS-CONACYTDoctoral Fellowship Cohort2010</td>
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<tr>
<td>Name:</td>
<td>Dr. Sara Gombatto PT, PhD</td>
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<td>Name:</td>
<td>Dr. Karen Kelly PT, PhD</td>
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<td>Dr. Kelly has assisted with subject recruitment, subject scheduling, subject consent, and interpretation of results</td>
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Funding Support:

1. **Award #new award** 03/01/2015-09/30/2016 2.4 calendar
   Office of Navy Research
   Program Evaluation of SEAL Delivery Vehicles Unit Level Training
   The primary aim of this project is to describe the physiological, physical, cognitive and sleep changes that occur during unit level training in a specialized military operational specialty.

2. **Award #N1421** 10/01/2014-09/30/2015 2.4 calendar
   Army Special Operation Command
   Validating Gender-Neutral Standards for Army Special Forces (SFAS) and Ranger (RASP) Selection
   The primary aims of this project are (1) To determine whether the selection criteria for entry into SFAS/RASP training are accurate predictors of success during SFAS/RASP training; and (2) To establish task-dependent selection and training criteria, which could then be viewed as “gender neutral,” thus meeting the directive of the Secretary of Defense.
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| N1336   | 09/01/2013 | 06/30/2015 | 9.0 calendar | Naval Special Warfare-WARCOM  
265,000.00  
Validating Gender-Neutral Standards for SEAL and SWCC Selection  
The primary aims of this project are (1) To determine whether the selection criteria for entry into SEAL/SWCC training are accurate predictors of success during SEAL/SWCC training; and (2) To establish task-dependent selection and training criteria, which could then be viewed as "gender neutral," thus meeting the directive of the Secretary of Defense. |
| N1324   | 03/01/2013 | 09/30/2016 | 0.6 calendar | Office of Navy Research  
Independent Evaluation of the ETOWL software program  
The Office of Navy Research funded Iowa University to develop a virtual Marine that will predict the effect of load on physiological and biomechanical parameters. This project aims to independently test the developed software using “live” active duty military personnel to determine the accuracy of the software program. |
| N1310   | 03/01/2013 | 09/30/2016 | 2.4 calendar | Program Manager-Infantry Combat Equipment  
Personal Protection Equipment Development  
The purpose of this project is to test a prototype of a novel plate carrier system against the existing plate carrier system in a variety of different load conditions as well as in various environments. |
| N1305   | 02/01/2012 | 09/30/2015 | 1.0 calendar | Congressionally Directed Medical Research Programs  
Lumbar Spine Musculoskeletal Physiology and Biomechanics During Simulated Military Operations  
The purpose of this project is to determine if lumbar disc and muscle degeneration alters the kinematics response of the lumbar spine to functional positions and loads, predisposing individuals to injury. |
| N1301   | 10/01/2012 | 09/30/2015 | 0.6 calendar |  

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<td>Naval Special Warfare - Group 1</td>
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<td>Androgen Deficiency in Navy SEALS</td>
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<td>The purpose of this project is to identify risk factors associated with hormonal imbalance in our elite forces. The study address caloric intake, expenditure, sleep hygiene, alcohol consumption as well as lifestyle choices that may influence hormone production in Navy SEALS.</td>
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<td>Space and Naval Warfare Systems Command</td>
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<td>Warrior Development</td>
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<td>The purpose of this project is to identify risk factors associated with decrements in performance and to evaluate means by which to improve the Special Warfighter.</td>
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<td>Space and Naval Warfare Systems Command</td>
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<td>Bureau of Medicine and Surgery</td>
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<td>Prescriptive Exercise Therapy Program to Reduce Hyper-arousal in Residential Treatment for Active Duty Service Members Diagnosed with Post-Traumatic Stress Disorder</td>
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<td>To improve the quality of exercise/physical training the service members are receiving while at OASIS, as well as to develop a new exercise program and assist in training the staff at OASIS to maintain the quality of physical training after the project is complete. It is hypothesized that with better exercise and physical training there will be improvements in symptoms of PTSD, better compliance with exercise, increased mood and thus functionality of the persons obtaining treatment at OASIS.</td>
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R01 HD073180-01A1 (PI: Ward)  04/01/2013 – 03/31/2018  
NIH/NICHD  
**The Physiological Basis of Rotator Cuff Muscle Rehabilitation**  
The goal of this project is to elucidate the structural, mechanical, and physiological consequences of tendinopathy-related muscle atrophy and degeneration after rotator cuff tears in humans. Architectural, passive mechanical, and gene expression profiles will be measured and compared amongst patients with different rotator cuff tear severities.

DoD (PRMRP/CDMRP)  
**Lumbar Spine Musculoskeletal Physiology and Biomechanics During Simulated Military Operations**  
The goals of this project are to; 1) understand lumbar spine and lumbar disc kinematics during simulated operational conditions, 2) understand the effect of load and body position on spine and disc kinematics when pathology is present, and 3) understand the influence of muscle structure and physiology on lumbar spine kinematics.

