Enhanced Technologies for Optimization of Warfighter Load (ETOWL)

- Background
- SANTOS-ETOWL
- Method: Predictive Dynamics
- SANTOS-ETOWL Software Demonstration

By: The Virtual Soldier Research
The University of Iowa
Why Human Simulation

Engineering Analysis

- Stress tests
- Vibration
- Sound
- Dynamics analysis (motion)
- Aerodynamics
- Thermal analysis
- Fluid analysis

Physical prototypes

Human Systems Integration
Human Performance
✓ Biomechanics
✓ Physiological modeling
✓ Strength & Fatigue
✓ Artificial intelligence
✓ Predicts behavior
✓ Physics-based
ETOWL

A human Simulator

Conduct trade off analysis

Assess Marine performance

Evaluate gear prior to procurement
SANTOS-ETOWL

Warrior Configuration
Access the ETOWL Equipment Library and configure a custom warrior for volumetric analysis or testing in the Simulation Builder.

Simulation Builder
Choosing from multiple scenarios and warrior configurations, build a simulation to run through predictive dynamics and view the resulting motion.

Extended Load Carriage
Simulate extended tasks on a warrior configuration and view the energy requirements.

Gear Import
Import new equipment model files, and assign the necessary properties for export into the Warrior Configuration Equipment Library.

Double click an application mode to launch.

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**GruntSim** male Marines

*Santos, 220 Male, 508 Male, 530 Male, 601 Male, 1719 Male, 1953 Male, 2033 Male, 2459 Male.*

- Anthropometry
- Weight
- Body type
- Strength

<table>
<thead>
<tr>
<th>Avatars</th>
<th>Height</th>
<th>Weight</th>
<th>Strength Percentile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Santos</td>
<td>6 ft. 1 in</td>
<td>173.72 lbs.</td>
<td>90 %</td>
</tr>
<tr>
<td>220 Male</td>
<td>5 ft. 7 in</td>
<td>160.94 lbs.</td>
<td>80 %</td>
</tr>
<tr>
<td>508 Male</td>
<td>5 ft. 7 in</td>
<td>143.52 lbs.</td>
<td>75%</td>
</tr>
<tr>
<td>530 Male</td>
<td>6 ft. 3 in</td>
<td>244.93 lbs.</td>
<td>90%</td>
</tr>
<tr>
<td>601 Male</td>
<td>6 ft. 2 in</td>
<td>155.43 lbs.</td>
<td>80%</td>
</tr>
<tr>
<td>1719 Male</td>
<td>5 ft. 11 in</td>
<td>177.91 lbs.</td>
<td>85%</td>
</tr>
<tr>
<td>1953 Male</td>
<td>5 ft. 7 in</td>
<td>195.11 lbs.</td>
<td>80%</td>
</tr>
<tr>
<td>2033 Male</td>
<td>6 ft. 3 in</td>
<td>217.82 lbs.</td>
<td>90%</td>
</tr>
<tr>
<td>2459 Male</td>
<td>5 ft. 4 in</td>
<td>122.14 lbs.</td>
<td>75%</td>
</tr>
</tbody>
</table>
## Female Avatar Statistics

<table>
<thead>
<tr>
<th>Avatars</th>
<th>Height</th>
<th>Weight</th>
<th>Strength Percentile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sophia</td>
<td>5 ft. 6 in</td>
<td>133.00 lbs.</td>
<td>80%</td>
</tr>
<tr>
<td>0752 Female</td>
<td>5 ft. 10 in</td>
<td>139.33 lbs.</td>
<td>80%</td>
</tr>
<tr>
<td>1806 Female</td>
<td>5 ft. 9 in</td>
<td>164.91 lbs.</td>
<td>85%</td>
</tr>
<tr>
<td>2096 Female</td>
<td>5 ft. 3 in</td>
<td>121.92 lbs.</td>
<td>75%</td>
</tr>
<tr>
<td>2316 Female</td>
<td>5 ft. 7 in</td>
<td>156.75 lbs.</td>
<td>90%</td>
</tr>
<tr>
<td>2324 Female</td>
<td>5 ft. 6 in</td>
<td>158.29 lbs.</td>
<td>90%</td>
</tr>
<tr>
<td>2531 Female</td>
<td>5 ft. 0 in</td>
<td>129.19 lbs.</td>
<td>85%</td>
</tr>
<tr>
<td>2563 Female</td>
<td>5 ft. 3 in</td>
<td>119.93 lbs.</td>
<td>75%</td>
</tr>
</tbody>
</table>
ETOWL ... is a platform
ETOWL consists of four modules:

- Warrior Configuration
- Simulation Builder
- Gear Import
- Extended Load Carriage
Predicting Human Motion
Objective: Minimize function

