DEVELOPMENT OF A MUSCULOSKELETAL HUMAN-SPACESUIT INTERACTION MODEL

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Introduction

Extravehicular Activity (EVA) is an important component of human spaceflight, and maintaining health and comfort inside the spacesuit is critical. The Extravehicular Mobility Unit (or EMU) is the current US spacesuit, and is pressurized to 29.6 KPa. Working in a gas-pressurized space suit results in numerous challenges, causing fatigue, unnecessary energy expenditure, and injury. These problems are exacerbated with the additional hours astronauts spend training inside the suit, especially underwater in the Neutral Buoyancy Laboratory (NBL). Although space suit performance and improved system designs have been investigated, injuries persist (Newman 1997, Williams 2003, Strauss 2004, Scheuring 2009).

Objective

To gain a better understanding of EVA injury mechanisms, in particular strain injuries caused by the EMU.

- Statistically evaluate muscle injury data as related to space suit components and astronaut anthropometry
- Develop a musculoskeletal human-spacesuit interaction model
- Determine the effects of the spacesuit on muscle activity
- Relate muscle activity to injury susceptibility

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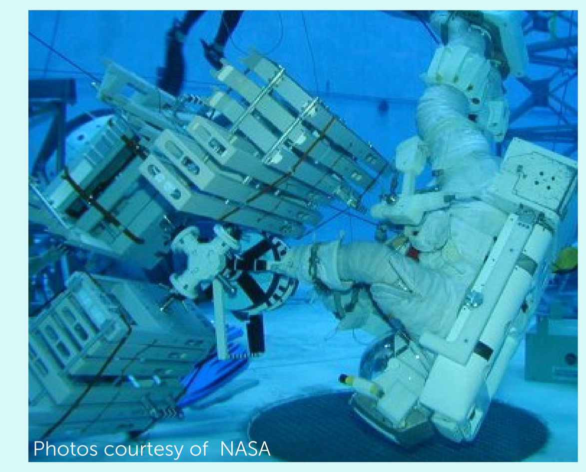
EVA injuries

EVA injuries can be divided in two different catergories:

Contact injuries: Occur at the surface of the body. Caused by hard impacts with the spacesuit or inverted positions during training. Results in contusions, abrasions, and discomfort.

Strain injuries: Occur within the body's tissues. Caused by use of heavy tools, restricted shoulder mobility, and repeated gripping. Results in repeated movements at high muscle forces, strains, overuse injuries.



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Previous work

Previous work related to the understanding of EVA injuries is categorized under Data Analysis, Experimental, and Simulation.

Data analysis
Training injuries (Williams D. and Johnson B. 2003; Strauss 2004; Scheuring 2012)
In-flight injuries (Scheuring 2009)
Hand injuries (Hochstein 2008; Opperman 2010)
Spacesuit trauma countermeasure system (Anderson 2012; Diaz 2012)

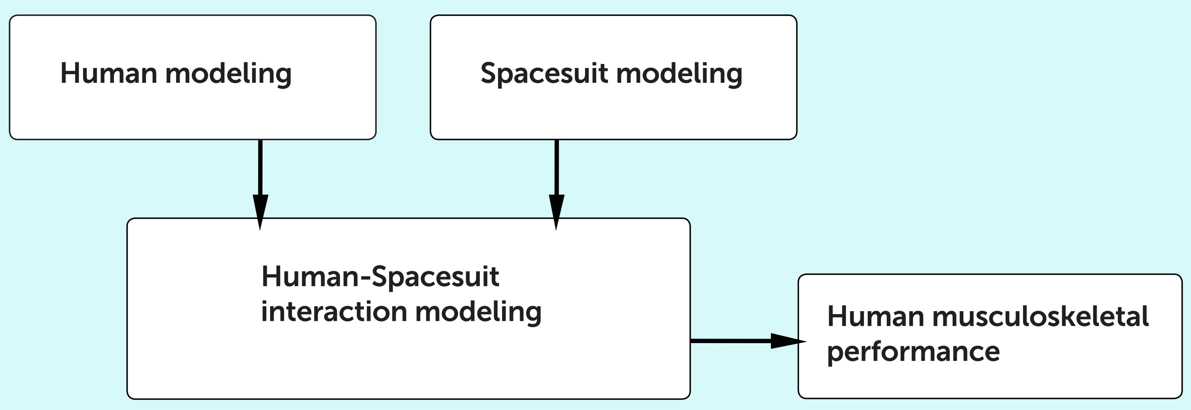
Experimentation
Hand injuries: skin blood flow and contact pressure (Ansari 2009, Opperman 2009)
Upper extremity: use of an extended ventilation tube (Jones 2008)

