# dynamicWalking 2006

**mechanics and control of human and robot locomotion**

**ann arbor, may 6-8**

# Scientific Program and Abstracts

**May 4 - 8**
**Computer Science and Engineering Building Room 1670**
**University of Michigan North Campus**
**Ann Arbor, MI**

Keynote Speakers

- Tad McGeer, University of Washington
- Chris Atkeson, Carnegie Mellon University
- Steve Collins, University of Michigan
- Max Donelan, Simon Fraser University
- Andy Ruina, Cornell University
- Martijn Wisse, Delft University

Meeting Chair

- Art Kuo, University of Michigan

# Dynamic Walking Tutorial Schedule

| Time | Event | Instructors |
|---|---|---|
| | **Thursday, May 4** | |
| 9:00a | **Simulation I**<br>Integrating equations of motion over one step, applying step-to-step transitions, building a library of helper functions<br>Goal: Perform simulations of a walking model over one step (by lunch!) | Art Kuo |
| 12:00n | **Lunch** | |
| 1:00p | **Equations of motion I: The TMT Method**<br>A method for numerically derivation, using only kinematic expressions | Martijn Wisse |
| 2:00p | **Simulation II**<br>Limit cycles, stability, and collision mechanics<br>Goal: Find a periodic gait and evaluate its stability and energetics | Art Kuo, Max Donelan |
| 4:30p | **Equations of motion II: The Dynamics Workbench**<br>A Mathematica package that symbolically derives equations. (Participants are recommended to install a trial version of Mathematica) | Art Kuo |
| 5:00p | **Robot engineering**<br>How to build walking robots that are efficient and stable, and how to evaluate energetics objectively | Steve Collins, Martijn Wisse |
| 6:00p | End tutorials day 1 | |
| | **Friday, May 5** | |
| 9:00a | **Simulation III**<br>Powered walking, parameter studies, and control<br>Goal: Produce a powered walking model and study its parametric behavior | Art Kuo |
| 11:00a | **Experimental methods I**<br>Measures and techniques for experimental study of humans and robots | Max Donelan, Steve Collins |
| 12:00n | **Lunch** | |
| 1:00p | **Experimental methods II**<br>Hands-on application of methods | Donelan, Collins, Wisse |
| 2:00p | **Simulation IV**<br>Model analysis, application of constraints, introduction of degrees of freedom<br>Goal: Devise advanced models with feedback-driven behaviors | Art Kuo |
| 4:00p | **Optimal control and learning I**<br>Introduction to dynamic programming methods, with practical application | Chris Atkeson |
| 6:00p | End of session | |
| | **Saturday, May 6** | |
| 9:00a | **Optimal Control and Learning II**<br>Methods for determining optimal control policies for dynamic walking | Chris Atkeson |
| 11:00a | **Theory and principles of locomotion** | Andy Ruina |
| 12:00n | End tutorials, beginning of workshop | |

All tutorials are progressive except for Equations of Motion; participants should attend all sessions of a progressive series. All tutorials will be held in 1670 CSE Bldg and the adjoining computer lab.

# Dynamic Walking Scientific Program

**Saturday, 6 May**

| Time | Event | Presenting Author | Page |
| --- | --- | --- | --- |
| 12:00n | **Keynote**: The early days of passive-dynamic walking, and those soon to come | Tad McGeer<br>University of Washington | 1 |
| 1:00p | **Lunch*** | | |
| 2:00p | The gait sensitivity norm<br>Daan Hobbelen and Martijn Wisse | Daan Hobbelen<br>Delft University | 4 |
| 2:15p | Dynamic bipedal walking on irregular terrain: An online adaptive algorithm<br>Subramanian Ramamoorthy and Benjamin Kuipers | Subramanian Ramamoorthy<br>University of Texas at Austin | 5 |
| 2:30p | Orbital stability of passive dynamic walking on an irregular surface<br>Jimmy Su and Jonathan Dingwell | Jonathan Dingwell<br>University of Texas at Austin | 6 |
| 2:45p | Stability of passive dynamic walking on uneven terrain<br>Katie Byl and Russ Tedrake | Katie Byl<br>Massachussetts Institute of Technology | 7 |
| 3:00p | Discussion: Stability measures | Steve Collins and Jonathan Dingwell (moderators) | |
| 3:15p | **Coffee break** | | |
| 3:45p | Animal biomechanics: Running over rough terrain<br>Monica Daley | Monica Daley<br>Harvard / Concord Field Station | 8 |
| 4:00p | Concepts and philosophy for a highly dynamic biped<br>Jonathan Hurst | Jonathan Hurst<br>Carnegie Mellon University | 8 |
| 4:15p | Design and control of a running biped with pneumatic artificial muscles<br>Koh Hosoda, Takashi Takuma, and Atsushi Nakamoto | Koh Hosoda<br>Osaka University | 9 |
| 4:30p | Biarticular spring action during walking<br>Jesse Dean and A. D. Kuo | Jesse Dean<br>University of Alberta | 10 |
| 4:45p | Passive elastic joint moments during human walking<br>Ben Whittington, Amy Silder, Bryan Heiderscheit, and Darryl Thelen | Ben Whittington<br>University of Wisconsin-Madison | 11 |
| 5:00p | **Keynote**: Why do we walk the way we do? Mechanical determinants of the metabolic cost of healthy and pathological gait | Max Donelan<br>Simon Fraser University | 1 |
| 6:00p | **Poster Session and Light Buffet Dinner**<br>CSE Atrium outside Room 1670 | | |

All events will be held in 1670 CSE Bldg, except Poster Session and Dinner

*Lunch: There are limited options for lunch for Saturday and Sunday. Sandwiches can be ordered for a fee of no more than $5. Place sandwich orders at the registration desk in the morning.

# Dynamic Walking Scientific Program

## Sunday morning, 7 May 2006

| Time | Event | Presenting Author | Page |
|---|---|---|---|
| 9:00a | **Keynote**: A particle collision model for calculating the energetic cost of legged locomotion | Andy Ruina<br>Cornell University | 2 |
| 10:00a | **Coffee break** | | |
| 10:15a | Suggested invariance of the human knee-ankle-foot roll-over shape for level ground walking<br>Andrew Hansen and Dudley Childress | Dudley Childress<br>Northwestern University | 12 |
| 10:30a | The advantages of a rolling foot in human walking<br>Peter G. Adamczyk and A. D. Kuo | Peter Adamczyk<br>University of Michigan | 13 |
| 10:45a | Electrifying aspects of human walking<br>Larry Rome and Louis Flynn | Louis Flynn<br>University of Pennsylvania | 13 |
| 11:00a | Estimation of leg stiffness in human locomotion<br>Susanne Lipfert, Yvonne Blum, and Andre Seyfarth | Susanne Lipfert<br>Locomotion Lab, Jena University | 14 |
| 11:15a | A telescoping inverted pendulum model directly applied to normal and pathological gait<br>Frank L. Buczek, Kevin M. Cooney, Matthew R. Walker, Michael J. Rainbow, M. Cecilia Concha, and James O. Sanders | Frank L. Buczek<br>Shriners Hospital, Erie, PA | 15 |
| 11:30a | **Coffee break** | | |
| 11:45a | Discovery of pendulum and spring dynamics in the early stages of walking<br>Kenneth Holt, Elliot Saltzman, Chia Ling Ho, Masayoshi Kubo, and Beverly Ulrich | Kenneth Holt<br>Boston University | 16 |
| 12:00n | An integrative view on legged locomotion obtained from the bipedal spring-mass dynamics<br>Hartmut Geyer, Andre Seyfarth, and Reinhard Blickhan | Hartmut Geyer<br>Massachusetts Institute of Technology | 17 |
| 12:15a | Passive dynamic walking with springy legs<br>Shawn M. O'Connor and A. D. Kuo | Shawn O'Connor<br>University of Michigan | 18 |
| 12:30n | No wonder it's harder ascending vs. descending inclines!<br>Paul DeVita, Erin Bushey, Patrick Rider, Paul Zalewski, and Allison Gruber | Paul DeVita<br>East Carolina University | 18 |
| 12:45p | Discussion: Models with springs | | |
| 1:00p | **Lunch sponsored by Function Bay** | | |
| 2:00p | **Afternoon Session Begins** | | |

