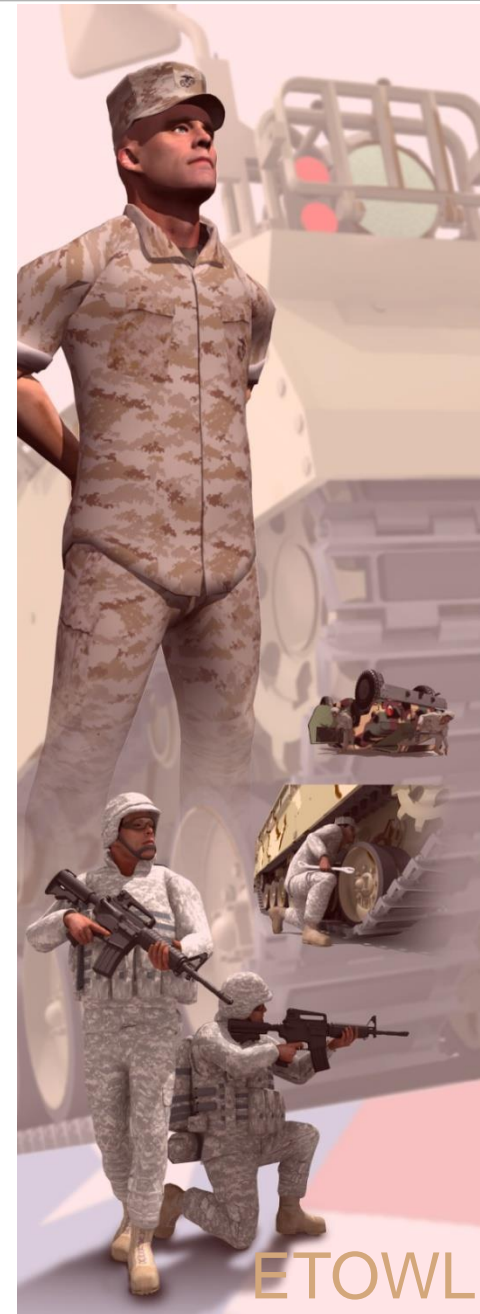
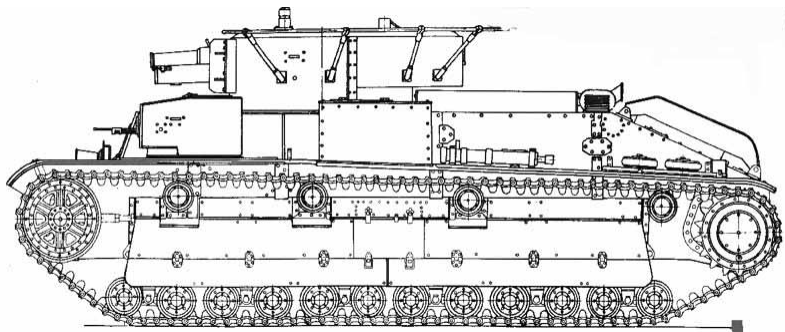


# ***Enhanced Technologies for Optimization of Warfighter Load (ETOWL)***

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



# Why Human Simulation



Physical  
prototypes



## Engineering Analysis

Stress tests

Vibration

Sound

Dynamics analysis (motion)

Aerodynamics

Thermal analysis

Fluid analysis

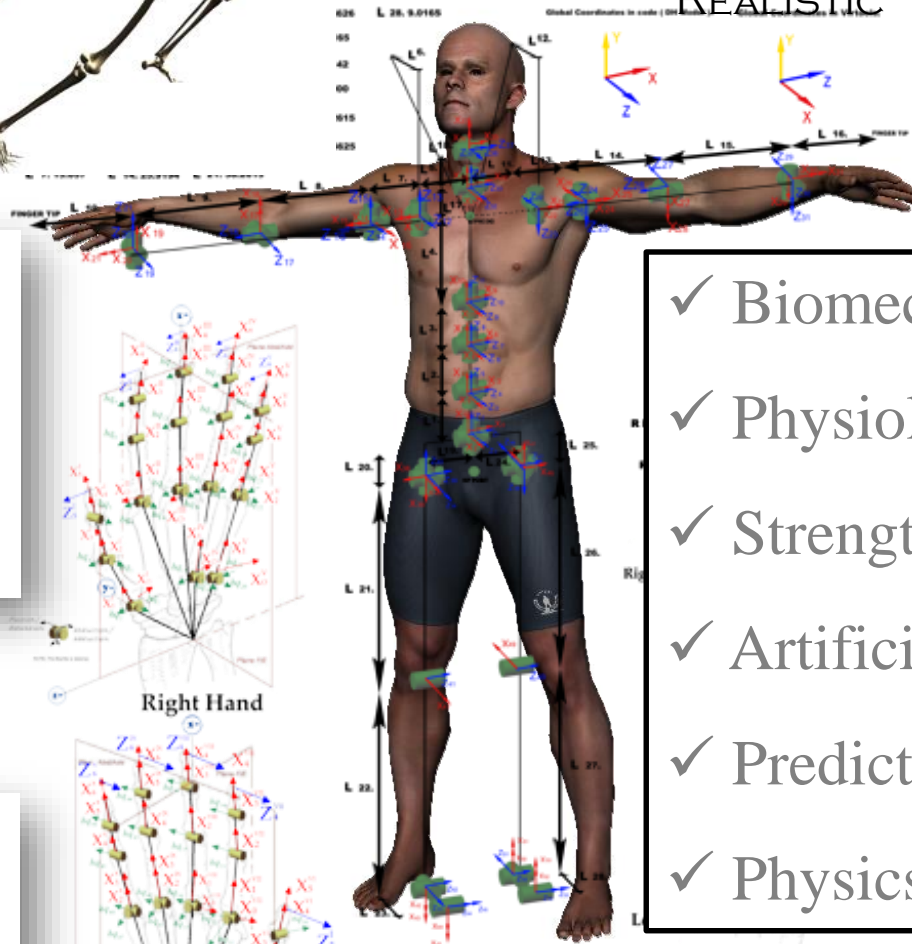


Human Systems Integration  
Human Performance

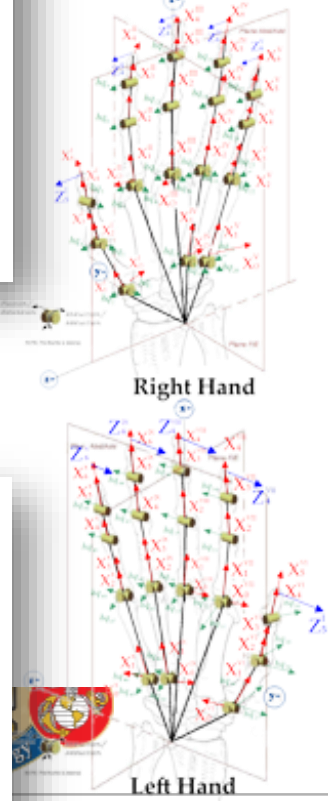




REALISTIC



- ✓ Biomechanics
- ✓ Physiological modeling
- ✓ Strength & Fatigue
- ✓ Artificial intelligence
- ✓ Predicts behavior
- ✓ Physics-based



Default link lengths: HANDS (mm)

L. 1. 2.36	L. 1. 2.36	L. 17. 2.14
L. 2. 5.02	L. 2. 5.02	L. 18. 2.164011
L. 3. 3.92	L. 3. 3.92	L. 19. 6.115989
L. 4. 3.16	L. 4. 3.16	L. 20. 4.12
L. 5. 9.26	L. 5. 9.26	L. 21. 2.34
L. 6. 9.3	L. 6. 9.3	L. 22. 1.86
L. 7. 2.86	L. 7. 2.86	
L. 8. 1.84	L. 8. 1.84	