Simulation
Shoulder range of motion (Opperman 2009)
Musculoskeletal performance: **Musculoskeletal human-spacesuit interaction model (A. Diaz)**

The research effort presented herein focuses on musculoskeletal performance and falls under 'simulation'. We are developing a human-spacesuit interaction model and focused on how this interaction affects human musculoskeletal performance.

Musculoskeletal Human-Spacesuit Interaction Model

Our approach develops a new musculoskeletal modeling framework to specifically analyze body-suit interaction and musculoskeletal performance during EVA. We combine a human model with a space suit joint torque model to determine the effects on human musculoskeletal performance measures. As a case study, muscle forces generated during knee flexion/extension are analyzed in "suited "and "unsuited" conditions.



Human Model

The human-spacesuit interaction model is being developed utilizing OpenSim, an open-source musculoskeletal platform (Delp 2007). Capabilities include: physics-based calculations (dynamics) including realistic muscle modeling using a GUI interface (Thelen 2003, Thelen 2006). Many researchers are now taking advantage of this open source code, resulting in enhanced capabilities that are continually updated and improved.

Human model: "Gait 2354 computer model" (Delp 1990)
–Height: 1.8 m; weight: 75 kg
–Fairly accurate lower body
–Three dimensional, 23 degrees-of-freedom, 54 musculotendon actuators

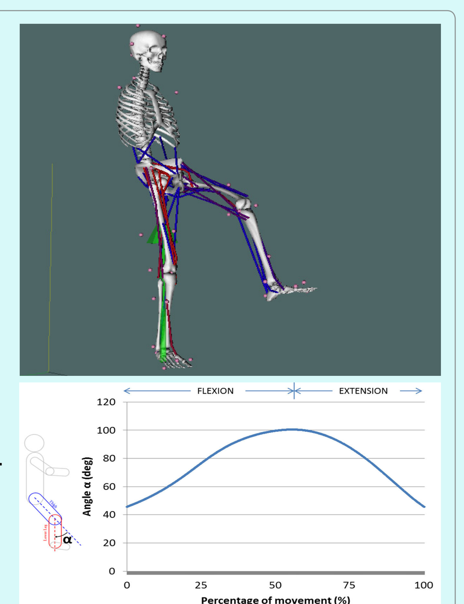


Figure 1: OpenSim human model "Gait 2354", and knee angle during the simulation. Muscles are represented by lines of action. During the simulation, muscle color changes according to their activation level.

Spacesuit Model

Given the lack of an available EMU spacesuit model, the effect of the spacesuit is represented as external forces/torques applied to the human body. Thus, effects of the spacesuit joints can be replicated by applying external torques to the corresponding human model joints, based on experimental EMU torque-angle relationships (Schmidt, Newman, Hodgson, 2001).