# Dynamic Walking Scientific Program

**Sunday afternoon, 7 May 2006**

| Time | Event | Presenting Author | Page |
|---|---|---|---|
| 2:00p | **Keynote**: What can dynamic walking teach us about robots and humans? | Steve Collins<br>University of Michigan | 2 |
| 3:00p | **Coffee break sponsored by Cyberbotics** | | |
| 3:15p | Using subject-specific simulations to understand muscle function during walking<br>Frank C. Anderson, Allison S. Arnold, Darryl G. Thelen, May Q. Liu, and Scott L. Delp | Frank C. Anderson<br>Stanford University | 19 |
| 3:30p | Push recovery: Teaching bipedal robots when and where to step<br>Jerry Pratt | Jerry Pratt<br>Institute for Human and Machine Cognition | 20 |
| 3:45p | Feedforward and feedback control of dynamic walking<br>A. D. Kuo and S. M. O'Connor | Art Kuo<br>University of Michigan | 20 |
| 4:00p | JenaWalker II: A robotic platform for investigating human walking and running<br>Andre Seyfarth, Andreas Karguth, and Fumiya Iida | Andre Seyfarth<br>Jena University | 21 |
| 4:15p | Identification of the mechanical impedance of the locomotor system during able-bodied walking<br>George Bertos, Dudley Childress, and Steven Gard | George Bertos<br>Northwestern University | 22 |
| 4:30p | **Coffee break sponsored by Cyberbotics** | | |
| 4:45p | Differentially flat design of bipeds ensuring limit-cycles<br>Vivek Sangwan and Sunil K. Agrawal | Sunil K. Agrawal<br>University of Delaware | 23 |
| 5:00p | A feedback strategy for robust enforcement of passive bipedal gaits<br>Eric Westervelt, Benjamin Morris, and Kathleen Farrell | Eric Westervelt<br>The Ohio State University | 24 |
| 5:15p | What's passivity got to do with it?<br>Mark Spong | Mark Spong<br>University of Illinois | 25 |
| 5:30p | Discussion: Control of walking | Mark Spong (moderator) | |
| 6:00p | Session ends, dinner on your own | | |

# Dynamic Walking Scientific Program

## Monday morning, 8 May 2006

| Time | Event | Presenting Author | Page |
|---|---|---|---|
| 9:00a | **Keynote**: Dynamic walking based on dynamic programming | Chris Atkeson<br>Carnegie Mellon University | 3 |
| 10:00a | **Coffee break** | | |
| 10:15a | Adaptive frequency oscillators applied to dynamic walking II. Adapting to resonant body dynamics<br>Jonas Buchli, Ludovic Righetti, and Auke Jan Ijspeert | Jonas Buchli<br>Ecole Polytechnique Federale de Lausanne | 26 |
| 10:30a | Optimization of stability and efficiency of dynamic walking<br>Katja Mombaur, Richard Longman, Johannes Schlöder, and Hans Georg Bock | Katja Mombaur<br>University of Heidelberg | 27 |
| 10:45a | Nonlinear inverse optimization and styles of human locomotion<br>Zoran Popovic | Zoran Popovic<br>University of Washington | 28 |
| 11:00a | On-line optimization of dynamic walking using stochastic policy gradient ascent<br>Jörg Stückler and Sven Behnke | Jörg Stückler<br>University of Freiburg | 29 |
| 11:15a | Legged locomotion: Energy optimization and simple models<br>Manoj Srinivasan and Andy Ruina | Manoj Srinivasan<br>Princeton University | 30 |
| 11:30a | **Coffee break** | | |
| 11:45a | Variable hip reciprocating mechanism for the hybrid orthosis system<br>Curtis To, Rudi Kobetic, and Ronald Triolo | Curtis To<br>Case Western Reserve University | 31 |
| 12:00n | Metabolic cost of moving the legs<br>Jiro Doke and A. D. Kuo | Jiro Doke<br>University of Michigan | 32 |
| 12:15a | How humans negotiate corners<br>Michael Orendurff | Michael Orendurff<br>Seattle VA Rehab R & D | 32 |
| 12:30p | Energetic cost of fixed ankle motion during human walking<br>Matthew Vanderpool and A. D. Kuo | Matthew Vanderpool<br>University of Michigan | 33 |
| 12:45p | Improved gait stability through restored ankle function<br>Harry Dankowicz | Harry Dankowicz<br>University of Illinois | 33 |
| 1:00p | **Lunch** (on your own, North Campus cafeteria) | | |
| 2:00p | **Afternoon Session Begins** | | |

# Dynamic Walking Scientific Program

## Monday afternoon, 8 May 2006

| Time | Event | Presenting Author | Page |
| --- | --- | --- | --- |
| 2:00p | **Keynote**: Stabilization and actuation of dynamic walking robots | Martijn Wisse<br>Delft University | 3 |
| 3:00p | **Coffee break** | | |
| 3:15p | On the design of biomimetic legged systems for walking<br>Hugh Herr | Hugh Herr<br>Massachussetts Institute of Technology | 34 |
| 3:30p | New prosthetic and orthotic technologies<br>Hugh Herr | Hugh Herr<br>Massachussetts Institute of Technology | 34 |
| 3:45p | Combining the expertise of modelers and clinical scientists to maximize the outcomes for rehabilitation<br>Beverly Ulrich | Beverly Ulrich<br>University of Michigan | 34 |
| 4:00p | Discussion: Rehab | Beverly Ulrich (moderator) | |
| 4:30p | **Coffee break** | | |
| 4:45p | Discussion: Proposed walking robots | Martijn Wisse (moderator) | |
| 5:15p | Discussion: Human experiments | Max Donelan (moderator) | |
| 5:45p | Discussion: Future of Dynamic Walking | Art Kuo (moderator) | |
| 6:00p | Session ends | | |
| | Drinks and discussion at Dominick's, 812 Monroe St, Ann Arbor (734) 662-5414 | | |

# Dynamic Walking Scientific Program

**Posters**: Peer-reviewed posters, to be presented in evening of 6 May 2006. Abstracts will be archived on-line.


| Poster | Event | Presenting Author | Page |
|---|---|---|---|
| 1 | Stable gait cycles and energetics of a simple walking model with feet<br>Gabriel Aguirre-Ollinger and Joseph Solomon | Gabriel Aguirre-Ollinger<br>Northwestern University | 35 |
| 2 | "Virtual" work: the d'alembert principle and dynamic movement in hybrid physical-virtual systems<br>Bradly Alicea | Bradly Alicea<br>Michigan State University | 37 |
| 3 | Bipedal locomotion control using nonlinear oscillators<br>Shinya Aoi and Kazuo Tsuchiya | Shinya Aoi<br>Kyoto University | 38 |
| 4 | Duality of dynamic locomotion and dynamic object manipulation<br>Borhan Beigzadeh, Majid Nili Ahmadabadi, and Ali Meghdari | Borhan Beigzadeh<br>Sharif University of Technology | 39 |
| 5 | Direct comparisons of local and orbital dynamic stability in human walking<br>Jonathan Dingwell and Hyun Gu Kang | Jonathan Dingwell<br>University of Texas | 40 |
| 6 | Is peripheral sensory feedback really necessary for stable walking in humans?<br>Jonathan Dingwell and Hyun Gu Kang | Jonathan Dingwell<br>University of Texas | 41 |
| 7 | Variability and local stability predict risk of falls for passive walking on an irregular surface<br>Jimmy Su and Jonathan Dingwell | Jonathan Dingwell<br>University of Texas at Austin | 42 |
| 8 | Comparison of coordination measures between able-bodied and functional electrical stimulation (fes) â " assisted paraplegic gait<br>Anirban Dutta and Ronald Triolo | Anirban Dutta<br>Case Western Reserve University | 43 |
| 9 | Stability of human walking at different velocities<br>Vanessa Everding, Anirban Dutta, and Elizabeth Hardin | Vanessa Everding<br>Case Western Reserve University | 44 |
| 10 | Gravity balancing of human leg using an external orthosis<br>Abbas Fattah and Sunil Agrawal | Abbas Fattah<br>University of Delaware | 45 |
| 11 | The trajectory center of mass in human level walking<br>Valery Kokshenev | Valery Kokshenev<br>Universidade Federal de Minas Gerais | 46 |
| 12 | Toward an objective interpretation of surface emg during gait<br>Dongchul Lee, Terry Horn, John Ramshur, and Dobriboje Stokic | Dongchul Lee<br>Methodist Rehabilitation Center | 47 |
| 13 | Exteroceptive control of passively stable dynamic running: antenna-based wall-following in cockroaches<br>Jusuk Lee, Andrew Lamperski, Robert Full, and Noah Cowan | Jusuk Lee<br>Johns Hopkins University | 48 |
| 14 | Stabilization of a 3d simplest walker by using a gyro<br>Kazuhiro Masui, N.Michael Mayer, and Minoru Asada | N. Michael Mayer<br>Handai FRC, Osaka University | 49 |
| 15 | Novel nonlinear elastic actuators for passively controlling robotic joint compliance<br>Shane Migliore, Edgar Brown, and Stephen DeWeerth | Shane Migliore<br>Georgia Tech | 50 |