# 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

## Male Avatar Statistics

Avatars	Height	Weight	Strength Percentile
Santos	6 ft. 1 in	173.72 lbs.	90 %
220 Male	5 ft. 7 in	160.94 lbs.	80 %
508 Male	5 ft. 7 in	143.52 lbs.	75%
530 Male	6 ft. 3 in	244.93 lbs.	90%
601 Male	6 ft. 2 in	155.43 lbs.	80%
1719 Male	5 ft. 11 in	177.91 lbs.	85%
1953 Male	5 ft. 7 in	195.11 lbs.	80%
2033 Male	6 ft. 3 in	217.82 lbs.	90%
2459 Male	5 ft. 4 in	122.14 lbs.	75%

# GruntSim female Marines



*Sophia, 0752 Female, 1806 Female, 2096 Female, 2316 Female, 2324 Female, 2531 Female, 2563 Female.*

## Female Avatar Statistics

Avatars	Height	Weight	Strength Percentile
Sophia	5 ft. 6 in	133.00 lbs.	80%
0752 Female	5 ft. 10 in	139.33 lbs.	80%
1806 Female	5 ft. 9 in	164.91 lbs.	85%
2096 Female	5 ft. 3 in	121.92 lbs.	75%
2316 Female	5 ft. 7 in	156.75 lbs.	90%
2324 Female	5 ft. 6 in	158.29 lbs.	90%
2531 Female	5 ft. 0 in	129.19 lbs.	85%
2563 Female	5 ft. 3 in	119.93 lbs.	75%



ETOWL ... is a platform

**ETOWL**

---

**SANTOS**

---

Warrior Configuration



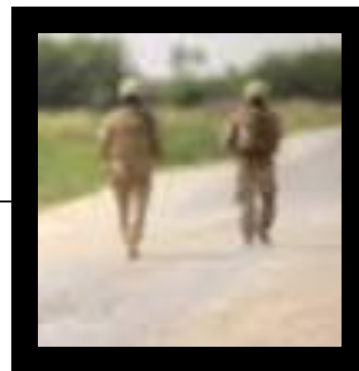
Simulation Builder



Gear Import



Extended Load Carriage



---

# Predicting Human Motion



***In 2004...***

**Objective:**

Minimize function

**Find:**

Joint angles

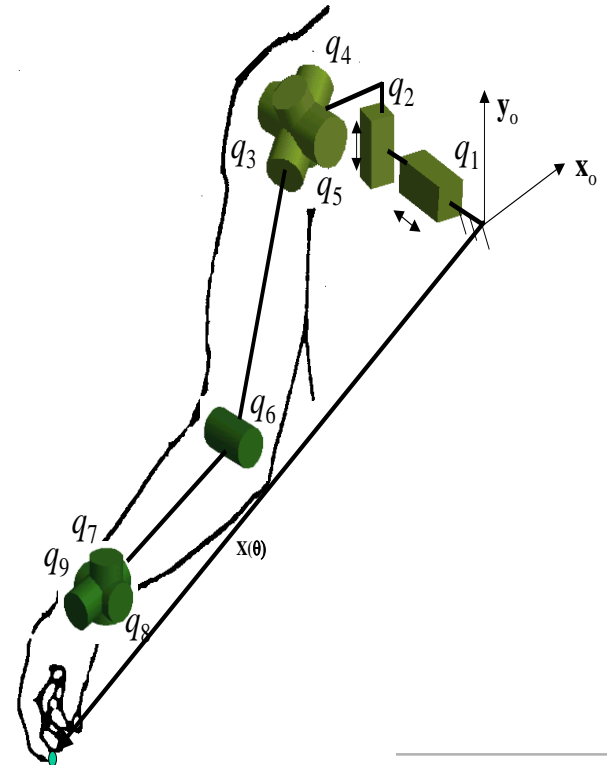
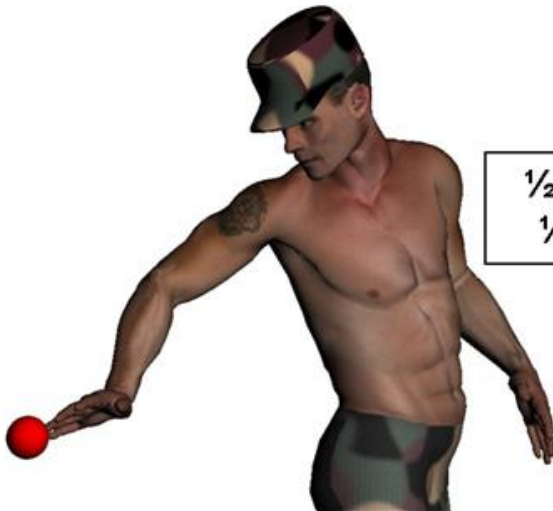
**Constraints:**