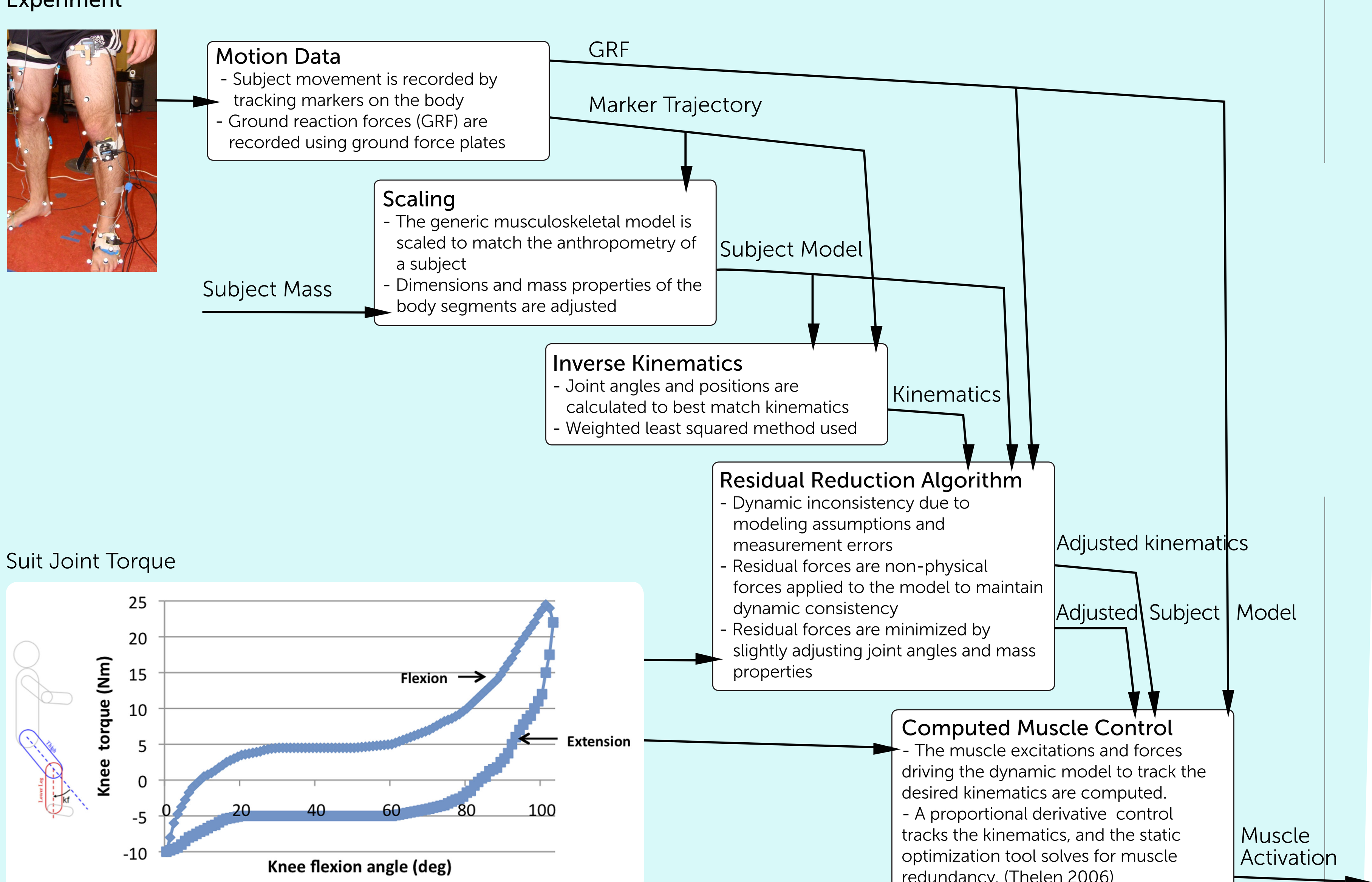
–Robotically applied internal torque
–Compilation of a torque-angle database on the EMU joints

Photos courtesy (Schmidt 2001)

Human - Spacesuit Interaction Model

Motion data and ground reaction forces from two subjects (two trials per subject) were collected using a Vicon motion capture system while performing left knee flexion/extension movements. These data were processed and integrated in OpenSim. Finally, in order to simulate "suited" conditions, EMU knee torque data based on experimental torque-angle database have been incorporated into the simulations (Schmidt, Newman, Hodgson, 2001).

Experiment



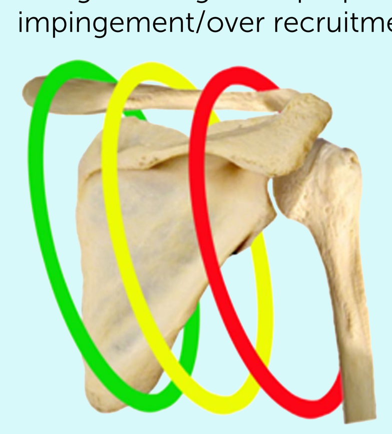
Data analysis

Shoulder muscle injury information will be statistically evaluated to determine the causal factors leading to injury. Our work will use a database compiled by NASA personnel. Shoulder injuries will be matched with anonymous astronaut subjects, time spent in the suit, selected space suit components, and the individual's anthropometric measurements. Uninjured astronauts will also be included for comparison. All subject data is de-identified and analyzed via an unique code. Variability in the data includes spacesuit pieces being adjusted and small sample size.