# Dynamic Walking Scientific Program


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|---|---|---|---|
| 16 | **Developing an artificial neural network controller for automated standing balance using functional neuromuscular stimulation following spinal cord injury**<br>Raviraj Nataraj, Musa Audu, Robert Kirsch, and Ronald Triolo | **Raviraj Nataraj**<br>Case Western Reserve University | 51 |
| 17 | **Accurate legged motion sensing with the personal odometry system**<br>Lauro Ojeda and Johann Borenstein | **Lauro Ojeda**<br>University of Michigan | 52 |
| 18 | **Adaptive frequency oscillators applied to dynamicwalking: i. Programmable central pattern generators**<br>Ludovic Righetti, Jonas Buchli, and Auke Jan Ijspeert | **Ludovic Righetti**<br>Ecole Polytechnique Federale de Lausanne | 53 |
| 19 | **Testing the hybrid pendulum-spring model of walking**<br>Daniel Russell and Dylan Brillhart | **Daniel Russell**<br>Penn State University - Berks | 54 |
| 20 | **Passive dynamic mimicking for actively powered walking**<br>Koray Safak | **Koray Safak**<br>Yeditepe University | 55 |
| 21 | **Effective foot length ratios for sound and prosthetic ankle foot systems of unilateral trans-tibial prosthesis users**<br>Pinata Sessoms, Andrew Hansen, Margrit Meier, Steven Gard, and Dudley Childress | **Pinata Sessoms**<br>Northwestern University | 56 |
| 22 | **Controlling walking velocity of a pneumatic actuated biped by changing hip passivity**<br>Takashi Takuma and Koh Hosoda | **Takashi Takuma**<br>Osaka University | 57 |
| 23 | **The speed of walking while synchronising to music**<br>Leon van Noorden, Frederik Styns, Dirk Moelants, and Marc Leman | **Leon van Noorden**<br>University of Ghent | 58 |
| 24 | **Mechanical design details for a highly dynamic biped**<br>Jonathan Hurst | **Jonathan Hurst**<br>Carnegie Mellon University | 59 |

# Dynamic Walking Scientific Program

**Last-Minute Posters**: These present late-breaking findings and are not peer-reviewed. Abstracts will not be archived.

| Poster | Event | Presenting Author |
|---|---|---|
| L1 | A four-legged robotic test bed for control of festo fluidic muscles<br>Nicole Kern, Kurt Aschenbeck, Richard Bachmann, and Roger Quinn | Nicole Kern<br>Case Western Reserve University |
| L2 | Effects of augmented push-off power during normal walking<br>James Norris, Melanie Mitros, Erica Byrne, Anthony Marsh, and Kevin Granata | James Norris<br>Virginia Tech-Wake Forest Univ |
| L3 | Initial experimental study on dynamic interaction between an amputee and a powered ankle-foot prostheses<br>Samuel Au and Hugh Herr | Samuel Au<br>MIT |
| L4 | Slider-crank mechanism: a simple monopod<br>Paul Muench | Paul Muench<br>US Army |
| | Upside down walking: a passive-dynamic brachiating robot toy<br>Michael Coleman | Michael Coleman<br>University of Vermont |
| L5 | Dynamic computation of muscle excitations for balance restoration in human bipedal standing<br>Musa Audu, Ronald Triolo, and Robert Kirsch | Musa Audu<br>Case Western Reserve University |
| L6 | Implicit feedback structure in passive dynamic walking<br>Yasuhiro Sugimoto and Koichi Osuka | Yasuhiro Sugimoto<br>Kyoto University |
| L7 | The mechanical and metabolic cost of rocking<br>Caroline Soo, Veronica Naing, and James Maxwell Donelan | Caroline Soo<br>Simon Fraser University |
| L8 | Conceptual design of an adjustable stiffness artificial tendon for legged robotic application<br>Reza Ghorbani and Qiong (Christine) Wu | Qiong (Christine) Wu<br>The University of Manitoba |
| L9 | Efficient walking of bipedal robots using adjustable stiffness tendons<br>Reza Ghorbani and Qiong (Christine) Wu | Qiong (Christine) Wu<br>The University of Manitoba |
| L10 | Ambulation after incomplete spinal cord injury using electromyogram triggered functional electrical stimulation<br>Anirban Dutta, Rudi Kobetic, and Ronald Triolo | Anirban Dutta<br>Case Western Reserve University |
| L11 | Mathematical modeling of stiffness and forcing in preadolescents with and without down syndrome<br>Beth Smith, David Black, Masayoshi Kubo, Kenneth Holt, and Beverly Ulrich | Beth Smith<br>University of Michigan |
| L12 | Footstep planning for biped robots<br>Joel Chestnutt, James Kuffner, Koichi Nishiwaki, and Satoshi Kagami | Joel Chestnutt<br>Carnegie Mellon University |
| L13 | Metabolic cost of arm swinging during human walking<br>Rajiv Ghosh, Peter Adamczyk, and A. D. Kuo | Rajiv Ghosh<br>University of Michigan |
| L14 | Hybrid modeling of variable contact situations in legged locomotion<br>Marion Sobotka and Martin Buss | Marion Sobotka<br>TU Muenchen |
| L15 | Torque constraints for the modeling of pathological gait<br>Theresa Hayes and Yasin Dhaher | Theresa Hayes<br>Northwestern University |
| L16 | Effects of hip spring and impulsive actuation on dynamic walking | Maxine Kwan |

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| | Maxine Kwan and Mont Hubbard | University of California, Davis |
| L17 | **Enhanced sensory feedback facilitation of locomotion**<br>Keith Gordon, Ming Wu, Yasin Dhaher, and Brian Schmit | **Keith Gordon**<br>Rehab Institute of Chicago |
| L18 | **Smart sensors for dynamic walking**<br>Christopher Messom | **Christopher Messom**<br>Massey University- CMU |
| L19 | **Energy expenditure in amputee walking; the predictive value of simple biomechanical models**<br>Marjolein van der Krogt and Han Houdijk | **Marjolein van der Krogt**<br>VU University Medical Center |
| L20 | **Effect of small waist and limb loads on temporal variables in walking women**<br>Marcie Myers, Marian Brittain, Heather Hirsch, and Dilangani Boralessa | **Marcie Myers**<br>College of St. Catherine |
| L21 | **Ground to wall transitions for rise, a walking/climbing robot**<br>Hanns Tappeiner | **Hanns Tappeiner**<br>Carnegie Mellon Robotics Institute |
| L22 | **Passivity and energetics of the human ankle in level and downhill walking**<br>Jonathan Holm, Sang-Wook Lee, and John Jang | **Jonathan Holm**<br>University of Illinois at Urbana-Champaign |
| L23 | **Different gaits for a powered passisivity based 2d walker**<br>Edwin Dertien and Stefano Stramigioli | **Edwin Dertien**<br>University of Twente |
| L24 | **Better disturbance behavior with damped compliant legs**<br>Daniël Karssen, Daan Hobbelen, and Martijn Wisse | **Daniël Karssen**<br>Delft University of Technology |
| L25 | **Stabilizing a very simple 3d biped without prior knowledge of the limit cycle**<br>Gijs van Oort and Stefano Stramigioli | **Gijs van Oort**<br>University of Twente |

# Dynamic Walking Keynote Abstracts

## The early days of passive-dynamic walking, and those soon to come

Tad McGeer
University of Washington

Passive-dynamic walking appeals, of course, to the simple-minded. I therefore came to embrace it in the mid-1980s, as a consequence of an accidental interest in legged robots, and in horror at the prospect of studying the various active-walking methods that had been proposed at the time. Tom McMahon's observations on ballistic walking, and on gravity-powered toys, pointed the way toward passive dynamics as an approach to simplifying the problem. It was gratifying indeed to calculate stable limits cycles for elementary walking models, and even more so to build a machine and see that they were actually “for real!” Questions followed naturally about “pumped” passive walking, knees (to avoid stubbing of the swing toe), and running, and as simple and illuminating answers fell into place, the passive-dynamic story became compellingly attractive. Andy Ruina and his students at Cornell, and their collaborators Martijn Wisse and Richard van der Linde at Delft, became energetic protagonists in the 1990s, with impressive success in expanding the field from 2 to 3 dimensions—success that was all the more remarkable and heroic in that it rested perhaps more on intuition and faith than on cycle analysis! Recently workers at Cornell, Delft, and MIT have gone on to implement various pumping techniques in 3D machines, and have demonstrated huge advantages in energy consumption over their "active-walking" competitors. Meanwhile analytical work has contributed substantially to understanding of animal locomotion, and has explored the technical options for robot design.

Are we ready for applications? Benefits may come first in prosthetics and rehabilitation. Practical legged robots may seem more far-fetched, and competing with real people, let alone horses or camels, will surely be tough. But last year's success of robotic SUVs in DARPA's Grand Challenge demonstrated that at least some of the real world can now be attacked autonomously at high speed. Perhaps rougher terrain is now within reach for a smart set of mechanical legs.