Joint range of motion

Joint Displacement only

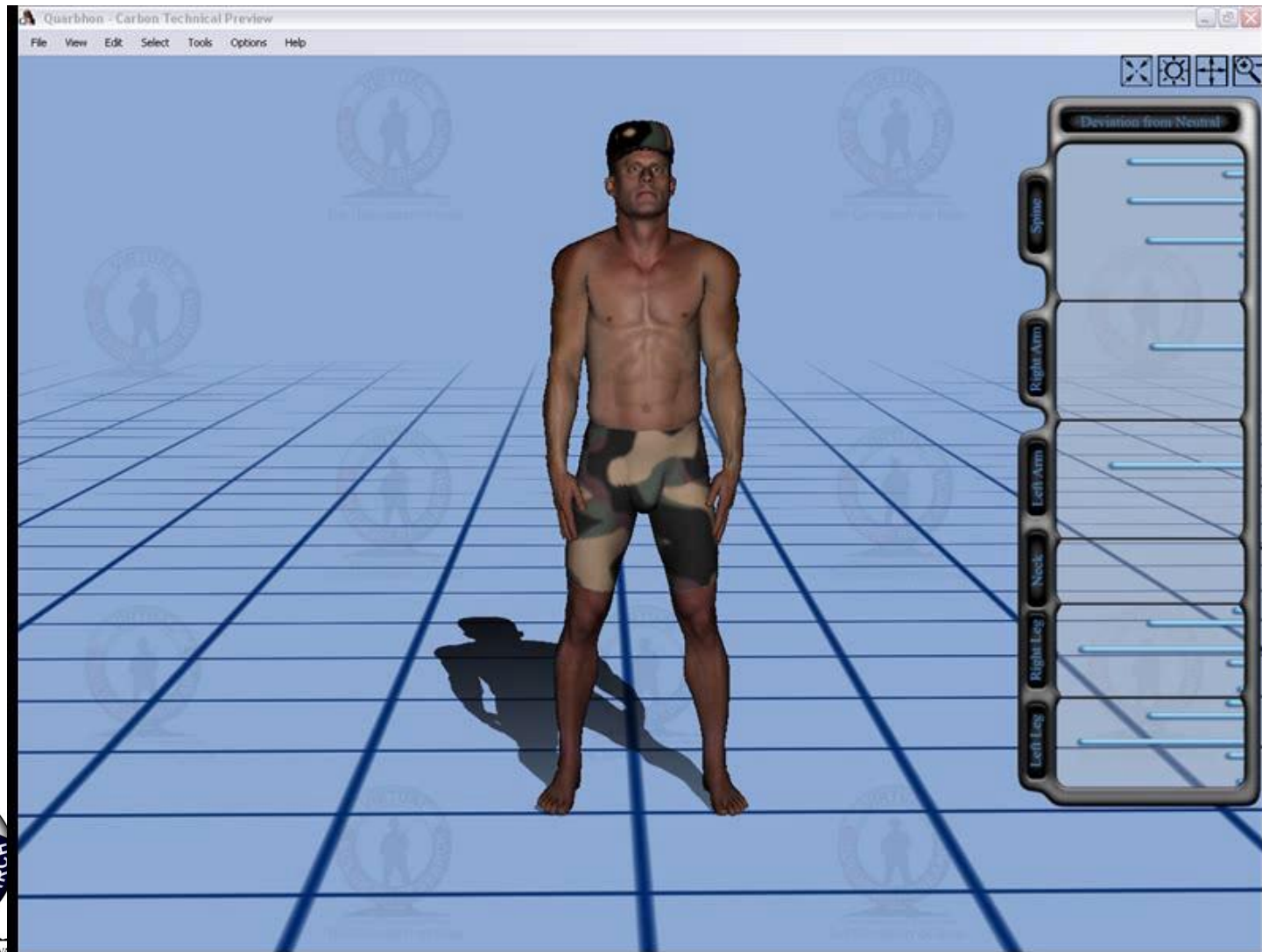


½ Visual Displacement  
½ Joint Displacement

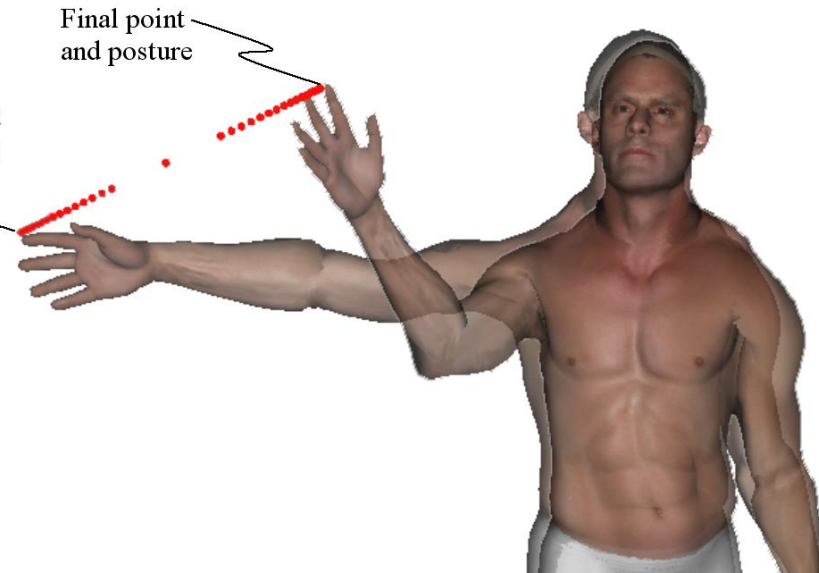


**In 2004/2005**

<https://youtu.be/Zwj6evMMQ0Q>

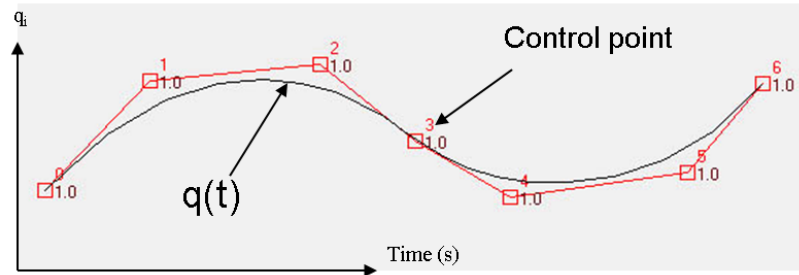


# Motion Prediction



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>



# Predictive Dynamics

- Physics based

- Predictive: cause and effect

## Objective:

Execute a task

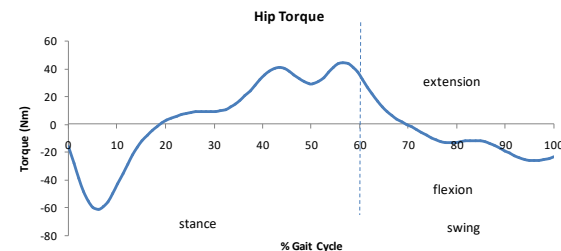
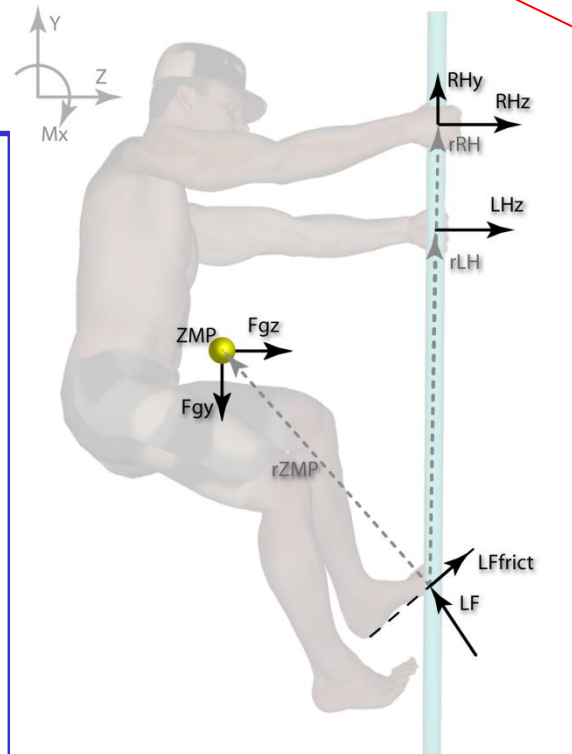
Find: Joint angles, **Torques**

## Constraints:

- Range of motion
- Distance to target
- Strength constraints
- 

- **Laws of Motion**

Significant Development  
Predictive Dynamics



## Laws of Motion

$$\boldsymbol{\tau} = \underbrace{\mathbf{M}(\mathbf{q})}_{\substack{\text{mass \& inertia} \\ \text{matrix}}} \ddot{\mathbf{q}} + \underbrace{\mathbf{V}(\mathbf{q}, \dot{\mathbf{q}})}_{\substack{\text{Coriolis \&} \\ \text{Centrifugal}}} + \underbrace{\sum_i \mathbf{J}_i^T m_i \mathbf{g}}_{\substack{\text{gravity-forces}}} + \underbrace{\sum_k \mathbf{J}_k^T \mathbf{F}_k}_{\substack{\text{external-forces}}} + \underbrace{\mathbf{K}(\mathbf{q} - \mathbf{q}^N)}_{\substack{\text{muscle-elasticity}}}$$

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

$$\begin{aligned} \text{st. : } & s^r \boldsymbol{\tau}_h - f(s^q \mathbf{q}_h, s^q \dot{\mathbf{q}}_h, s^q \ddot{\mathbf{q}}_h, s^t \mathbf{t}_h) = 0 \\ & \mathbf{g}(\Upsilon_h) \leq 0 \\ & s^q \mathbf{q}^L \leq s^q \mathbf{q}_h \leq s^q \mathbf{q}^U \\ & s^r \boldsymbol{\tau}^L \leq s^r \boldsymbol{\tau}_h \leq s^r \boldsymbol{\tau}^U \end{aligned}$$



# Statics versus Dynamics



$$\boldsymbol{\tau} = \underbrace{\mathbf{M}(\mathbf{q})}_{\text{mass \& inertia matrix}} \ddot{\mathbf{q}} + \underbrace{\mathbf{V}(\mathbf{q}, \dot{\mathbf{q}})}_{\text{Coriolis \& Centrifugal}} + \underbrace{\sum_i \mathbf{J}_i^T m_i \mathbf{g}}_{\text{gravity-forces}} + \underbrace{\sum_k \mathbf{J}_k^T \mathbf{F}_k}_{\text{external-forces}} + \underbrace{\mathbf{K}(\mathbf{q} - \mathbf{q}^N)}_{\text{muscle-elasticity}}$$

# Statics versus Dynamics



$$\boldsymbol{\tau} = \underbrace{\mathbf{M}(\mathbf{q})}_{\text{mass \& inertia matrix}} \ddot{\mathbf{q}} + \underbrace{\mathbf{V}(\mathbf{q}, \dot{\mathbf{q}})}_{\text{Coriolis \& Centrifugal}} + \underbrace{\sum_i \mathbf{J}_i^T m_i \mathbf{g}}_{\text{gravity-forces}} + \underbrace{\sum_k \mathbf{J}_k^T \mathbf{F}_k}_{\text{external-forces}} + \underbrace{\mathbf{K}(\mathbf{q} - \mathbf{q}^N)}_{\text{muscle-elasticity}}$$