Find: Joint angles

Constraints: Joint range of motion

In 2004...
In 2004/2005

https://youtu.be/Zwj6evMMQ0Q
Motion Prediction

Formulation

Find: control points for B-spline curves

To optimize:

Human performance measure(s)

Subject to:

1) Follow path
2) Stay within ROM
3) Avoid collisions
In 2005/2006

https://youtu.be/JkXNVwzq-8Q
**Objective:**
Execute a task

**Find:** Joint angles, Torques

**Constraints:**
- Range of motion
- Distance to target
- Strength constraints
- Laws of Motion
Laws of Motion

\[ \mathbf{\tau} = \mathbf{M}(q) \mathbf{\ddot{q}} + \nabla(q, q) + \sum_{i} \mathbf{J}^T_i \mathbf{m}_i g + \sum_{k} \mathbf{J}^T_k \mathbf{F}_k + \mathbf{K}\left(\mathbf{q} - \mathbf{q}^N\right) \]

\[ J_1(q, \mathbf{\tau}, t) = \int_{t=0}^{T} \mathbf{\tau} \cdot \mathbf{\tau} \, dt \]

s.t.:\n\[ s^r \mathbf{\tau}_h \rightarrow \int (s^g q_h, s^g \mathbf{q}_h, s^g \mathbf{\dot{q}}_h, s^r \mathbf{t}_h) = 0 \]
\[ g(\mathbf{\Gamma}_h) \leq 0 \]
\[ s^g \mathbf{q}^L \leq s^g \mathbf{q}_h \leq s^g \mathbf{q}^U \]
\[ s^r \mathbf{\tau}^L \leq s^r \mathbf{\tau}_h \leq s^r \mathbf{\tau}^U \]
Statics versus Dynamics

\[ \tau = M(q) \ddot{q} + V(q, \dot{q}) + \sum_{i} J_i^T m_i g \cdot \sum_{i} J_i m_i g \cdot \sum_{k} J_k^T F_k + K(q - q^N) \]

- \( M(q) \) is the mass and inertia matrix
- \( V(q, \dot{q}) \) is the Coriolis and Centrifugal term
- \( \sum_{i} J_i m_i g \cdot \sum_{i} J_i \) are the gravity forces
- \( \sum_{k} J_k^T F_k \) are the external forces
- \( K(q - q^N) \) is the muscle elasticity term
Statics versus Dynamics

\[ \mathbf{\tau} = \mathbf{M}(q) \mathbf{\ddot{q}} + \mathbf{V}(q, \mathbf{\dot{q}}) + \sum_{i} \mathbf{J}_i^T \mathbf{m}_i \mathbf{g} + \sum_{k} \mathbf{J}_k^T \mathbf{F}_k + \mathbf{K}(q - q^N) \]

- Mass & inertia matrix
- Coriolis & Centrifugal
- Gravity forces
- External forces
- Muscle elasticity
Understand the task

Obtain expert advice

Obtain Motion Capture

Formulate tracking

Obtain energy and physiology data

Predictive Dynamics
Understand contact points

Define contact duration

Amend formulation with constraints

Determine cost functions

Derive gradients for optimization

Formulation
**Experiments & Validation**

- Draft experimental protocol
- Get **IRB** approval
- Recruit subjects
- Perform experiments

**PD Simulation**

Refine formulation based on validation feedback

**Cause & Effect**

Add dynamic constraints
Add cognition/learning
Refine and check robustness

**Validation**

Determinants of motion

**IRB**
Experimental Studies Conducted under ETOWL
Dynamic Strength Experiments
Male knee flexion with 40lb loaded walking simulation
gait with 40 lb backpack
crane joint
50% strength
**Extended Load Carriage**

### Input

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Male</strong></td>
<td>Average Marine</td>
</tr>
<tr>
<td><strong>Weight</strong></td>
<td>75Kg</td>
</tr>
<tr>
<td><strong>Distance</strong></td>
<td>15km</td>
</tr>
<tr>
<td><strong>Time</strong></td>
<td>3 hours 45 mins</td>
</tr>
<tr>
<td><strong>Speed</strong></td>
<td>1.11 m/sec</td>
</tr>
<tr>
<td><strong>External Load</strong></td>
<td>50-60 lbs (22.62 - 27.14 Kg)</td>
</tr>
<tr>
<td><strong>Terrain factor</strong></td>
<td>Paved road</td>
</tr>
<tr>
<td><strong>Slope</strong></td>
<td>flat</td>
</tr>
</tbody>
</table>