## Why do we walk the way we do? Mechanical determinants of the metabolic cost of healthy and pathological gait

Max Donelan
Dept. of Kinesiology, Simon Fraser University

Humans and other animals require metabolic energy to walk. Minimizing this metabolic cost appears to determine many aspects of how we walk (e.g. our preferred speed). While the importance of metabolic cost in determining our preferred walking biomechanics was recognized long ago, an understanding of why walking exacts a metabolic cost has remained elusive. Our approach has been to use mathematical models inspired by passive dynamic walking to make quantitative predictions regarding the determinants of metabolic cost and test these predictions using empirical experiments on humans and other animals. In this manner, we have identified two major biomechanical determinants of the metabolic cost of healthy human walking, step-to-step transition and limb swing costs, that account for about 90% of total metabolic cost at moderate speeds. There is a tradeoff between these two costs-transition costs are minimized with short narrow steps while swing costs are minimized with long wide steps. Minimizing the sum of these two costs predicts measured preferred walking biomechanics remarkably well. Another intriguing determinant of the metabolic cost of walking is balance. Our theoretical and empirical results support the idea that lateral motion is passively unstable, is actively stabilized using medio-lateral foot placement, and this active stabilization exacts a modest metabolic cost (~10%). A new direction for our research is towards understanding the determinants of the metabolic cost of pathological gait. Dynamic walking models predict that symmetrical transitions, those during which the trailing leg performs an equal amount of positive work to replace the energy dissipated by the leading leg negative work, minimize the required mechanical work. Two common characteristics of pathological gait-be it from stroke, spinal cord injury or amputation-is left-right asymmetry and an elevation of the metabolic cost of gait. In subjects with hemiparesis due to stroke and in healthy subjects with simulated hemiparesis, we are currently testing the general hypothesis that the elevated metabolic cost of pathological gait is due to the increased muscle mechanical work required of asymmetrical step-to-step transitions. Our early empirical results are generally supportive of this hypothesis. It is our intention to use the results to guide the design of rehabilitation strategies, rehabilitation devices and assistive devices aimed at lowering metabolic cost and increasing patient mobility by improving transition symmetry.

## What can dynamic walking teach us about both robots and humans?

Steve Collins
Dept. of Mechanical Engineering, University of Michigan

Experience with dynamic walking robots can provide insight on human walking. I will discuss three experiences that have bridged the gap between robots and humans. The first was the tendency of the Cornell 3D biped to slip and rotate about the yaw axis, due to the motion of the swing leg. We countered this tendency by adding mechanical arms that moved in opposition to the legs, much as in humans. A subsequent modeling study at University of Michigan (UM) shows that arm motion can significantly reduce the yaw angular momentum, preventing the robot from rotating and reducing the yaw reaction torque that the human most produce in the stance leg. The second experience was with powering the Cornell Efficient Biped to push off with the ankle. This push-off is necessary to restore energy lost in the collision of the swing leg with ground. At UM, we have applied these principles to the design of a prosthetic foot that stores the collision energy in a spring, and controls its release in a manner that resembles push-off. The device appears to cut the energetic penalty of walking with a prosthesis in half. The third experience was with the instability of the robots in the lateral direction. Both robots used wide feet with carefully shaped bottoms to provide static stability, which was very sensitive to perturbations. Humans do not have wide feet, and must use other mechanisms such as lateral foot placement to stabilize walking. We have found that this lateral instability predicts many features of foot placement variability. In addition, a model of dynamic walking with noisy inputs reproduces many of these features and explains a number of apparently chaotic measures in a simple way. Dynamic walking is a tool for building practical, efficient robots, and for studying the control of human walking.

## A particle collision model for calculating the energetic cost of legged locomotion

Andy Ruina
Dept. of Theoretical and Applied Mechanics, Cornell University

Terrestrial legged locomotion requires repeated ground-reaction forces to redirect the body's motion from generally down to generally up. Here we approximate an animal as a point mass and the redirection as being accomplished by impulsive leg forces. For a forward-moving animal these impulses cause small-angle glancing collisions. Using freshman-physics style calculations we calculate the work absorbed and generated in these collisions. If we then approximate the metabolic cost as being proportional to positive muscle work we can calculate the food energy needed for legged locomotion and end up in the right ball park. The cost of bipedal running estimated from this collisional model, becomes less than that of walking when v/sqrt(g l) is greater than about .6, the speed when people switch from walking to running. One strategy for reducing the collisional cost is to have the leg muscles simulate purely-elastic springs, as is observed in real human running. Another strategy is to use a sequence of collisions in one redirection phase. Apparent examples of this sequencing in nature are a) the "ba-da-dump" pattern of a horse gallop and b) having a push-off just before heel strike in human walking.

# Dynamic Walking Keynote Abstracts

## Dynamic walking based on dynamic programming

Chris Atkeson
CMU Robotics Institute

We are currently exploring a number of optimization approaches applied to bipedal walking in robots. This talk focuses on approaches based on dynamic programming. A key research challenge is handling the "curse of dimensionality". One approach is to develop controllers for simpler systems, and then apply them to the original system. Another approach is to use local trajectory optimizers to generate a set of trajectories that collectively represent a globally optimal value function.

## Stabilization and actuation of dynamic walking robots

Martijn Wisse
Delft University, The Netherlands

This presentation will introduce the new robot that we are developing, which goes by the name “Flame.” It is a joint effort by DELFT, CMU, and Northwestern University. You can use this presentation to your benefit in two ways: (1) be inspired with ideas for your own actuated “limit cycle walker”, or (2) be motivated to join our effort. For option (2), this presentation is sort of a sales pitch… ☺

Flame is a 3D robot with 7 actuated degrees of freedom: the pitch DoFs of the ankles, knees, and hips, plus a “hip roll” DoF for sideways foot placement. The hip roll DoF has a bisecting mechanism such that both legs move outward or inward simultaneously. In addition, the robot has two passive lateral ankle DoFs. The feet are flat. All actuated joints are powered with geared electric DC motors (Maxon) with cables between the motor output shaft and the joint shaft. There is enough space to put springs in the cables, so that we can make the drive train into Series Elastic Actuation.

All motors and all joints have position encoders. These can be used to derive velocities, and when Series Elastic Actuation is used, they can also provide force information. The control loop runs at 1 kHz using Linux RTAI. We are also working on a multibody simulation in ADAMS which can run the same controller code (written in C) as the robot.

Now the question is: how does this design differ from the traditional HONDA-style designs? Well, the main issue is that the mechanical structure is very close to our previous machines (www.dbl.tudelft.nl). With this incremental approach, we can keep using the "limit cycle approach" for the controller design, which basically means that the gait is a stable sequence of forward falls. If we were to add too many DoF at once, it would become unfeasible to find stable limit cycles; there would be too many unknown ways to fall for the robot. Actually, we hope that we have not added too many DoF already; we are still working on simple controller ideas for the posture of the upper body, for the ankle push-off, and for the lateral foot placement.

# The Gait Sensitivity Norm



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## GOAL

This abstract presents a new measure for the disturbance rejection behavior of ‘limit cycle walkers’, i.e. actuated biped robots having their roots in ‘passive dynamic walking’. We call the new measure the ‘Gait Sensitivity Norm’, as it measures how badly the gait is disturbed by a typical disturbance. We test the Gait Sensitivity Norm on a simple walking model (Fig. 1).

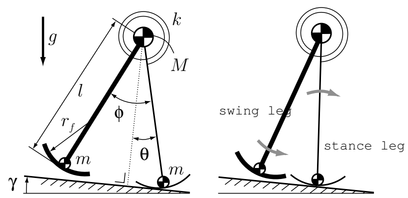


Fig. 1. The Simplest Walking Model [1] extended with a foot radius and a hip spring.

## I. CONCEPT

The gait sensitivity norm quantifies how badly the gait is affected by a disturbance. It requires two decisions from the designer:

1) **Disturbances *e***. The designer has to decide which type of disturbances he wants to investigate, and if there are more than one type, he has to decide how they are weighted. For example, one could define that a step-down in the floor of 1 mm height is equal to a continuous backward push (e.g. wind drag) of 1 N. In this abstract, we will only consider disturbances in the form of a single step-down in an otherwise flat, downward sloped floor.
2) **Gait indicators *g*.** This is the hardest decision. The designer has to decide which measured quantity best indicates the ‘chance of falling’. We may need a different indicator for each way the robot can fall. For example, a fall forward is characterized by the fact that the step time is too short for the swing leg to timely reach a forward position. Thus, the variability of the step time is a good indicator for the chance of falling. For a sideways fall, one could consider the lateral sway variability. However, in this abstract, we do not need any other indicators than the step time, because most of the falls of the 2D model (Fig. 1) are forward falls.

With these choices, we can now define the size of dynamic response $\|\frac{\partial \mathbf{g}}{\partial \mathbf{e}}\|_2$. The dynamic response of the system is the variability of the gait indicators as a result of the input disturbances. This dynamic response is an essential factor in measuring disturbance rejection. This claim is supported by several human gait analysis studies that indicate a strong correlation between gait variability and the occurrence of falling. In control engineering the size of a system’s dynamic response is measured by system norms. The Gait Sensitivity Norm uses the $H_2$-norm, which gives the standard deviation of the system output response to white noise inputs as well as impulse inputs. Therefore it quantifies the disturbance rejection of a walking gait for single perturbations (e.g. step down in the floor) as well as for continuously varying disturbances (e.g. floor with randomly varying height).

## II. RESULTS

Figure 2 compares our new Gait Sensitivity Norm to the maximum disturbance the model can handle, resulting in more than 80% correlation. It also shows that the correlation between the maximum Floquet multiplier $max(|\lambda|)$ is much less, and may even be inverse.