# Predictive Dynamics



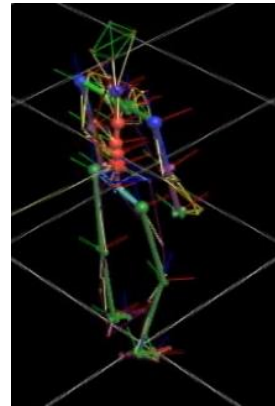
Understand  
the task



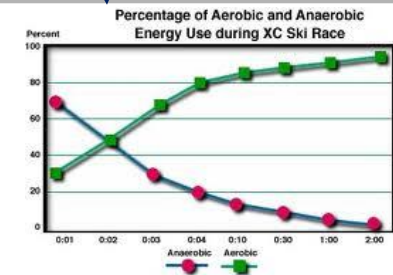
Obtain  
expert  
advice



Obtain  
Motion  
Capture



Formulate  
tracking

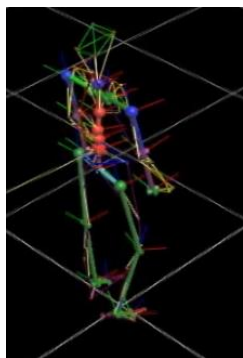


Obtain  
energy and  
physiology data

# Formulation



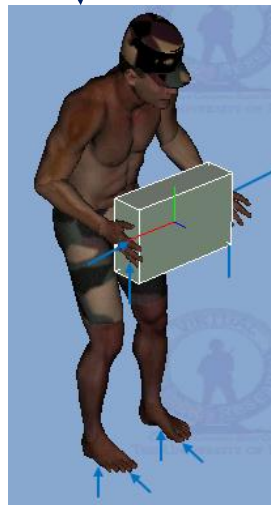
Understand contact points



Define contact duration



Amend formulation with constraints



Determine cost functions



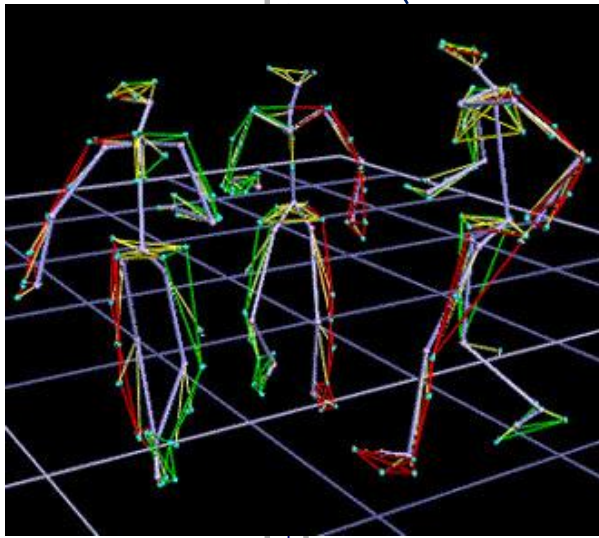
Derive gradients for optimization



# Experiments & Validation



IRB



Validation

Determinants  
of motion

PD Simulation

Refine  
formulation  
based on  
validation  
feedback

Cause &  
Effect

Add dynamic constraints  
Add cognition/learning  
Refine and check robustness

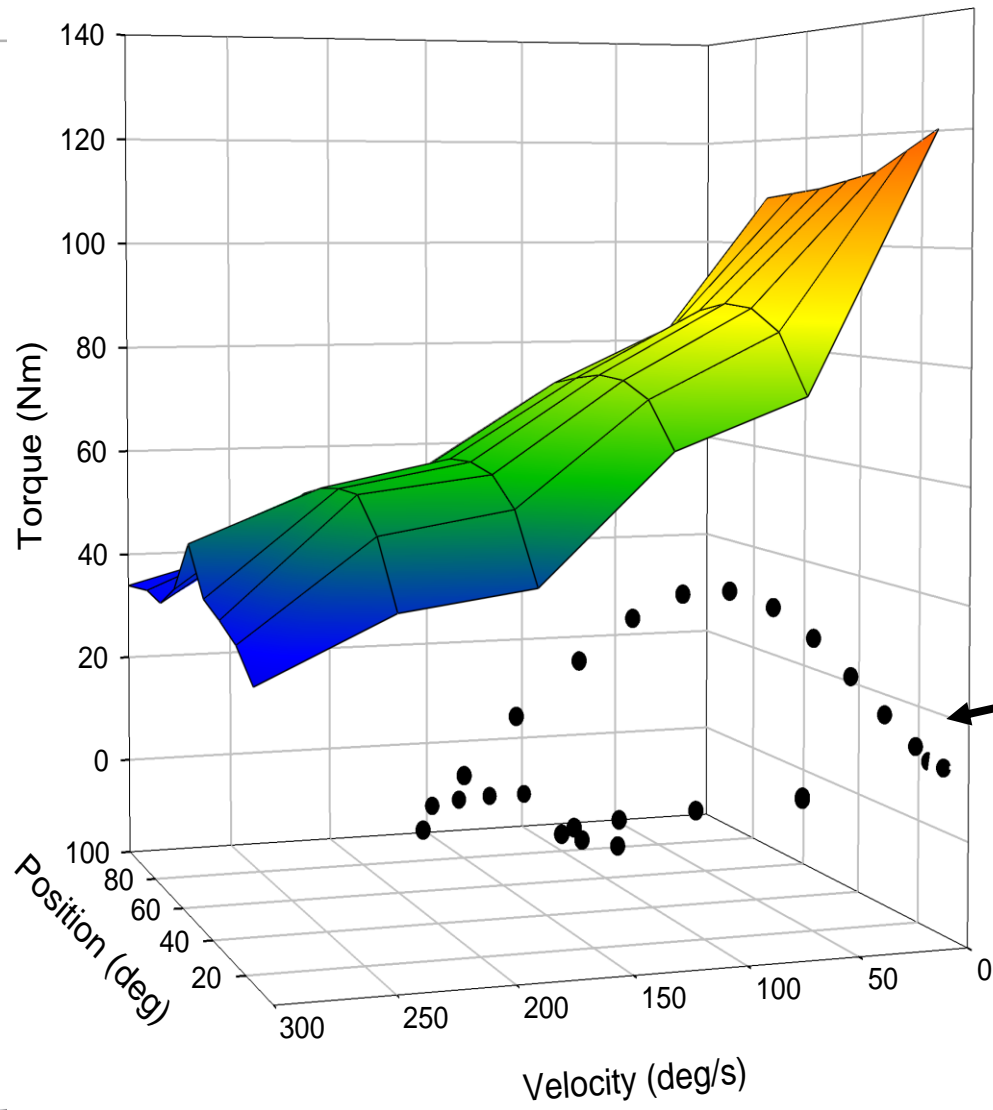
- Draft experimental protocol
- Get **IRB** approval
- Recruit subjects
- Perform experiments

# Experimental Studies Conducted under ETOWL



# Dynamic Strength Experiments





gait with 40 lb backpack  
 knee joint  
 50% strength



# Extended Load Carriage

## CASE 2: 15KM IN 3 HOURS 45 MINS

### Input

Male

- Average Marine

Weight

- 75Kg

Distance

- 15km

Time

- 3 hours 45 mins

Speed

- 1.11 m/sec

External Load

- 50-60 lbs (22.62- 27.14 Kg)

Terrain factor

- Paved road

Slope

- flat

### Output

Fatigue levels

- 3.11 L/min or 78% of max

Energy expenditure

- 319.58 Watts or 274 kcal/hour

### Assumptions

Weather

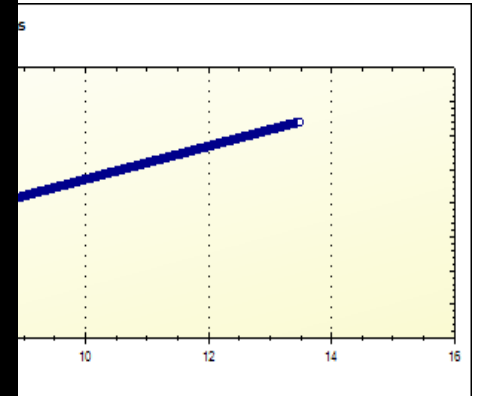
- Iowa City conditions 31C (87F), 79% humidity,

