Engineering an Anthropomorphic Exoskeleton for Actively Controlled Space Suit Simulation

Forrest Meyen

Qualifying Exam Research Presentation
January 28, 2012

Professor Dava Newman
Advisor

Project is a Collaboration of Aurora Flight Sciences and the MIT Man Vehicle Laboratory

Funded by NASA and the National Science Foundation
Testing and Training for Human Exploration

2005 Mars Simulation (Credit Jessica Marquez)

NASA eZLS (Perusek et al. 2007)

NASA ARGOS (NASA)
Introduction

Space suits impose resistive torques to joint motion
- Due to joint volume, pressure, and structural effects\(^1\)
- Nearly 30 N-m Torque during EMU knee flexion
- Joint torques affect EVA performance, consumables, and fatigue

Why not just use a real suit?
- EMU weight 125 kg (275 lb)\(^2\)
- Cost $12 million\(^3\)
- Access
- Pressurization
- Environment (Dust, abrasion)


Schmidt (2001)
Proposed Solution

Hypothesis

– A programmable exoskeleton using pneumatically powered actuators can effectively simulate space suit joint torque profiles.

Objective

– Build a pneumatically powered exoskeleton that can actively vary resistance to hip, knee, and ankle motions.

Success Criteria

– Match each joint to EMU joint torque data within a RMS error of 10% for the hip, knee, and ankle joints.
The State of the Art

**Upper Body Exoskeletons**
- Ivanova et al. 2011
- Brackbill et al. 2009
- Kousidou et al. 2006
- Carignan and Liszka 2005

**Resistive Exoskeletons**
- Mao and Agrawal 2011
- Crocher 2011
- Bergamasco et al. 2009
- Hall et al. 2012
- Duda et al. 2011
- Zurich et al. 2011
- Cherry et al. 2009
- Dollar and Herr 2008
- Carr and Newman 2007
- Meyen 2013

**Lower Body Exoskeletons**
- Gordon and Ferris 2012
- Lewis and Ferris 2011
- Banala et al. 2009
- Cao et al. 2009
- Kwa et al. 2009
- Beyl et al. 2008
- Lockheed Martin 2008
- Kazerooni and Streger 2006
- Kazerooni et al. 2005
- Low et al. 2006
The State of the Art

Assistance
Rehabilitation
Augmentation
Simulation

Resistive Exoskeletons

Upper Body Exoskeletons

Ivanova et al. 2011
Brackbill et al. 2009
Kousidou et al. 2008
Carignan and Liszka 2005

Lower Body Exoskeletons

Mao and Agrawal 2011
Duda et al. 2011
Zurich et al. 2011
Cherry et al. 2009
Dollar and Herr 2008
Carr and Newman 2007

Kwa et al. 2009
Beyl et al. 2008
Lockheed Martin 2008
Kazerooni and Streger 2006
Low et al. 2006
Kazerooni et al. 2005

Gordon and Ferris 2012
Lewis and Ferris 2011
Banala et al. 2009
Co et al. 2009
The State of the Art

Assistance
Rehabilitation
Augmentation
Simulation

Resistive Exoskeletons

Mao and Agrawal 2011

Hall et al. 2012
Duda et al. 2011
Zurich et al. 2011
Chen et al. 2009

Meyen 2013

Lower Body Exoskeletons

Gordon and Ferris 2012

Upper Body Exoskeletons

Ivanova et al. 2011
Brackbill et al. 2009
Kousidou et al. 2006
Raytheon 2010
Carignan and Liszka 2005
Suzuki et al. 2007
Low et al. 2006
Kazerooni et al. 2005

Introduction
Background
Methods
Results
Conclusion
The State of the Art

The following is a list of references for various categories of exoskeletons:

**Upper Body Exoskeletons**
- Kwa et al. 2009
- Banala et al. 2009
- Brackbill et al. 2009
- Bergamasco et al. 2009
- Cao et al. 2009
- Carignan and Liszka 2005

**Lower Body Exoskeletons**
- Dollar and Herr 2008
- Gordon and Ferris 2012
- Lewis and Ferris 2011
- Banala et al. 2009
- Cao et al. 2009
- Kazerooni and Streger 2006
- Kazerooni et al. 2005

**Resistive Exoskeletons**
- Carignan and Liszka 2005
- Suzuki et al. 2007

**Assistance**
- Resistive Exoskeletons
- Rehabilitation
- Augmentation
- Simulation

**Background**
- The State of the Art
- Upper Body Exoskeletons
- Lower Body Exoskeletons
- Resistive Exoskeletons
The State of the Art

Resistive Exoskeletons

Duda et al. 2011

Kwa et al. 2009

Banala et al. 2009

Brackbill et al. 2009

Bergamasco et al. 2009

Cao et al. 2009

Carignan and Liszka 2005

Cherry et al. 2009

Crocher 2011

Dollar and Herr 2008

Ivanova et al. 2011

Hall et al. 2012

Gordon and Ferris 2012

Kazerooni and Streger 2006

Kazerooni et al. 2005

Kousidou et al. 2006

Lewis and Ferris 2011

Low et al. 2006

Meyen 2013

Mao and Agrawal 2011

Zurich et al. 2011

Raytheon 2010

Suzuki et al. 2007

Beyl et al. 2008

Carr and Newman 2007

Lower Body Exoskeletons

Assistance
Rehabilitation
Augmentation
Simulation
The State of the Art

Upper Body Exoskeletons
- Ivanova et al. 2011
- Crocher 2011
- Bergamasco et al. 2009