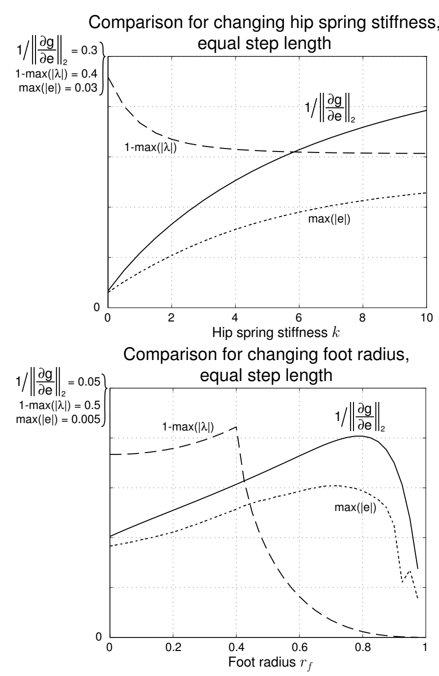


Fig. 2. Comparison of three disturbance rejection measures for changing hip stiffness and changing foot radius in the walking model (Fig. 1). Both graphs show a strong correlation between the Gait Sensitivity Norm $\|\frac{\partial \mathbf{g}}{\partial \mathbf{e}}\|_2$ and the largest disturbance the walker can handle $max(|e|)$, while the correlation between the maximum Floquet multiplier and $max(|e|)$ is much less.

## REFERENCES

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# Dynamic Bipedal Walking on Irregular Terrain: An Online Adaptive Algorithm

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## INTRODUCTION

We present a qualitative approach to the dynamical control of bipedal walking that allows us to combine the benefits of passive dynamic walkers with the ability to walk on uneven terrain. We demonstrate an online control strategy, synthesizing a stable walking gait along a sequence of irregularly spaced stepping-stones.

Researchers have recently begun to explore the problem of actuating passive walkers, in order to extend their domain of applicability. In realistic applications, actuation is required for stable walking in level, uphill, or irregular environments, and active planning is essential to allow the robot to react to environmental uncertainty. The algorithmic challenge is to gain the benefits of actuation and active planning without compromising the use of natural dynamics. Our approach to solving this problem uses qualitative descriptions of the dynamics of the system, and a hybrid control framework for composing the walking behavior from simple component behaviors.

## METHODS

We consider a slightly modified version of the simple walker models discussed in [1, 2] - we assume that the walker can quickly change the effective length of the swing leg.

Our approach to gait synthesis is based on composing multiple segments of periodic orbits in an online fashion. Instead of constructing a robot to have a single stable periodic gait, we select good orbits from an infinite family of periodic orbits available to our dynamical system and adaptively synthesize a hybrid orbit on each step. This idea is illustrated in the conceptual schematic of figure 1. In this model, the only active control is to apply constant forces for a brief period during the double support phase, to enforce the desirable orbit for the next step. At all other times, the natural nonlinear dynamics are allowed to evolve uncontrolled. Desired orbits are selected by solving an optimization problem that uses a cost based on kinematic specifications (i.e., desirable footholds) and kinetic energy of the stance leg.

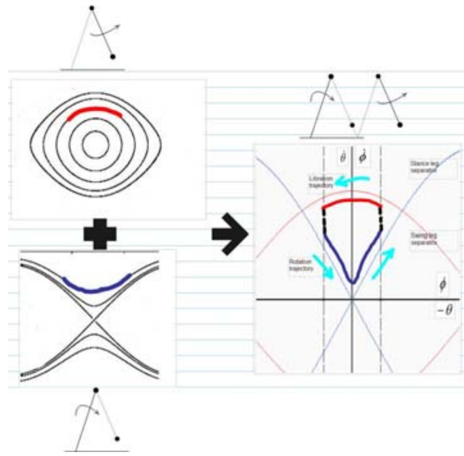

**Figure 1. Conceptual schematic of the construction of a hybrid trajectory on each step. The initial conditions of each trajectory are selected by solving an optimization problem, after which the system dynamics evolves uncontrolled.**

## RESULTS AND DISCUSSION

Figure 2 displays a typical trace of a robot utilizing this algorithm, navigating a flight of stairs. We have obtained similar results for other random terrain situations, e.g., with footholds drawn from a Gaussian distribution in height and forward displacement.

## CONCLUSIONS

We address the open problem of actuating passive walkers to navigate uneven terrains and an uncertain environment.

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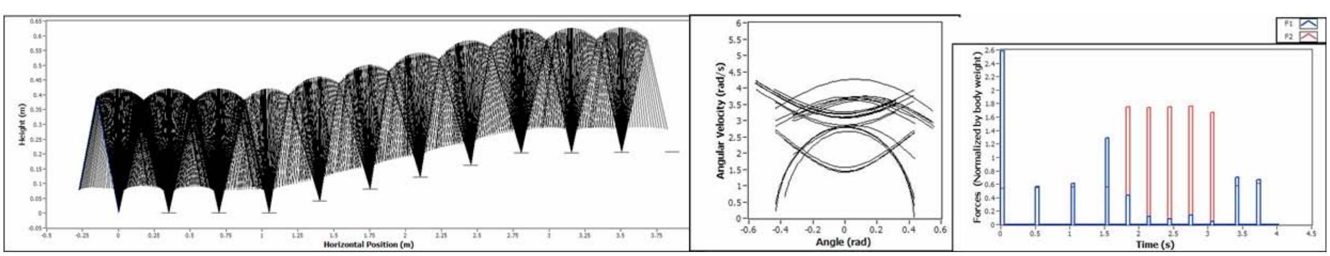

**Figure 2. Time capture of robot poses, phase space trajectories and corresponding forces (blue and red correspond to trailing and leading legs respectively) used over time during dynamic walking to climb a flight of stairs.**

# Orbital Stability of Passive Dynamic Walking on an Irregular Surface

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## INTRODUCTION

Passive dynamic walkers (PDWs) can walk down shallow slopes with no motors or feedback controllers, using gravity as their only source of power input into the system. These systems have been used to examine the stability of human locomotion. The orbital stability of these systems under "ideal" conditions has been well established [3]. However, like humans, these PDWs can fall over if subjected to sufficiently large perturbations. Little has been done to quantify the stability properties of PDWs under non-ideal conditions. We demonstrate that orbital stability is inherent to the system itself regardless of perturbations.

For humans, walking on bumpy terrain causes increased variability [5]. This suggests that increased variability may cause increased instability. However, stability should be an inherent property of the system and not based on perturbations applied. In mechanics, stability is quantified by how a system *responds* to perturbations. For limit cycle systems, "orbital stability" is defined from Floquet theory which describes how a system responds to small perturbations from one cycle to the next [1,2]. We hypothesized that the orbital stability of the system would be uncorrelated to locomotor variability because orbital stability is properties of the system itself and does not depend on the magnitude of the applied perturbations.

## METHODS

We modified a version of the "simplest" 2D model of passive dynamic walking [2] to simulate walking down a shallow, bumpy slope. The modified equation was $\phi(t) - 2\theta(t) = \delta = \varepsilon \cdot U[-0.5, +0.5]$, where ϕ and θ are defined as in Figure 1. The amplitude, ε (in rad), of the uniform white noise, *U*, was applied to the system. Ten trials of 300 strides were simulated for each of 6 perturbation amplitudes ($0 \le \varepsilon \le 0.1$). All trials simulated walking down a slope of angle $\gamma = 0.009$ rad, which corresponded to a stable period-1 limit cycle.

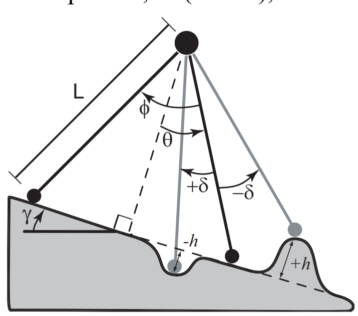


**Fig 1:** Random perturbations applied to leg angle at heelstrike.

Since Floquet theory assumes the system is purely periodic, the data for each stride were normalized to 101 samples (0% to 100%). Orbital stability was quantified by calculating the Floquet Multipliers (FM) based on standard techniques [1-4]. For an orbitally stable system, these complex-valued FM must lie inside the unit circle. We extracted the maximum FM occurring at any point in the gait cycle, then performed a linear regression between the Max FM and the perturbation, ε. Because the system can only be as stable as when it is most unstable, Max FM is important for determining the system's overall stability.