Marine weight

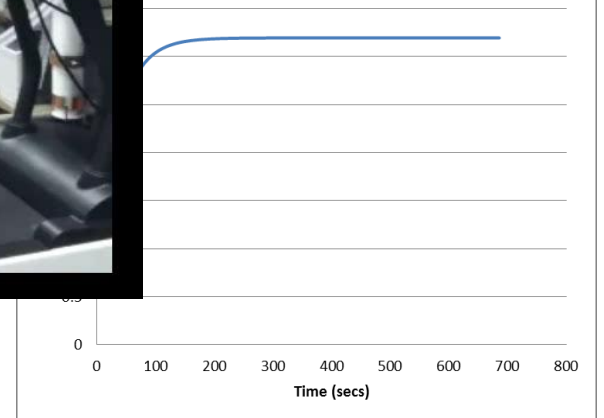
- 75 Kg

Strength and fitness

- Average, fatigue effects ignored

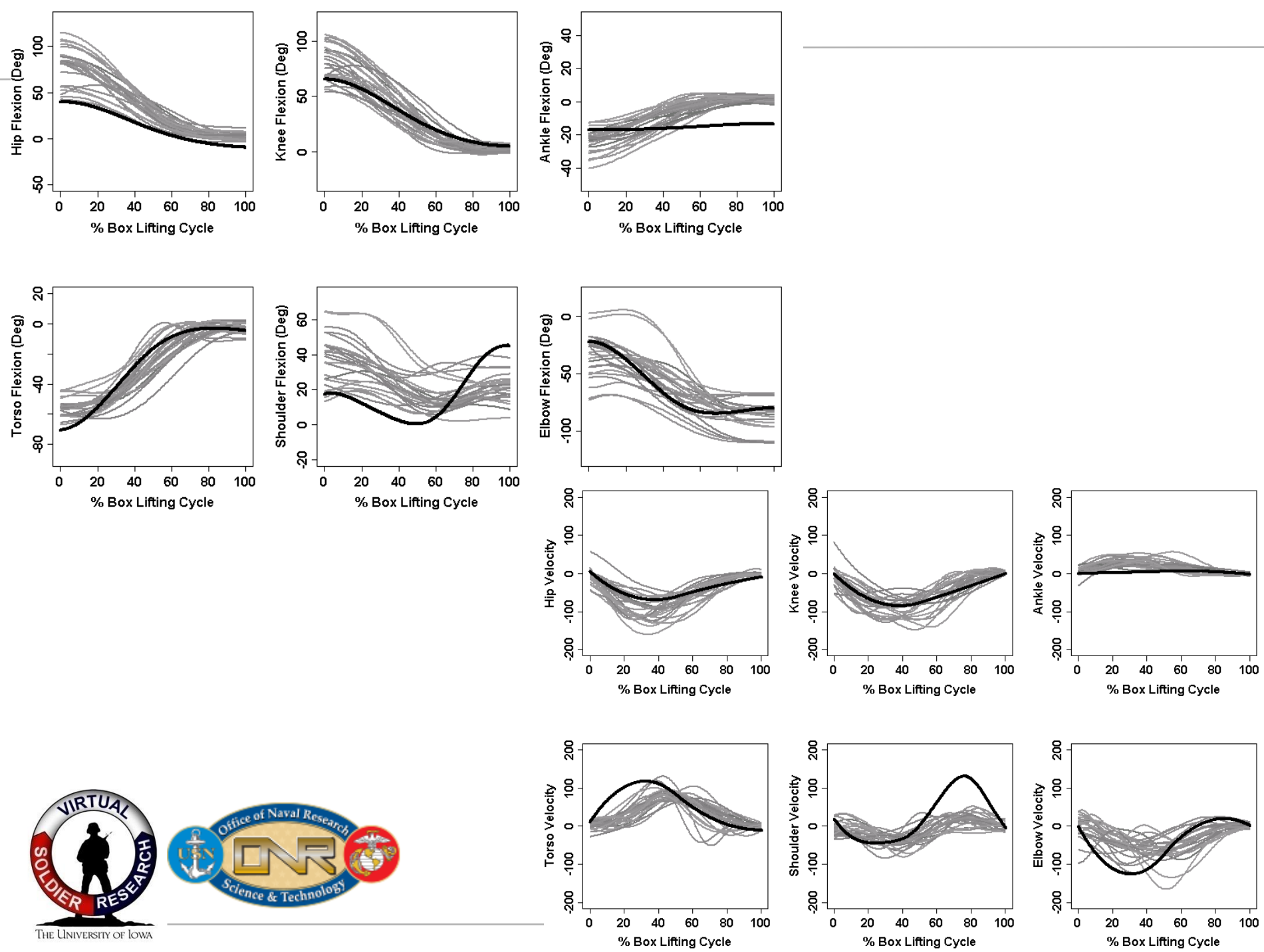


VO2 Vs Time



# 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

View and edit center of gravity

Equipment Editor

Model Information

Model Properties

Size: M

Weight: 25

Center of Gravity:

X: -0.018

Y: -0.1

Z: 0.002

Inertia:

XX: 0.603 XY: -0.047

YY: 0 YZ: 0.123

ZZ: 0.002 XZ: 0.682

Model Collision

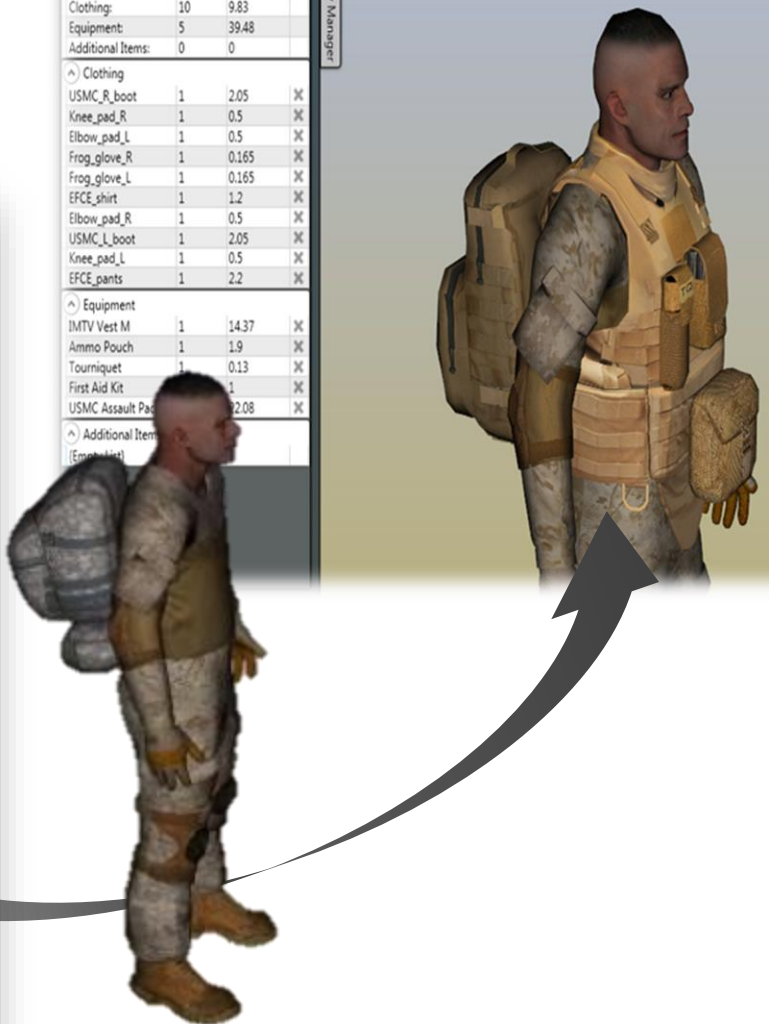
Visibility

Center of Gravity  Collision Spheres

Object Axis

None Add Root Add Branch Move Marker Rotate Marker Translate Marker

Name	Quantity	Weight
Total By Group		
Clothing:	10	9.83
Equipment:	5	39.48
Additional Items:	0	0
Clothing		
USMC_R_boot	1	2.05
Knee_pad_R	1	0.5
Elbow_pad_L	1	0.5
Frog_glove_R	1	0.165
Frog_glove_L	1	0.165
EFCE_shirt	1	1.2
Elbow_pad_R	1	0.5
USMC_L_boot	1	2.05
Knee_pad_L	1	0.5
EFCE_pants	1	2.2
Equipment		
IMTV Vest M	1	14.37
Ammo Pouch	1	1.9
Tourniquet	1	0.13
First Aid Kit	1	1
USMC Assault Pack	1	2.08
Additional Items		
(Empty Slot)		