Our analysis builds on the work of others in analyzing correlations in anthropometry, space suit components, and injury (Hochstein, 2008; Opperman et al., 2009. 2010; Scheuring et al., 2012). A subset of relevant anthropometric dimensions being included are:

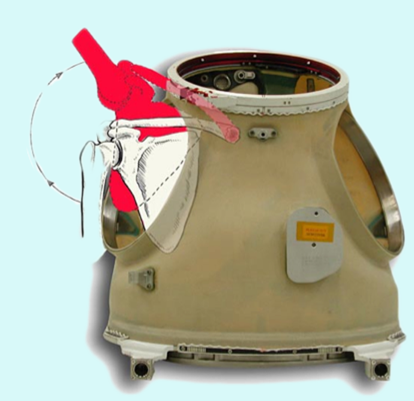
1. Height
2. Cervical Height
3. Mid Shoulder Height
4. Acromion Height
5. Arm Reach
6. Expanded Chest
7. Inter-Acromion Distance
8. Chest Breadth
9. Bideltoid Breadth
10. Acromion-Radiale Length
11. Lower Arm Length
12. Shoulder Circumference

It is hypothesized that astronauts with HUTs that are tightly fitting and loosely fitting compared to the originally intended sizing have a greater propensity for shoulder injury. In both cases, injury is caused by impeded scapulothoracic motion and impingement/over recruitment of rotator cuff motion.



Loosely fitting HUTs have shoulder bearings located more laterally than properly fitting HUTs, restricting rotation of the scapula and clavicle with arm abduction.

Photos courtesy (Williams & Johnson 2003)



Tightly fitting HUTs have reduced clearance, meaning impingement occurs more often and with less range of motion.

Photos courtesy (Williams & Johnson 2003)

Preliminary results

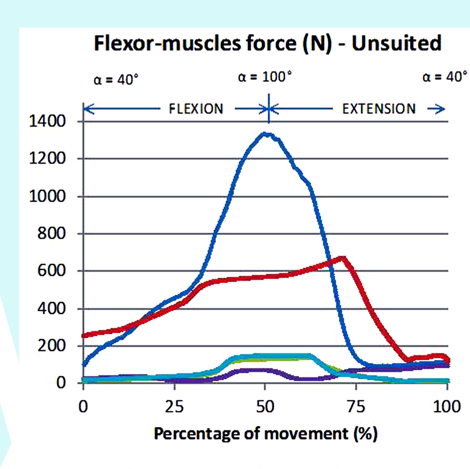


Figure 2: Forces developed by the knee flexor muscles of subject A during the movement in "unsuited" conditions.

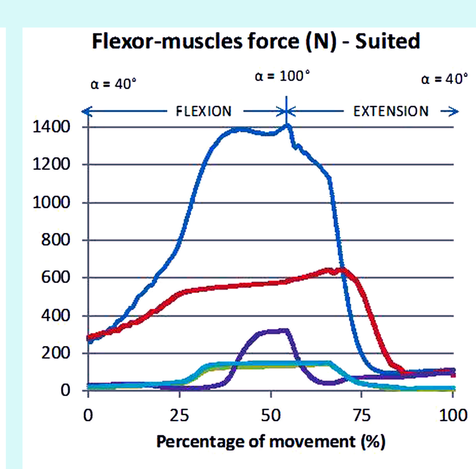


Figure 3: Forces developed by the knee flexor muscles of subject A during the movement in "suited" conditions.

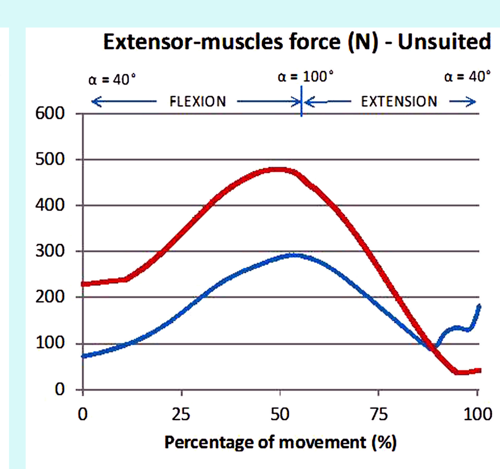


Figure 4: Forces developed by the knee extensor muscles of subject A during the movement in "unsuited" conditions.