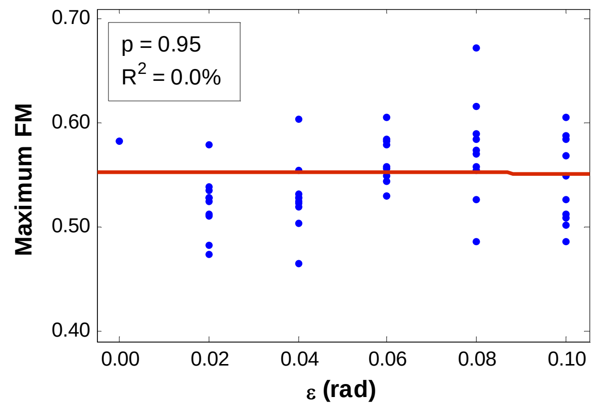


**Fig 2:** Linear regression between ε and both the largest maximum FM occurring at any point in the gait cycle.

## RESULTS AND DISCUSSION

The PDW remained orbitally stable (Max FM < 1) across all perturbation magnitudes. The maximum FM remained constant as ε were increased (Fig 2). By contrast, mean kinematic variability increased exponentially with ε (not shown). The FM values were also similar to those from human walking and also support our hypothesis that orbital stability is inherent to the system itself.

## CONCLUSIONS

By examining how orbital stability varies as the surface bumpiness of walking increases, we can better understand walking stability. Our results imply that walking stability can be studied without using a wide range of perturbations.

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## ACKNOWLEDGEMENTS

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# Stability of Passive Dynamic Walking on Uneven Terrain

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## INTRODUCTION

We present a stability analysis for passive compass gait walkers on uneven (rough) downhill terrain. Although deterministic definitions of stability do not apply, for sufficiently low levels of noise the resulting dynamics are governed by a stochastic convergence to a "metastable" (long-living) limit cycle. For unbounded noise models (e.g. Gaussian), the walker will eventually exit (or "escape") from this metastable cycle with a probability of one as time goes to infinity, entering an absorbing state (falling or standing still). Experimental walking machines are subject to similar random disturbances; statistics of the associated stochastic process, such as the mean first passage time (MFPT) to a fallen state, may be the correct way to quantify walking stability.

## METHODS

The data presented here come from Monte Carlo simulations of the equations of motion for a 2D compass gait (CG) as it walked down an uneven slope. Each simulation run began with a particular double-stance initial condition, and histograms of the number of success steps taken were recorded and used to estimate the MFPT as a function of the initial state. The CG has a mass, $m_h$, at its hip and a mass, $m$, at distance $a$ measured from the toe along each unit-length leg ($L$=1); ground collisions were modeled as inelastic. The ground slope between the stance and swing leg at each collision had a Gaussian distribution, with a mean slope of 4 degrees. We compare two walkers, listed in Table 1.

## RESULTS AND DISCUSSION

Figure 1 shows the deterministic basin of attraction (top) and a map of initial state dependence for MFPT (the "stochastic basin of attraction"), for walker #1 on terrain with a std of 0.5°. Along the ridge of the stochastic basin, the MFPT is about 20 steps. Qualitatively, the stochastic basin resembles a low-pass filtered version of the deterministic basin; it identifies how "safe" states are relative to each other. The deterministic basin for walker #2 (not shown) is wider than that of #1, and this walker is also not as sensitive to noise in ground slope. For a std of 1°, the MFPT for walker #2 is about 150 steps, compared to about 6 steps for walker #1.

For a std of 0.5 deg, the failure or "leakage" rate (the inverse of the MFPT) from the metastable basin for walker #2 is empirically so slow that Monte Carlo estimation seems impractical. We are developing algorithms to efficiently estimate the entire FPT distribution for these systems by discretizing the state-space and writing the stochastic step-to-step return map as a Markov chain. Iterating the transition matrix of the Markov chain can produce the entire first passage time distribution, and the *mean* FPT can be calculated directly (no iterations) from the transition matrix.

**Table 1:** CG geometry and MFPTs on uneven terrain.

| | $m_h/m$ | a (m) | MFPT: std .5° | MFPT: std 1.0° |
|---|---|---|---|---|
| walker #1 | 2.0 | .6 | 20 | 6 |
| walker #2 | 0.3 | .7 | >>100,000 | 150 |

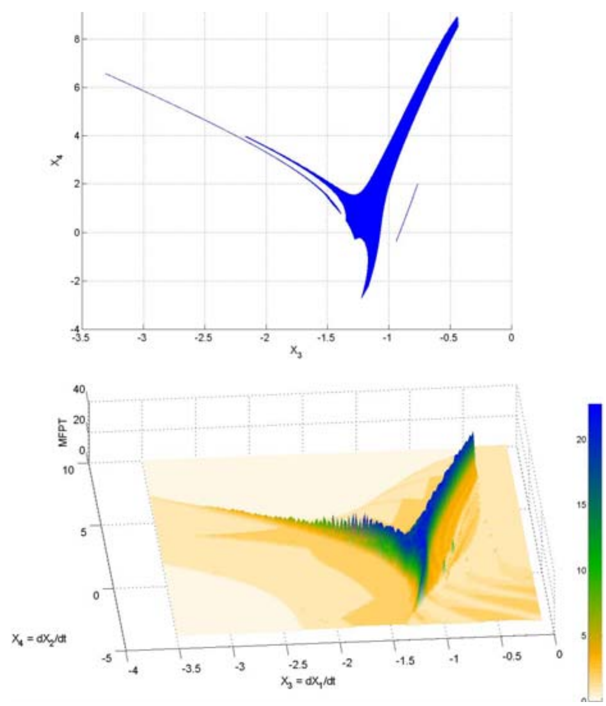


**Figure 1**: Deterministic basin of attraction (top) and a plot of MFPT (bottom) for walker #1. x-y axes are the stance leg and inter-leg angle velocities (rad/s), $X_3$ and $X_4$, for a post-collision initial condition on a 4 degree slope with an inter-leg angle of approximately 33.4°.

## CONCLUSIONS

The concept of metastability can be used in modeling of a variety of stochastic noise sources (uneven terrain, elasticity of ground collision, disturbance forces and torques, etc.). The MFPT provides a way of comparing the relative stability of different mechanical passive designs, and it can also be used in optimizing actively-controlled walkers based on passive dynamic principles. In our own research group, for instance, this metric has particular significance as a goal for optimization in reinforcement learning.

## Running over rough terrain

Monica Daley
Concord Field Station, Harvard University

Legged animals routinely negotiate rough, unpredictable terrain with agility and stability that outmatches any human–built machine. Yet, we know surprisingly little about how animals accomplish this, because our knowledge is largely limited to studies of steady movement. These have revealed fundamental mechanisms used by all terrestrial animals for steady locomotion. However, it is unclear whether these models provide an appropriate framework for the neuromuscular and mechanical strategies used to achieve dynamic stability over rough terrain. Perturbation experiments shed light on this issue, revealing the interplay between mechanics and control. We measured limb mechanics of an avian biped, the helmeted guinea fowl (Numida meleagris), running over an unexpected drop in terrain, comparing the bird's response to predictions of the mass-spring running model. Surprisingly, although limb stiffness varies dramatically, it does not influence the response dynamics. Instead, automatic adjustment of limb contact angle explains 80% of the variation in stance phase limb loading following the perturbation. This experimental result supports a recent extension of the mass-spring model, although it differs from previous findings on humans hopping and running over surfaces of varying compliance. Additionally, guinea fowl sometimes deviate from mass-spring dynamics through posture-dependent limb actuation, leading to substantial energy production or absorption following the perturbation. This allows rapid energy management when the limb's interaction with the ground suddenly changes. Evidence from joint dynamics and in vivo muscle measurements suggest that posture-dependent limb actuation results from the intrinsic mechanics of the ankle extensor muscles. This suggests a simple extension of the mass-spring model that provides inherent stability and velocity control of running over rough terrain.

## Concepts and philosophy for a highly dynamic biped

Jonathan Hurst
Carnegie Mellon University

We seek to understand principles of legged locomotion and apply those principles to robotics. To test our understanding of several principles, we are designing and building a robot to be capable of running, walking, jumping, and hopping in an efficient and robust manner.

Our primary focus, which is often ignored in legged robot design, is the dynamic behavior of the mechanical system. Our robot will be built with close attention to the details of mechanical dynamics, in an effort to create an integrated control system made up of mechanical and software components seamlessly working together. Specifically, we believe that a large mechanical leg spring is necessary for running, and that control of the spring stiffness is important. For a realistic ballistic walking gait, a passive leg swing may be important.

This talk will discuss the conceptual ideas behind the biped we are building, show some background work, and provide a brief preview of the biped mechanical design.

# Design and Control of a Running Biped with Pneumatic Artificial Muscles

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## INTRODUCTION

We humans utilize body compliance provided by antagonistic muscles to realize dynamic locomotion such as running and jumping. In this paper, we introduce design of a biped driven by antagonistic pairs of artificial pneumatic muscles so that the robot can change compliance according to the desired locomotion. We propose simple controllers for realizing such dynamic motions. We report several experimental results on its walking, jumping, and running.

## DESIGN OF A WALKING/RUNNING BIPED

We have designed a biped "Que-Kaku-R" driven by antagonistic pairs of pneumatic actuators (Figure 1). Its height, width and weight are 0.9[m], 0.26[m], and 6.0[kg], respectively. It has 5 degrees of freedom: 1 hip, 2 knees and 2 ankles so that it can jump and run. Every joint is driven by a pair of antagonistic pneumatic muscles. The supplied air pressure is 0.6 [MPa]. It has two touch sensors on its feet to sense the impact.