# GruntSim – Warrior Configuration

<https://youtu.be/iHJipX83Gml>

- ✓ Intuitive
- ✓ Drag-and-drop
- ✓ Weight and Volume Analysis
- ✓ Range-of-motion Analysis
- ✓ Stability Analysis
- ✓ Cocoon Analysis



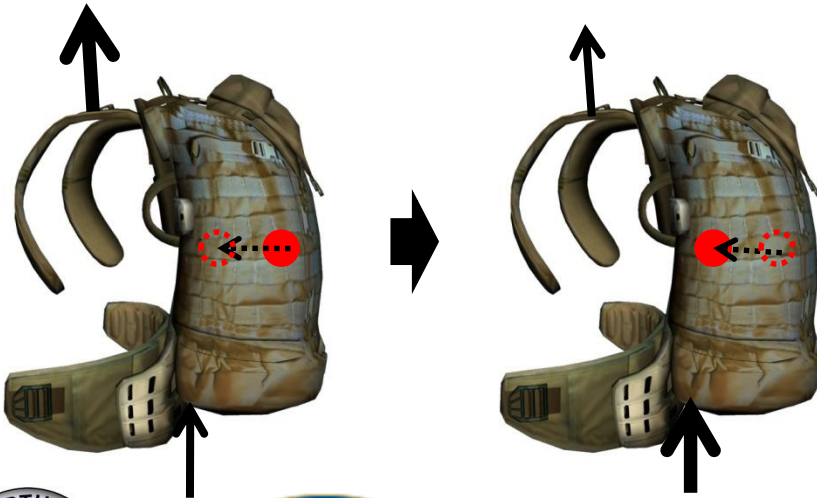
# Equipment Simulation – Static Load Analysis

Example: Jammer Pack 3D Model

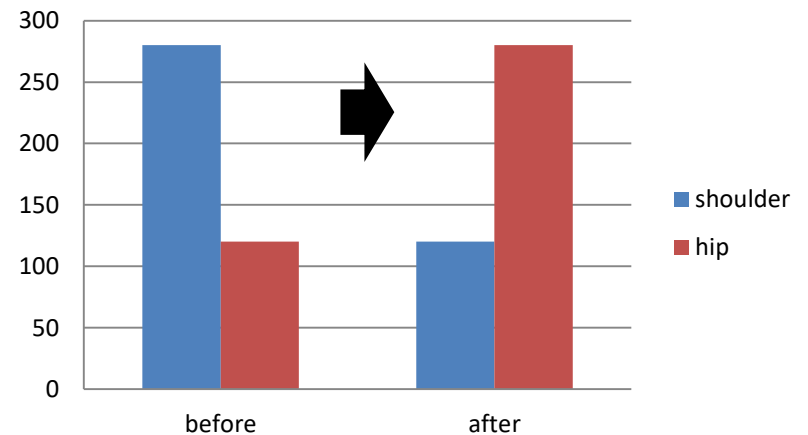
- Posture analysis
- Soldier's load and combat readiness



Example: Changing CG



Vertical Reaction forces(N), 40.8 kg backpack



# GruntSim – Warrior Configuration

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

**Total Equipment Weight: 57.38 Pounds**

Name	Quantity	Weight
<b>Total By Group</b>		
Clothing:	10	9.83
Equipment:	4	47.55
Additional Items:	0	0
<b>Clothing</b>		
USMC_R_boot	1	2.05
Elbow_pad_L	1	0.5
Elbow_pad_R	1	0.5
Frog_glove_R	1	0.165
EFCE_shirt	1	1.2
Frog_glove_L	1	0.165
Knee_pad_L	1	0.5
USMC_L_boot	1	2.05
Knee_pad_R	1	0.5
EFCE_pants	1	2.2
<b>Equipment</b>		
IMTV Vest L	1	14.37
ECH Helmet M	1	3.6
USMC Assault Pack	1	22.08
M16A4	1	7.5
<b>Additional Items</b>		
(Empty List)		

**Output**

- Generate Report
- Export OBJ
- Warrior Specs
- Cocoon
- Bounding Box
- Avatar Visibility

**Inventory Manager**

- Generate Report
- Export OBJ
- Warrior Specs
- Cocoon
- Bounding Box
- Avatar Visibility



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# Warrior Performance – Dynamic Task Analysis

<https://youtu.be/DlccUCOkKek>



## Training and analysis

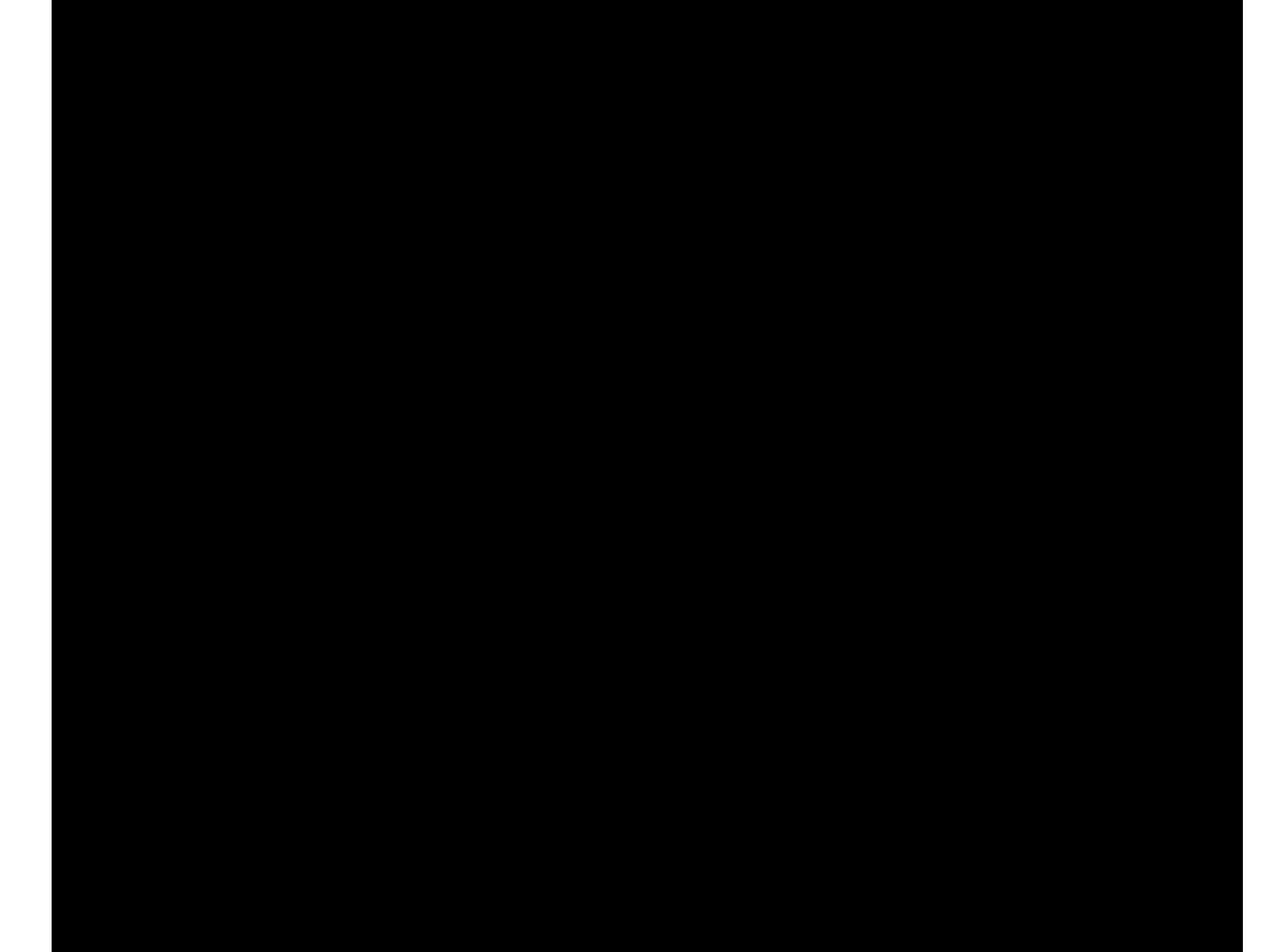
- Asymmetric loading
- How to carry loads
- How to perform a task
- Effects of Biomechanics
- Cause & Effect
- Effect of C.G.
- Learn to avoid possible errors