Lower Body Exoskeletons
- Gordon and Ferris 2012
- Lewis and Ferris 2011
- Banala et al. 2009
- Cao et al. 2009

Resistive Exoskeletons
- Hall et al. 2012
- Duda et al. 2011
- Zurich et al. 2011
- Cherry et al. 2009
- Dollar and Herr 2008
- Carr and Newman 2007

Assistance
Rehabilitation
Augmentation
Simulation

Introduction
Background
Methods
Results
Conclusion
Torque Transmission

Introduction

Background

Methods

Results

Conclusion

Flexion/Extension

Straight torque to moment arm (Straight)

Advantages
Simple design

Disadvantages
Changing moment arm

Guiderails needed

Hard to protect actuators

Actuator bent around a spool (Bent)

Advantages
Large actuator contraction
Generates large forces
Leverage body shape (knee)

Disadvantages
Increase bulk (hip)

Guiderails needed

Selected for knee

Actuating spool mounted cables (Cable)

Advantages
Very adjustable
Can use spools or cams
Lowest form factor
Slide rails not needed

Disadvantages
Require more parts (spools)

Selected for hip

Abduction/Adduction

Example

Flexion

Extension

Straight

Bent

Cable
**Actuator Sizing**

**Hip Range of motion requirements**
- Derived from space suit torque database
- Actuator 1 Requirements
  - ROM of 20°
  - Max torque of 28 N-m
- Actuator 2 Requirements
  - ROM of 120°
  - Max. Torque of 31 N-m

- Minimizes actuator weight (cost function)
- Constraints
  - Torque
  - Range of motion
  - Spool shear stress
- Revised to minimize actuator length

Spool fixed with respect to hip structure and rotates within thigh structure.

\[ \text{Torque} = R \times F \]

F = Cable tension produced by actuator

Potential actuator and spool size options
Torque Transmission

- Actuator size optimized for directions independently
- Actuators create cable tension that results in spool torque
- Cam and single spool designs also considered

Linear carriage mounted bracket allows motion
Torque Transmission

- Actuator size optimized for directions independently
- Actuators create cable tension that results in spool torque
- Cam and single spool designs also considered
- Snap rings for quick assembly and disassembly
- 1.8 Factor of Safety
Fitting the Human Operator

- Sizing NASA Standard 3000
- Fit to 5% female to 95% male
- Telescopic tubing for quick size adjustments
- Adjustable straps for leg girth
- External frame backpack used for support adjusts similarly
- Bearings allow for hip rotation, flexion/extension, and abduction/adduction
- Push button locking pins are used for fast size modification
Final Hip Joint Design

COTS Pack Frame

Electronics Storage

Abd./Add. Actuators

Compressed Air

Abduction/Adduction Joint

Flexion/Extension joint

F/E Actuator 1

F/E Actuator 2

Thigh Structure
Ankle and Knee Joint Designs

Knee and ankle joints also in development

Ankle Prototype

Knee Prototype
**Control System**

- Proportional Controller
- Potentiometers provide joint location and movement direction
- A lookup table determines the appropriate joint torque for the current space suit
- Pressure is adjusted to meet that torque value
Robotic Testing

Knee Testing Observations
• Test with active control
• Torque generation adequate
• Simulated hysteresis curve

Hip Testing Observations
• Slow actuator response

Testing Plan
• Programmed motions
  • Ankle
  • Knee
  • Hip A/A
  • Hip F/E
• RMS Error
  • 0.2, 0.5, 1 Hz cycles
  • 10 cycles

Preliminary knee flexion data
Display Design Pilot Study

2 Displays
6 trials per display
10 Subjects
Starting display randomized

Paired Student’s T-Test

\[ H_0: \mu_A = \mu_B \]
\[ H_A: \mu_A \neq \mu_B \]
\[ \alpha = 0.05 \]

**Average Violation Response Time**

Display A = 1.98 seconds
Display B = 0.60 seconds

Reject \( H_0 \) Display B is better for response time \( (p = 0.0001) \)

**Average Situational Awareness Score**

Display A = 0.93
Display B = 0.85

Do not reject \( H_0 \) Display A may be better for SA \( (p = 0.0957) \)
Conclusion

My contributions

• Designed and built a pneumatically actuated hip exoskeleton
  – Actuator optimization
  – Novel actuator application
  – Mechanical design and verification
• Designed and built a prototype ankle actuator
• Robotic testing on hip and knee components
• Design integration
• Preliminary display design and pilot study

Limitations

• Fitting the human in all cases
• Joint axis alignment for complex joints
• Quality of space suit joint torque data available
• Replicating suit feel as well as joint torque values
• Current system response time

Video: Walking in EVA S3
Future Work

Next steps
• Passive joint development
• Continued robotic testing
• Hip abd./add. advancements
• Control system enhancement

Potential work beyond Phase 2
• Human rated device
• Human performance testing
References

References

Backup Slides
Conceptual Development
Fabricated Hip Joint
Methodology

1. Create joint torque database

2. Prototype Design

3. Develop Control System

4. Build Prototype Joints

5. Robotic Testing

6. Modifications and system assembly

7. System verification