## WALKING, JUMPING, AND RUNNING EXPERIMENTS

We basically adopt a walking controller utilizing passive dynamics [1]. A sequence of valve operation is pre-programmed, and it is initiated by the touch sensation of the feet. Control parameters such as duration of opening a valve is determined by trial and error. A walking sequence is shown in Figure 2.
For jumping and running, we adopt the same strategy with different control parameters. Figure 2 and 3 show sequences of jumping and running, respectively. It can realize fully dynamic motions by effectively utilizing its dynamics and compliance of the pneumatic actuators.

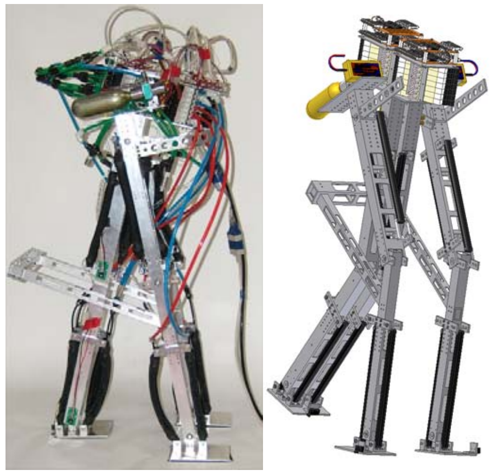

**Figure 1**: A Biped robot "Que-Kaku-R" that can walk and run.

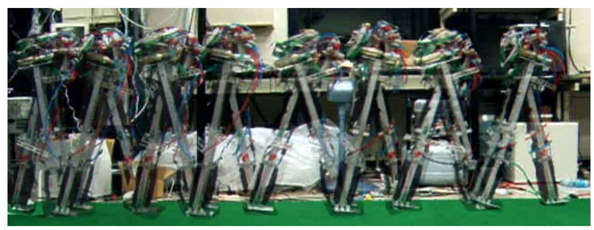

**Figure 2**: A walking sequence

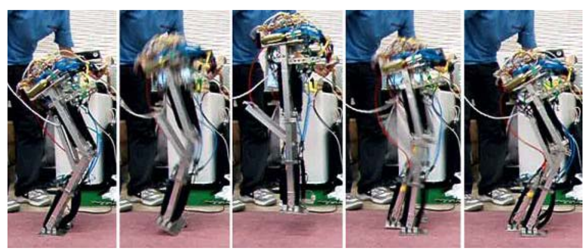

**Figure 3**: A jumping sequence

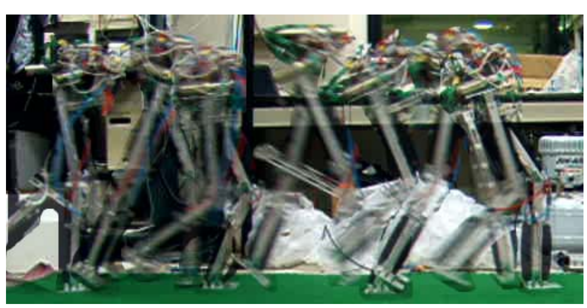

**Figure 4**: A running sequence

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## Biarticular spring action during walking

Jesse Dean
University of Alberta

Passive dynamic walking can be powered by push-off impulses applied along the trailing leg in both straight-legged models and following the addition of knees. In these models, walking speed is determined by the magnitude of the push-off impulse, which controls the length of the steps. However, the step frequency remains relatively constant across walking speeds, at stepping rates lower than those typically seen in human gait. We have previously shown that the step frequency can be increased to human-like values through the addition of passive torsional springs at the hip and knee. We propose that biarticular springs crossing both the hip and knee can also be used to increase step frequency. Walking simulations were performed using a planar kneed model, consisting of four segments with anthropometrically distributed mass. The model was powered by push-off impulses, and tuned by linear springs with attachment points above the hip and on the contralateral shank below the knee. The moment arms about the hip and the knee were determined by the attachment points. We found that step length was predominantly governed by push-off impulse, while step frequency was controlled by the biarticular spring stiffness and the moment arm about the hip. At higher walking speeds, a non-zero moment arm about the knee was required to ensure that knee lock occurred before foot touchdown. Stable gaits at typical human speeds and step frequencies (1.2 m/s, 1.8 Hz) were generated for a range of parameter values. Peak spring forces were minimized by choosing the smallest knee moment arm for which knee lock still occurred before touchdown. The addition of biarticular springs to a simple walking model allowed the generation of gaits powered solely by push-off impulses, with joint angles and moments similar to those seen during normal human walking.

# PASSIVE ELASTIC JOINT MOMENTS DURING HUMAN WALKING

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## INTRODUCTION

Both passive and active components contribute to the joint moments used during walking. In particular, it has been suggested that passive elastic mechanisms acting about the hip may serve as an efficient energy storage and release mechanism [1]. The purpose of this study was to quantify the contributions of passive elastic mechanisms to the net power absorbed and generated at the hip during human walking.

## METHODS

Four healthy young adults participated in the study. Passive joint moments were measured in a side lying position. A subject's dominant lower limb was supported on a table via low friction carts placed under the medial side of the thigh and leg. A physical therapist slowly manipulated the limb using hand-held 3D load cells. Six trials were performed in which the full hip and knee range of motions were traversed. Lower extremity kinematics were collected using a passive motion capture system. EMG signals were monitored to ensure that muscles remained relaxed. Subjects were then asked to walk at a comfortable speed across an instrumented walkway, with kinematics recorded using the same marker set as in the passive testing.

Measured forces and motion data were used to compute the hip, knee and ankle joint angles and moments. Double exponential functions, that accounted for the stretch of both uni- and bi-articular muscles, were used to describe the passive hip moment as a function of hip and knee angles [2]. With joint angles as inputs, these relationships were then used to estimate the hip moments during walking that could be attributed to passive-elastic mechanisms. Joint moments were dotted with the joint angular velocities to compute joint powers, and subsequently integrated to compute work quantities.

## RESULTS

A substantial portion of the net hip moments and powers during walking were attributable to passive components (Fig. 1). Energy was stored passively from heel contact until peek hip extension was reached during late stance, with much of the energy absorbed during the net hip power absorption phase H2. Passive elastic energy was then released during pre-swing as a component of the positive hip power burst H3. Mean net and passive works done during H3 were 0.1511 J/kg and 0.0539 J/kg, respectively.

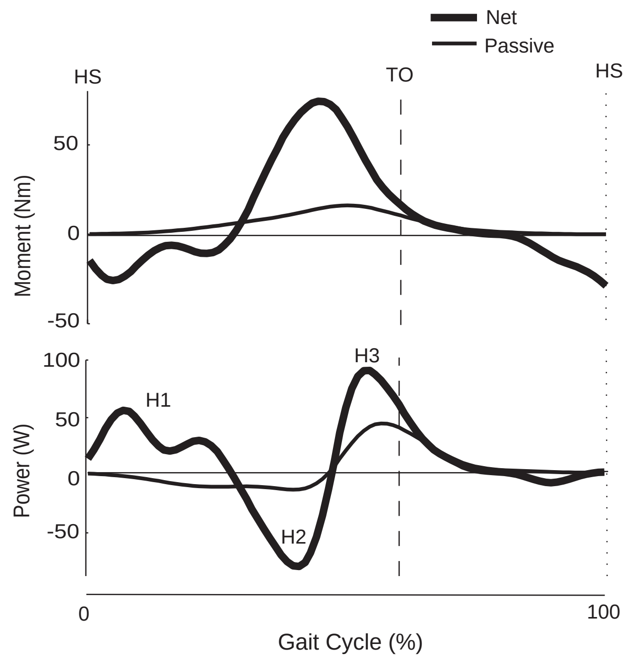


**Figure 1**: Representative estimates of the net joint moments and powers attributable to passive elastic mechanisms over a gait cycle.

## DISCUSSION

Our results provide quantitative support for the suggestion that passive elastic mechanisms about the hip are utilized during human walking [1]. This mechanism reduces the amount of the pre-swing hip power burst that must be generated actively to initiate leg swing. On average, the positive work attributable to passive elastic mechanisms during H3 was estimated to be 36% of the net positive work. It is important to note that our analysis did not include a slight hysterisis in the passive moment-angle data, which would act to reduce the energy returned. Future studies will consider how neuromuscular changes (e.g. hip contractures) associated with aging affect the usage of passive elastic mechanisms during walking [3].