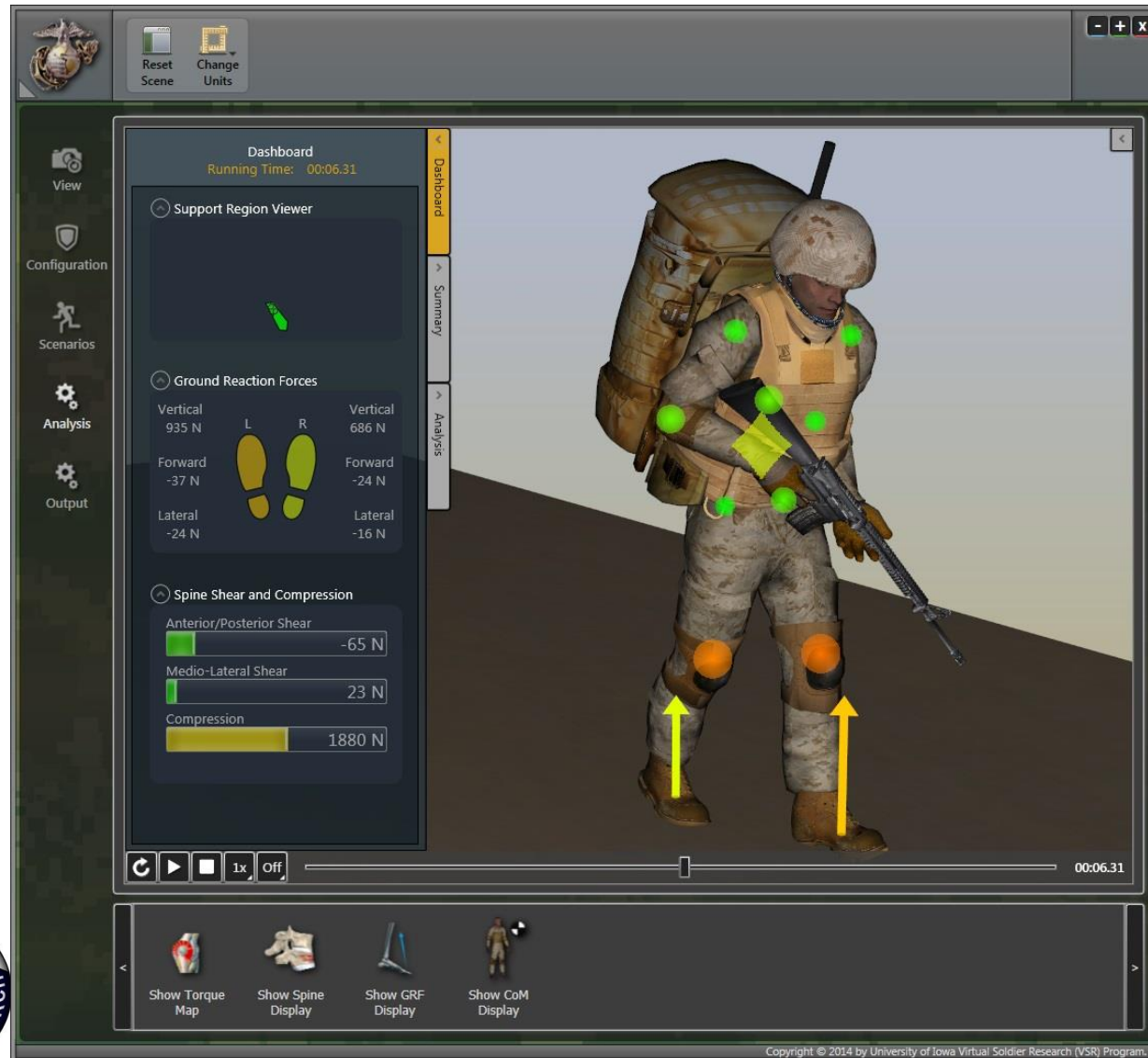
<https://youtu.be/qpl7uhxMz7I>



<https://youtu.be/EAqoJNwbAUI>







Transitioned to the Marine Expeditionary Rifle Squad (MERS)

# Warrior Configuration



# Asymmetric Heavy Load



# Simulation Builder

The interface features a top toolbar with a Marine Corps emblem, 'Reset Scene', 'Change Units', and 'Help' buttons. A left sidebar contains 'View', 'Avatars', 'Configuration', 'Scenarios', and 'Output' options. The main 3D view shows a soldier with a backpack and rifle on a set of stairs with a handrail and a ladder. A playback control bar at the bottom of the 3D view includes a play button, a '1x' speed indicator, and a progress bar showing '00:00.00'. A tooltip for the speed indicator reads 'Click and hold (right) click for more options'. Below the 3D view is a task bar with icons for 'Stair Ascend', 'Stair Descend', 'Stair Ascend Steep', 'Stair Descend Steep', 'Vertical Jump', and 'Ladder Climb'.



# Cause and effect

No  
Backpack



90 Kg (198 lb)  
Backpack



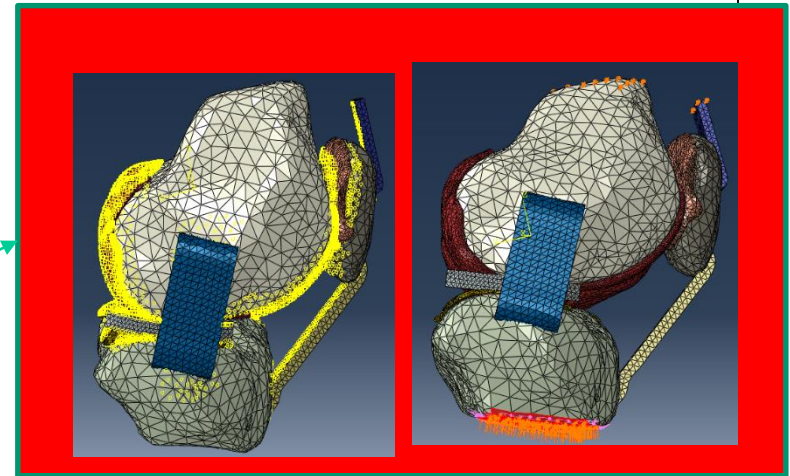
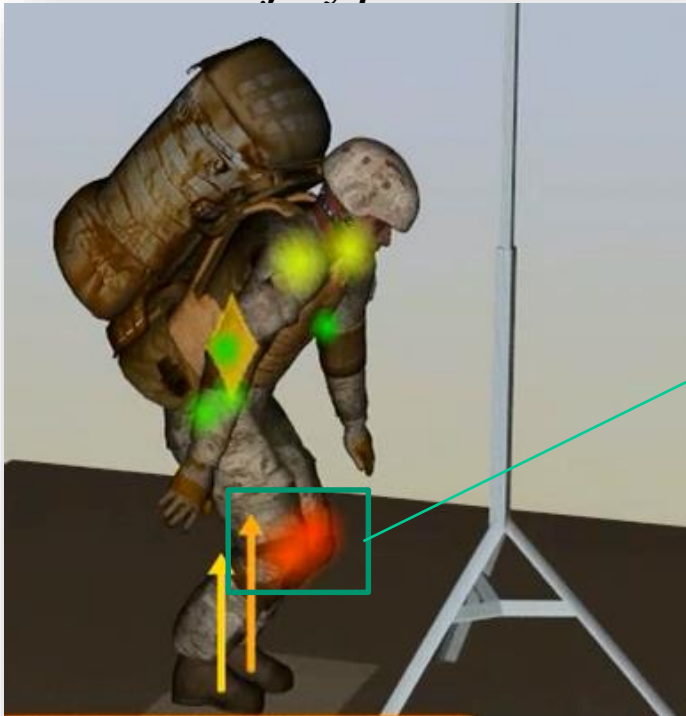
100 Kg (220 lb)  
Backpack