### Output

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fatigue levels</strong></td>
<td>3.11 L/min or 78% of max</td>
</tr>
<tr>
<td><strong>Energy expenditure</strong></td>
<td>319.58 Watts or 274 kcal/hour</td>
</tr>
</tbody>
</table>

### Assumptions

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Weather</strong></td>
<td>Iowa City conditions 31C (87F), 79% humidity,</td>
</tr>
<tr>
<td><strong>Marine weight</strong></td>
<td>75 Kg</td>
</tr>
<tr>
<td><strong>Strength and fitness</strong></td>
<td>Average, fatigue effects ignored</td>
</tr>
<tr>
<td><strong>Clothing</strong></td>
<td>long sleeves and jacket and long underwear</td>
</tr>
</tbody>
</table>

### Case 2: 15km in 3 hours 45 mins
Task Validation
ETOWL Software demonstration
GruntSim – Equipment and Models

- Import equipment
- Large selection of gear
- Accurate models
- Attachment to body

- Configure the load
- Pick and place
GruntSim – Warrior Configuration

https://youtu.be/iHJipX83Gml

- Intuitive
- Drag-and-drop
- Weight and Volume Analysis
- Range-of-motion Analysis
- Stability Analysis
- Cocoon Analysis
Equipment Simulation – Static Load Analysis

Example: Jammer Pack 3D Model

- Posture analysis
- Soldier’s load and combat readiness

Example: Changing CG

Vertical Reaction forces (N), 40.8 kg backpack

- Before
- After
GruntSim – Warrior Configuration

Configure the Warfighter and perform weight, volume, and “cocoon” analysis
Training and analysis

- Asymmetric loading
- How to carry loads
- How to perform a task
- Effects of Biomechanics
- Cause & Effect
- Effect of C.G.
- Learn to avoid possible errors

https://youtu.be/DlccUCOkKek

https://youtu.be/qpl7uhxMz7I

https://youtu.be/EAgqJNwbAUJ
Demo GruntSim ™ Program
Transitioned to the Marine Expeditionary Rifle Squad (MERS)
Warrior Configuration
Asymmetric Heavy Load
Cause and effect

No Backpack

90 Kg (198 lb) Backpack

100 Kg (220 lb) Backpack
Injury Prediction:

- Physics-based human motion prediction (predictive dynamics) for simulating tasks and injury prediction

- Joint limits
- Ground penetration
- Foot strike position
- Dynamic stability (ZMP)
- No slip
- Symmetry condition
- Equations of motion
- Etc.

Contact Surfaces  B.C. & Loading

99128 Elements, C3D4 Tetrahedral
<table>
<thead>
<tr>
<th>Height (m)</th>
<th>Santos</th>
<th>Man3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.498672</td>
<td>2.180130</td>
</tr>
<tr>
<td></td>
<td>2.401210</td>
<td>2.174497</td>
</tr>
<tr>
<td></td>
<td>2.310071</td>
<td>2.119108</td>
</tr>
<tr>
<td></td>
<td>2.131725</td>
<td>2.015748</td>
</tr>
<tr>
<td></td>
<td>1.990143</td>
<td>1.946092</td>
</tr>
</tbody>
</table>

Santos 79 kg

Man3 111 kg
<table>
<thead>
<tr>
<th>Height (m)</th>
<th>Woman1</th>
<th>Sophia</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.383437</td>
<td>2.511551</td>
<td>2.283680</td>
</tr>
<tr>
<td>2.298920</td>
<td>2.426401</td>
<td>2.191515</td>
</tr>
<tr>
<td>2.089685</td>
<td>2.025596</td>
<td>2.025596</td>
</tr>
<tr>
<td>1.932893</td>
<td>1.896856</td>
<td>1.896856</td>
</tr>
</tbody>
</table>

Woman1: 51 kg
Sophia: 60 kg
“ETOWL (GruntSim) fits perfectly within ONR’s mission to develop groundbreaking technologies that enhance the resilience, physical superiority and overall warfighting performance of U.S. Marines,”

Brig. Gen. Kevin Killea
Vice Chief of Naval Research
“The benefits of ETOWL are numerous, said. For example, the Marine Corps can use data from the virtual tests to quickly design real-world prototypes for testing by live Marines.”

“It’s very exciting to see ETOWL transition from ONR prototype to a technology that will enhance human load and performance for the Marine Corps, this is the kind of research that’s very rewarding because it provides a direct benefit to our nation’s warfighters.”

Dr. Peter Squire  
ONR Program Manager  
Expeditionary Maneuver Warfare and Combating Terrorism department
Women in Combat
The Future

✓ Automated task development
✓ Expanded libraries of models and tasks
✓ Increased intelligence and learning
✓ Training aid
✓ Injury prediction and avoidance
Thank you!

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