NIH/NICHD  
**Microsensor for Intramuscular Pressure Measurement**  
The purpose of this grant is to develop a miniature pressure transducer to measure tissue fluid pressure in skeletal muscle and then to determine the effects of muscle architecture, fascia, limb orientation and type of activation on pressure. The study employs the rabbit tibialis anterior muscle model and consists primarily of in situ muscle physiological experimentation combined
with continuum mechanics modeling.

A6239R (PI: Lieber, CO-I: Ward) 10/01/2012-09/30/2016
Veterans Medical Research Foundation

**Mechanical Basis for Tensioning Tendon Transfers**
The purpose of this proposal is to measure the *in vivo* properties of muscles commonly used in tendon transfer surgery. We propose to develop a new instrument for measuring sarcomere lengths intraoperatively and to assess post-operative function in these patients.

1P30AR061303 (PI: Lieber, Core-Director: Ward) 09/01/2011-08/31/2016
NIH (NIAMS)

**San Diego Skeletal Muscle Research Center**
The purpose of this Center is to establish a consortium of skeletal muscle scientists between UC San Diego, Sanford-Burham, the Scripps Research Institute, and San Diego State University. The Center provides education, pilot funding, and direct scientific support.

NIH/NIAMS

**Rotator Cuff Degeneration and Repair.**
The purpose of this study is to measure the passive mechanical and related protein changes in rat skeletal muscle after rotator cuff tears.

NIH/NICHD

**“National Center for Muscle Rehabilitation Research.”**
The purpose of this grant is to provide a resource to the rehabilitation professionals to perform state-of-the-art muscle experiments. Disciplines include physiology, microscopic imaging, MR imaging and clinical measurements. In addition, the Center provides sabbatical opportunities and pilot project support to rehabilitation professionals interested in skeletal muscle research.

5 R01 AR057393 (Co-PI: Lieber, Ward) 7/01/2010 – 6/30/2015
NIH/NIAMS

“Muscle Biological and Biomechanical Response in Cerebral Palsy.”
The purpose of this proposal is to understand the changes that occur in muscles after contracture formation and to test conservative treatment options. This is due to the large number of children with CP seen in the rehabilitation setting and the number who undergo surgical correction for contracture (making their muscle tissue available).

R01 AR057013-01A1 (PI: Ward, Samuel) 07/01/2009 – 06/30/2014

NIH/NIMAS

Muscle Structure, Toxin Dose, and Exercise Affect Botulinum Toxin Efficiency.
The purpose of this grant is to understand the acute and chronic effects of botulinum toxin type A on skeletal muscle structure and function. Experiments include muscle physiology, histology, cellular biology, MRI and bioluminescence measurements.

- Has there been a change in the active other support of the PD/PI(s) or senior/key personnel since the last reporting period?
  - Nothing to report
- What other organizations were involved as partners?
  - **Organization Name:** San Diego State University
  - **Location of Organization:** San Diego, CA
  - **Partner's contribution to the project**
    - **Collaboration:** Sara Gombatto PT, PhD. Provided assistance during data collection and data interpretation

8. **SPECIAL REPORTING REQUIREMENTS**
- **COLLABORATIVE AWARDS:** None
- **QUAD CHARTS:** See attached FY1516_QuadChart_W81XWH-13-2-0043

9. **APPENDICES:**
- Quad Chart: FY1516_QuadChart_W18XWH-13-2-0043.pptx
**Study/Product Aim(s)**
- To compare lumbar spine kinematics in simulated operational conditions in Marines with measurable disc pathology
- To quantify changes in lumbar spine muscle architecture in Marines with measurable lumbar disc pathology

**Approach**
Each Marine undergoes high-resolution structural and physiological imaging of the lumbar vertebrae and discs in a high strength (3T) supine MRI. Marines then undergo a 3D imaging protocol in an upright, low strength (0.6T) MRI in standing unloaded, standing loaded (25lb body armor), sitting loaded and prone on elbows positions. To investigate the effect of load magnitude and distribution, some Marines were scanned in standing unloaded and standing loaded conditions (6 conditions: 22kg, 33kg, 45kg x 50/50, 20/80 anterior/posterior). Back pain history is recorded for each subject at time of data collection.

**Goals/Milestones**

**CY13 Goal** – Initiate subject recruitment/scanning
- Begin acquiring data on minimum 8 subjects

**CY14 Goals** – Develop measurement tools
- Validate tool for measuring kinematics
- Diffusion Tensor Calculations
- Scan >40 subjects

**CY15 Goal** – Data Analysis
- Scan remaining subjects
- Analyze data from 80% of the subjects

**CY16 Goal** – Disseminate findings
- Correlate kinematic physiologic data
- Disseminate Findings

**Comments/Challenges/Issues/Concerns**
Nothing to Report

**Budget Expenditure to Date**
Projected Expenditure: $719,948 total cost (fully expend the award through the NCE period)
Actual Expenditure: $565,656.76 total cost