# Injury Prediction

## Injury Prediction:

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



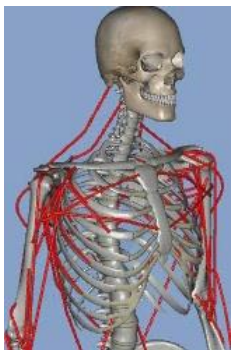
Contact Surfaces    B.C. & Loading

Joint limits  
 Ground penetration  
 Foot strike position  
 Dynamic stability (ZMP)  
 No slip

Symmetry condition  
 Equations of motion  
 Etc.

99128 Elements,  
 C3D4 Tetrahedral

# History of Santos



2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015

Robotics  
Optimization  
Biomechanics  
Interactive  
Real time  
High fidelity  
CAD import

Posture prediction  
Ergonomics

Vision

Realism  
Anthropometry  
Physics based

Hand & grasping

Strength & fatigue  
Task simulation

Physiology  
Thermal, hydration, energy

**Human Predictive dynamics**  
Human performance

Clothing/armor

Armor

PPE-Blast

Psychological

Real-time

Musculoskeletal Injur

Validation      Validation      Validation      Validation      Validation

Height (m)

2.498672

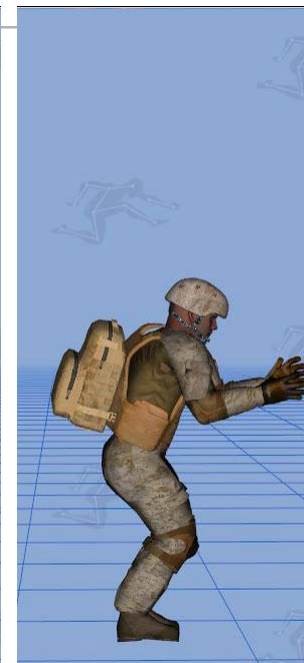
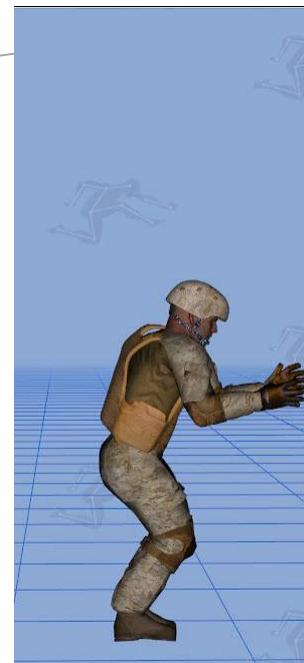
2.401209

2.310071

2.131725

1.990143

Santos  
79 kg



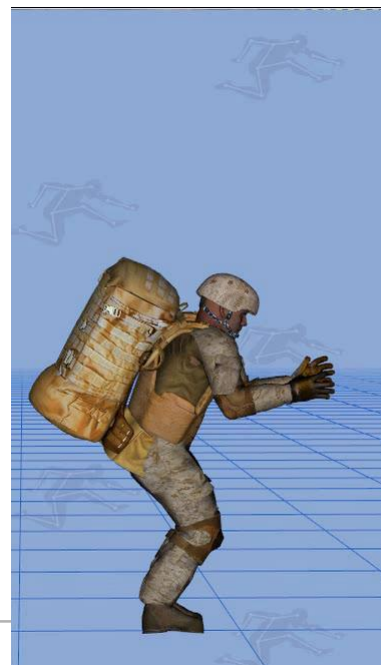
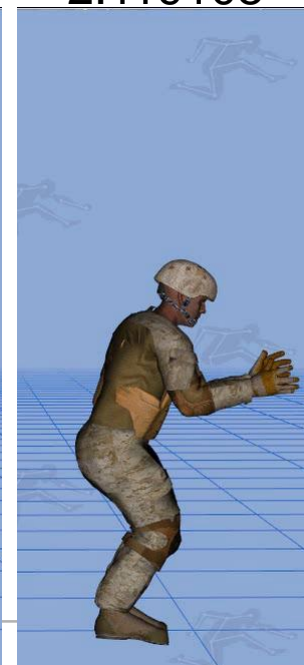
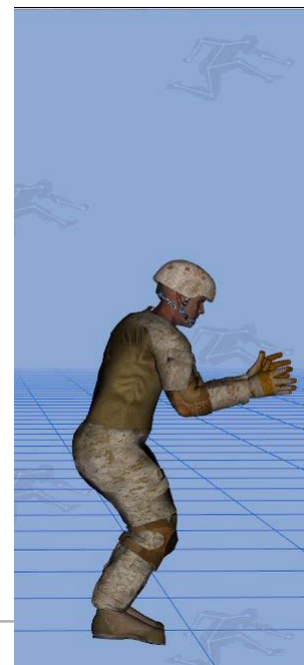
2.180130

2.174497

2.119108

2.015748

1.946092



Man3  
111 kg



Height (m)

2.383437

2.283680

2.191515

2.025596

1.896856

Sophia  
60 kg



2.511551

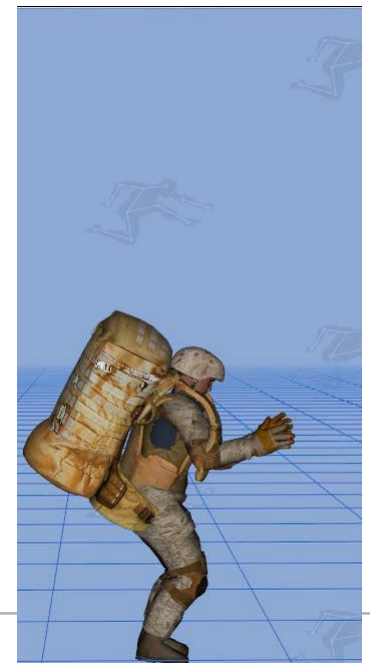
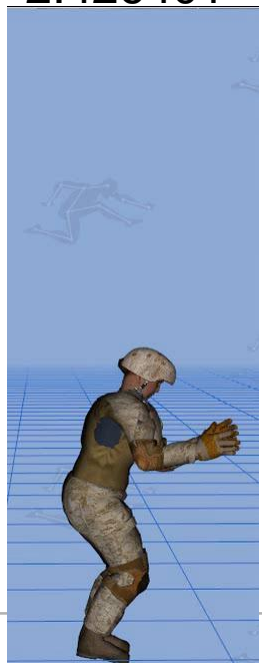
2.426401

2.298920

2.089685

1.932893

Woman1  
51 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 UNIVERSITY OF IOWA



“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





**MARINES**  
**THE FEW. THE PROUD.®**

## Women in Combat



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



# Thank you!



Contact:  
Karim Abdel-Malek, PhD  
Professor and Director  
Virtual Soldier research  
University of Iowa  
[amalek@engineering.uiowa.edu](mailto:amalek@engineering.uiowa.edu)



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