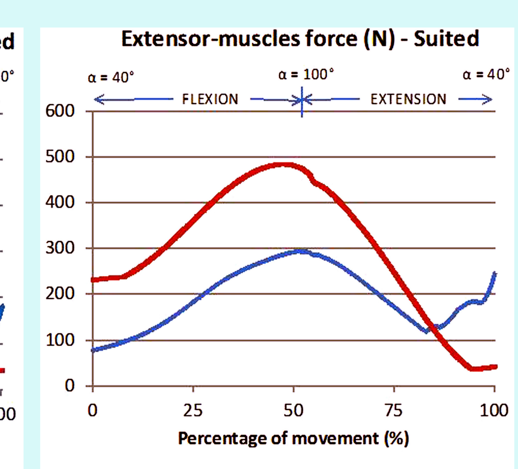


Figure 5: Forces developed by the knee flexor muscles of subject A during the movement in "suited" conditions.

Preliminary data suggest that, in "unsuited" conditions, the knee flexors generating higher peak forces are the BFL and BFS (Figure 2). The rest of the knee flexor muscles don't seem to contribute too much to the movement. Data in "suited" conditions (Figure 3) suggest that the BFL and GM are significantly affected by the presence of the spacesuit. Preliminary statistical analysis on peak forces shows significant differences between "unsuited" and "suited" conditions (BFL p=0.032; GM p<0.0005).

On the other hand, knee-extensor muscles do not show a large difference between "unsuited" and "suited" conditions (Figure 4 and 5). These results are consistent with the intrinsic nature of a highly pressurized spacesuit, which has a tendency to come back to its neutral position.

Statistical methods

Muscles peak forces exerted by knee flexors and knee extensors were compared in "suited" and "unsuited" conditions (Table 1). A mixed ANOVA was used, including the subjects as the random blocking variable, in order to account for inter-subject differences.

Randomized Complete Block Design:

Experimental design	"Unsuited"	"Suited"
Subject A	AU1 AU2	AS1 AS2
Subject B	BU2 BU2	BS1 BS2

Table 1: Muscles peak forces (Mean ±SE of the four trials) in "unsuited" and "suited" conditions.

Muscles	Unsuited	Suited	P-value
Knee flexors			
Biceps femoris long head (BFL)	1318±30	1422±15	**0.032**
Biceps femoris short head (BFS)	682±5	674±11	0.325
Gracilis (GR)	136±3	145±1	0.054
Sartorius (SR)	134±11	152±1	0.151
Gastrocnemius medialis (GM)	110.2±8	368±26	**<0.001**
Knee extensors			
Rectus femoris (RF)	295±13	334±16	0.079
Vastus intermedialis (VI)	365±55	440±60	0.35

*Values in Newtons (N)

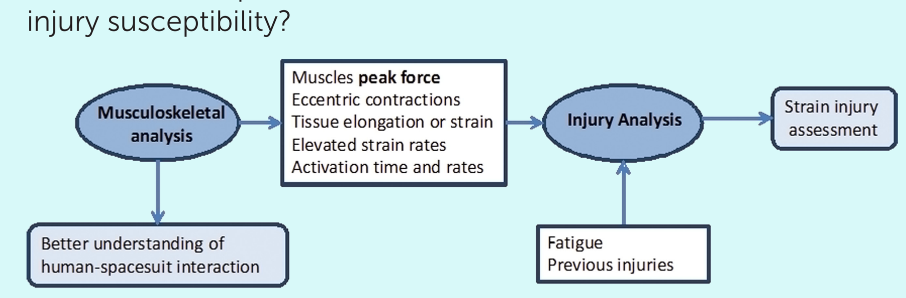
Conclusions

A new framework has been developed to analyze human-spacesuit interaction during EVA. The musculoskeletal analysis developed will provide new insights into the human musculoskeletal performance inside the space suit, and will contribute to the assessment of astronaut health and safety during EVA:

- Better understanding of astronaut musculoskeletal health and safety
- Spacesuit torque limits on musculoskeletal performance
- Feasibility of tasks during EVA

Future work

What are the implications of these results in terms of injury susceptibility?



Ongoing research includes analysis of data from additional subjects, together with knee flexion/extension motion capture data from one subject wearing the EMU collected at Johnson Space Center. Future work includes refining the spacesuit model by incorporating EMU torques in additional joints, and using an enhanced human musculoskeletal model that contains musculotendon actuators in the upper torso and arms.

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