A Neuromuscular Model of Human Locomotion and its Applications to Robotic Devices

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Seungmoon Song
Robotics Institute
Carnegie Mellon University
smsong@cs.cmu.edu
http://www.cs.cmu.edu/~smsong
How does human walk?

Geyer Group

Hartmut Geyer

DIRECTION
Theoretical Foundation of Legged Dynamics and Control

DIRECTION
Computational Models of Neuromuscular Control to
(a) further understanding of the human nervous system
(b) identify control algorithms for robotic limbs
(c) establish simulation platform for rapid innovation in rehabilitation robotics

DIRECTION
Robotic Limbs with human-like Behavior and Dexterity

1999
self-stable spring mass running

2002
positive force feedback generates compliant stance leg behavior

2003
compliant stance leg behavior explains walking dynamics

2006
DARPA M3 & NSF Dynamic Systems Programs

2010
spinal reflex control predicts human muscle activations in steady walking

2011
powered ankle prosthesis with reflex-like control inherits adaptation to environment

2012
NSF ERC on Quality of Life

2013
revised swing reflex control generates robust foot placement

2012
angular momentum control in segmented running systems

2013
3-D bipedal robot based on spring-mass model arrives at CMU

deadbeat stable running and steering in 3D environments

2015
embedding of deadbeat stable running in 2-D biped testbed

2015
DIRECTION
Computational Models of Neuromuscular Control to
(a) further understanding of the human nervous system
(b) identify control algorithms for robotic limbs
(c) establish simulation platform for rapid innovation in rehabilitation robotics

2015
NIH funds testbed for studying and transferring reflex control to articulated robotic legs

2014
prediction of amputee gait with powered leg prostheses using different control algorithms

2015
integration with supraspinal pathways generalizes 3-D model to variety of human locomotion behaviors

2015
development of powered knee prosthesis with reflex-like control for fall prevention in amputee gait

2015
DIRECTION
Robotic Limbs with human-like Behavior and Dexterity
Content

Background

Neuromuscular model of human locomotion

Using the model to control bipedal robots
Current understanding of human locomotion control

Human locomotion is well described at the behavioral level
- Kinematics, dynamics, muscle activations, ...

Not much is understood at the neural circuit level
- Spinal and supraspinal control layers
- Central pattern generators (CPGs), reflexes, ...
Simulation studies may provide better understanding

<table>
<thead>
<tr>
<th>model</th>
<th>mechanics</th>
<th>control</th>
<th>locomotion behaviors</th>
<th>robustness</th>
<th>EMG correlation</th>
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<tbody>
<tr>
<td>Taga et al. (1991-1998)</td>
<td>2D, 7 seg 6 torques</td>
<td>CPG + reflex 0 all segments</td>
<td>walk (run, obst)</td>
<td>25 Ns BW push, +15 kg at pelvis</td>
<td>n/a</td>
</tr>
<tr>
<td>Hase et al. (1998-2011)</td>
<td>3D 14 seg 60 muscles</td>
<td>CPG + reflex 0 (5 ms) all segments</td>
<td>walk, run</td>
<td>±0.5 cm GND (±2 cm GND)</td>
<td>not reported</td>
</tr>
<tr>
<td>Ogihara et al. (2001-2012)</td>
<td>2D 7 seg 18 muscles</td>
<td>CPG + reflex 0 none</td>
<td>walk</td>
<td></td>
<td>not quantified</td>
</tr>
<tr>
<td>Günther et al. (2003)</td>
<td>2D 11 seg 28 muscles</td>
<td>reflex (λ-model) 0 trunk</td>
<td>stand→walk</td>
<td>2° slopes, 0.07~3 × gravity</td>
<td>not quantified</td>
</tr>
<tr>
<td>Jo et al. (2004-2008)</td>
<td>2D 7seg 18muscles</td>
<td>mSyn realistic trunk</td>
<td>stand→walk (kick, obst)</td>
<td>15 Ns pushes, +15 kg at trunk</td>
<td>not quantified</td>
</tr>
<tr>
<td>Geyer et al. (2010)</td>
<td>2D 7 seg 14 muscles</td>
<td>reflex realistic trunk</td>
<td>walk</td>
<td>ground: ±4cm</td>
<td>51%-99%</td>
</tr>
</tbody>
</table>

