Neuromechanical Redundancy for Gait Compensation in Transtibial Amputees

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Introduction

• Transtibial Amputees
  – Limb length
  – Ankle
  – Normal joint mobility
  – Direct muscular control
  – Local proprioception [Perry, 1992]

• Joint kinematics
  – Injured rats shown to return to pre-injured limb level goal kinematic trajectories [Bauman and Chang, 2010]
  – Understanding of recovery after injury [Bauman and Chang, 2010]
Introduction

- **Human locomotion: highly redundant**  
  [Srinivasan and Ruina, 2006, Latash, Scholz, Schoner, 2002]

- **Lower limbs have three major joints**
  - Leg length and orientation are limb level **GOALS**
  - Kinematic motor redundancy: multiple joint configurations for a desired **GOAL**

- Amputees: How do you coordinate if you are missing one of those joints?
Introduction

• Quantify motor redundancy by analysis of variance [Scholz, Reisman, Schoner, 2001]

• Deviations at one joint counteracted by other joints allows decreased variance at the limb level [Chang, et al., 2009, Heiderscheit, 2000, Yen, 2009, Auyang, 2009]

• Importance:

↑ vs. ↓

[Barrett, Noordegraaf, Morrison, 2008]
Purpose

• Understand differences in healthy and amputee gait
• Understand how the nervous system of an amputee coordinates joint kinematics to compensate

– Better gait rehab strategies
Spoiler Alert!: Conclusions

• Sound limb
  – Sound limb is affected by amputation
  – Remaining joints and limb level goals work to maintain similarity
  – Return to ‘pre-amputation’ kinematics may not be as important as symmetry
  – Focus rehab to prevent overuse injuries

• Amputees use redundancy to stabilize limb level goals
Hypotheses

1. Mean prosthetic side limb level goals will be preserved to able-bodied state.

2. Within prosthetic side, joints act to preserve invariant leg orientation and leg length.
Methods

• 5 unilateral traumatic, transtibial amputees
• 7 able-bodied control subjects
• Three 30 second walking trials at 1.2 m/s
• Kinematic data collected from a six-camera motion analysis system (120 Hz, VICON)

Courtesy of Karen Liu
GT Computer Graphics Lab
R$^2$: an approximator for determining similarity of 2 trajectories

- R$^2$ > 0.5 means trajectories are similar
- R$^2$ < 0.5 means trajectories are different

[Chang, 2009]

**Variance**: Measure of the average variability from step to step
Leg Orientation

$R^2 = 0.985$
$R^2 = 0.45$
$R^2 = 0.25$
Leg Orientation

$R^2 = 0.997$
$R^2 = 0.74$
Amputee Joint Kinematics

Ankle Angle

- Prosthesis
- Sound

R² = 0.39

Knee Angle

R² = 0.94

Hip Angle

R² = 0.98
Variance of Joints and LO

- Prosthetic (excludes Ankle)
  - Total Variance Per Joint: p=0.03
  - LO Variance: *p=0.01

- Sound
  - Total Variance Per Joint: p=0.01
  - LO Variance: *p=0.01

- Control
  - Total Variance Per Joint: p=0.01
  - LO Variance: *p=0.01
Leg Length Variance

- Prosthetic (excludes Ankle)
- Sound
- Control

LL Variance
Discussion of Major Findings

• Hypothesis 1 partially accepted: Preservation of LO and LL in amputees
  • LO preserved  [Bauman and Chang, 2010]
  • LL not preserved
Discussion

• Leg Length:
  – Different region of the task space
• Symmetry
  – LO
  – LL
  – Sound limb affected
  – Joints
    • Asymmetry can lead to other health problems [Tura, 2010, Sanderson and Martin, 1997]
Discussion

• Hypothesis 2 accepted: Redundancy used to stabilize limb level goals
  – Similar limb level variances (LO and LL)
  – Achieving same level of performance [Auyang, 2009, Yen, 2009]

• Amputees coordinate only 2 joints to stabilize invariant leg orientation and leg length
  – Injured cats coordinate joints [Chang, 2009]
Limitations & Future Work

• Limitations:
  – No single, standardized prosthesis

• Future Work:
  – Congenital amputees
  – Transfemoral amputees
  – Kinetic analysis
Take Home Message

• Symmetry in gait more important than return to pre-amputated gait
• Amputees use redundancy
References

• Scholz, Reisman, Schoner, 2001 Exp Brain Research 141:485-500 Effects of varying task constraints on solutions to joint coordination in a sit-to-stand task
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• My subjects
Questions?
Additional Slides...
Variance Per Joint: Amputees and Able-Bodied $v=1.2 \text{ m/s}$
Stance and Swing Times, $v=1.2$ m/s

![Graph showing stance and swing times for Control R, Control L, Amp Px, and Amp Sd with error bars.](image)
Amputee Stride Length, $v=1.2$ m/s
Symmetry in Amputee Gait: Leg Length
R² values

Ankle     Knee      Hip      Leg Orientation      Leg Length

1

0.5

0

Prosthetic vs Control   Sound vs Control   Prosthetic vs Sound

Range of Similarity
Comparison of Prosthetic and Sound Kinematics of Amputee

- Symmetry
Discussion

- Overall trajectory shapes of the ankle, knee and hip were similar, but differences seen (p<0.05) at various points in the gait cycle between:
  - Prosthetic/sound and control ankles
  - Prosthetic and sound ankles
  - Prosthetic/sound and control knees
  - Prosthetic and sound knees

- No differences were found at any point of the gait cycle for the hip joint

- Ankle and knee joints on both the prosthetic and sound sides may be responsible for compensation after amputation
Methods/Data Analysis

• Limb level goals
  – Leg Orientation (LO): angle of vector defined by anterior superior iliac spine (ASIS) and toe markers
  – Leg Length (LL): length of the vector defined by ASIS and toe markers