+ robust 3D locomotion
+ diverse locomotion behaviors
+ predictive model
Background

Neuromuscular model of human locomotion


Using the model to control bipedal robots
Musculoskeletal system

- Muscle actuator
- Joint torque → Skeleton configuration
- Skeletal system
- Contact force → Ground reaction force
- Environment

7 segments
8 DOFs
22 MTUs

$F_{ce} = A F_{max} f_l(l_{ce}) f_v(v_{ce})$

$F_{mtu} = F_{se} = F_{ce} + F_{pe}$

CE: Contractile element
SE: Series elasticity
PE: Parallel elasticity
Neurophysiological transmission delays are modeled

**Neural transmission delay**

- SS → SC: 15 ms
- SC: 2.5 ms
- SC: 5 ms
- SC: 10 ms
- Total: 10 + 15 + 15 + 10 = 50 ms

**Other sources of system delay**

- $S_m \rightarrow ECC \rightarrow A_m$
- Muscle dynamics
- Excitation-contraction coupling (ECC): ~35 ms

excitation-contraction coupling (ECC): ~35 ms
Spinal control consists of reflex modules that embed key functions essential for legged locomotion.

**Stance**

Compliant leg behavior realizes walking and running

Positive force feedback generates compliant leg behavior

\[
S_m = S_0 + GF_m (t - \Delta t)
\]

**Stance → Swing**

\[
\alpha_{tgt} = \alpha_0 - c_d d - c_v v
\]

**Swing**

LIPM [Kajita EA, 2001]

SIMBICON [Yin EA, 2007]
Energy optimal control parameters generates human-like walking

The neural control is plausible
The neural control \textit{predicts} normal human locomotion
Energy optimal walking shows human-like muscle activation

The differences come from ...
- simplified musculoskeletal model
- energy optimal control parameters
The model can generate diverse locomotion behaviors

Robust walking (±10 cm)

Slope ascend and descend
The model can generate diverse locomotion behaviors

**Speed change**

- \(0.8 \text{ ms}^{-1} \rightarrow 1.8 \text{ ms}^{-1}\)
- \(1.8 \text{ ms}^{-1} \rightarrow 0.8 \text{ ms}^{-1}\)

**Direction change**

**Obstacle avoidance**

The proposed model can generate human-like robust walking and diverse locomotion behaviors.

The motor patterns of many human locomotion behaviors can be generated by chains of reflexes in the lower layer controller.

The model is implemented in MATLAB Simulink
The model can be downloaded from: http://www.cs.cmu.edu/~smsong/nmsModel/nmsModel.html
Our neuromuscular model has been used in different studies

Controllers for prosthetic legs and bipedal robots

- BionX (BiOM) [Eilenberg EA, 2010]
- EPFL (COMAN) [van der Noot EA, 2015]
- GeyerGroup [Schepelmann EA, 2015]
- GeyerGroup [Thatte EA, 2015]

Simulation testbeds for assistive devices

- Delft Univ. [van Dijk EA, 2013]
- Samsung [Seo EA, 2015]
- GeyerGroup [Thatte EA, 2015]
- Stanford Univ. [Wang EA, 2012]

Controllers for graphical characters

- Utrecht Univ. [Geijtenbeek EA, 2013]
Background

Neuromuscular model of human locomotion

Using the model to control bipedal robots

Current robot walking controllers have not yet reached the robustness of human locomotion control

- **Centralized controllers**
  - [Urata EA, 2012]
  - [Feng EA, 2014]

- **Heuristic policy-based controllers**
  - [Raibert EA, 2008]
  - [Nelson EA, 2012]
The reflex-based neuromuscular control may provide an alternative controller

Virtual neuromuscular control (VNMC)

ATRIAS robot
- human size
- trunk mass: 58 kg, leg mass: 2 kg (x 2)
- no foot
- series elastic actuators (SEA)
With VNMC, ATRIAS can walk on a terrain with height changes of ±20 cm in a 2D simulation environment.
The stance leg control is tested on hardware
Other Applications

– Controller and simulation testbed for prosthetic legs


vs. impedance control [Sup EA 2008]
Other Applications

– Simulation testbed for studying foot biomechanics


Simulation testbed for locomotion studies

Controller for robotic platforms

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