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## ACKNOWLEDGEMENTS

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# Suggested Invariance of the Human Knee-Ankle-Foot Roll-over Shape for Level Ground Walking

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## INTRODUCTION

Rockers are commonly used as feet on passive dynamic walking machines [1,2] and in models of human walking [3]. A recent method was developed to measure the effective rocker shape that the able-bodied knee-ankle-foot (KAF) system conforms to during walking [4]. We call the resulting rocker the KAF *roll-over shape* (ROS). This abstract describes the results of three studies that were conducted in an effort to see how the ROS changes with different conditions of level ground walking. The conditions examined were changes in walking speed [4], the use of shoes with different heel heights [5], and the carriage of different loads on the trunk [6]. We found that the KAF ROS keeps nearly the same radius and forward shift location on the leg under all conditions studied. This finding suggests that the human adapts to small changes occurring in level ground walking to maintain an invariant KAF ROS. We have used this finding to develop a prosthetic foot for low-income countries [7] and to describe the process of trans-tibial prosthesis alignment [8].

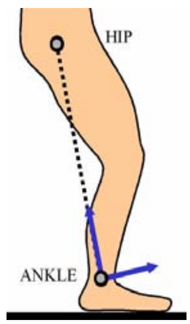


**Figure 1**: Leg-based coordinate system.

## METHODS

(1) Twenty-four able-bodied subjects participated in a study investigating the effects of walking speed on the KAF ROS. Subjects walked at three self-selected speeds (slow, normal, and fast). (2) Ten able-bodied women participated in a study investigating the effects of shoe heel height on the KAF ROS. Subjects walked with three shoes they considered to be low-heel, mid-heel, and high-heel. (3) Ten able-bodied subjects participated in a study investigating the effects of load carriage on the KAF ROS. Subjects walked with no added load, 25 pounds of added load, and 50 pounds of added load. In all three studies, gait data were acquired and the KAF ROSs were measured by transforming the center of pressure of the ground reaction force into a coordinate system based on the leg (shown in Figure 1) between heel contact and opposite heel contact. The ROSs were fitted with circular arcs and the radii and the anterior location of the arc's nadir in leg coordinates were examined as functions of speed, heel height, and added weight.

## RESULTS AND DISCUSSION

Radii of all roll-over shapes measured are shown in Figure 2 as functions of speed, heel height, and added weight. The radii do not appear to change with any of the three conditions. The anterior location of the arc's nadir is also unchanged with speed, heel height, and added weight. The median radius from all three studies tended to be about 0.16 times the height (or about 0.3 times leg length).

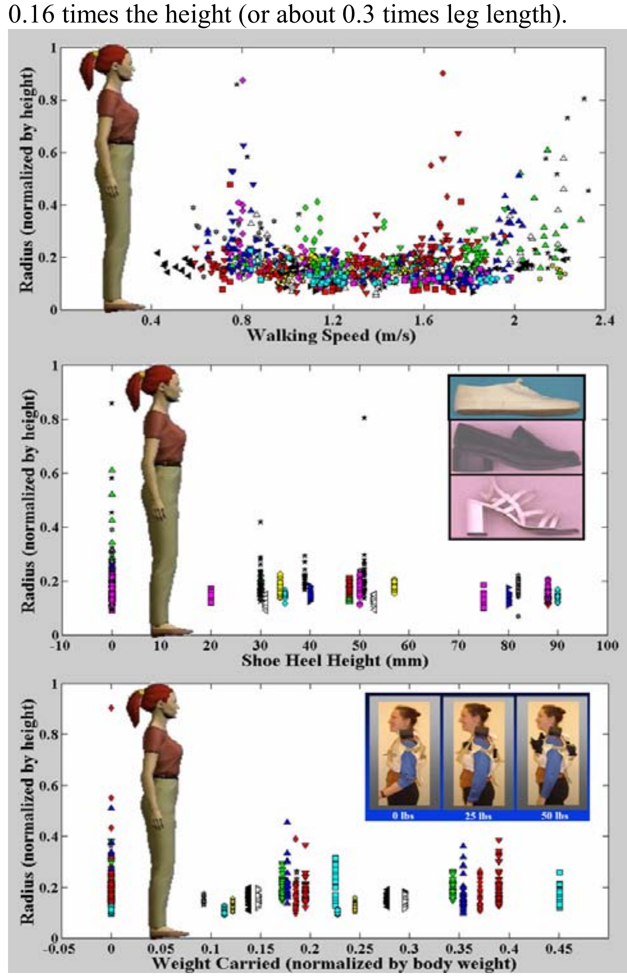


**Figure 2 –** Radii of best-fit circular arcs to KAF ROSs as functions of speed, heel height and weight carried.

## CONCLUSIONS

Humans appear to adapt to changing conditions of level ground walking to maintain an invariant KAF ROS. McGeer's prediction that humans use a radius of 0.3 times leg length [1] is supported by our findings.

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## The advantages of a rolling foot in human walking

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In human walking, the leg supports the body much like a rigid strut, atop a foot-ankle complex that effectively "rolls" on the ground. The circular "roll-over shape" most similar to the natural foot (radius 0.3 times leg length) is largely invariant to gait parameters such as speed, carried load, and footwear. Using a simple Dynamic Walking model, we investigated the effects of changes to the size and position of round feet on the predicted mechanical costs of walking. Closed-form results from the *simplest model* predict that the negative work $W$ performed on the model's COM should fall with increasing roll-over radius $\rho$, $W \propto (1-\rho)^2$. Simulation results confirm this prediction, but demonstrate that increasingly anthropomorphic models may exhibit an energetic minimum, depending on the details of mass distribution, geometry, and step-to-step transition powering. To test the simplest model's prediction, we fixed human subjects' ankles in a neutral position and interchanged different-sized soles of circular profile on the bottom of their feet. We measured mechanical work performed on the COM and metabolic cost during walking with soles of different radii. Results show that COM negative work $W$ falls with increasing roll-over radius $\rho$ as predicted by the *simplest model*, $r^2 = 0.95$. Metabolic cost also falls with low, increasing radius, but it rises again after reaching a minimum for radius close to that of the natural roll-over shape. Metabolic cost may diverge from measured COM work because metabolic measurements include other costs, such as joint stabilization and balance. We conclude that the *simplest model* is a good predictor of the mechanical cost of walking, but metabolic cost only follows trends in work when gait changes do not affect other demands on the body.

## Electrifying aspects of human walking

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University of Pennsylvania

We developed the Suspended-load Backpack which converts mechanical energy from the vertical movement of carried loads (20-38 kg) to large levels of electricity during normal walking (up to 7.4 W). Unexpectedly, little extra metabolic energy (compared to a rigid backpack) is required during electricity generation. This is likely due to a compensatory change in gait or loading regime which reduces the metabolic power required for walking with a load. Indeed we found that the forces exerted on the body as well as the vertical fluctuation of the center of the hip were significantly lower during walking with the electricity-generating backpack. The electricity generation can help provide field scientists, explorers, and disaster-relief workers freedom from the heavy weight of replacement batteries, and thereby extend their abilities to operate in remote areas. This level of electricity can also provide unexpectedly large health and societal benefits for people in developing countries who live off the electric-grid. For instance, a scourge in these villages is the contaminated drinking water. SteriPen is a low power portable UV light device, which can kill the microbes in a 0.5 liter of water using only 225 Joules of electricity (5W for 45 s) is easily powered by the backpack and a rechargeable battery.

# Estimation of leg stiffness in human locomotion

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## INTRODUCTION

It is possible for humans to alter the stiffness of their leg spring during hopping and running [1]. For these kinds of movements one simple linear leg spring is sufficient to describe the effective behavior of the musculo-skeletal system. Adding another linear spring to the model has been shown to predict the mechanics of walking very well [2].

Different calculation methods using experimental data can result in different outcomes of leg stiffness. Also, the time and effort to collect kinematic and kinetic data is not always feasible.

Goal of this research is a) to present vertical stiffness and leg stiffness in human walking and b) to discuss different calculation methods to determine leg stiffness, especially from easy accessible parameters like step frequency and contact time.

## METHODS

We collected 3D kinematic and kinetic data on 21 subjects, who were asked to walk on an instrumented treadmill at different speeds related to their preferred transition speed. For each contact the vertical displacement of the center of mass (CoM) was calculated by twice integrating the vertical acceleration derived from the ground reaction force (GRF). Total vertical GRF was then plotted over CoM displacement for each walking contact to represent vertical stiffness ($k_{vert}$). Leg length was defined as the distance between CoM and center of pressure (CoP). Leg stiffness related leg force ($F_{leg}$) and leg shortening (Δleg).

To test for parameters suitable for easier determination of leg stiffness, we calculated a range of stable areas within the k-α space (leg stiffness k, leg angle α) using a spring-mass model [3]. Within the stable region we calculated the gradients of the predicted parameters step frequency (f) and contact time ($t_c$).

## RESULTS AND DISCUSSION

The stiffness plot from experimental data showed a kink where double and single support exchange. A very similar kink in the vertical stiffness predicted by the spring-mass model for walking strongly supports the idea of higher stiffness as a consequence of two springs in parallel during double support.

The gradients of step frequency and contact time within the k-α space were almost perpendicular with respect to each other in a large range of leg stiffness typical for human locomotion. This indicates that for a given forward speed leg stiffness and angle of attack can be estimated by simply measuring step frequency and contact time.

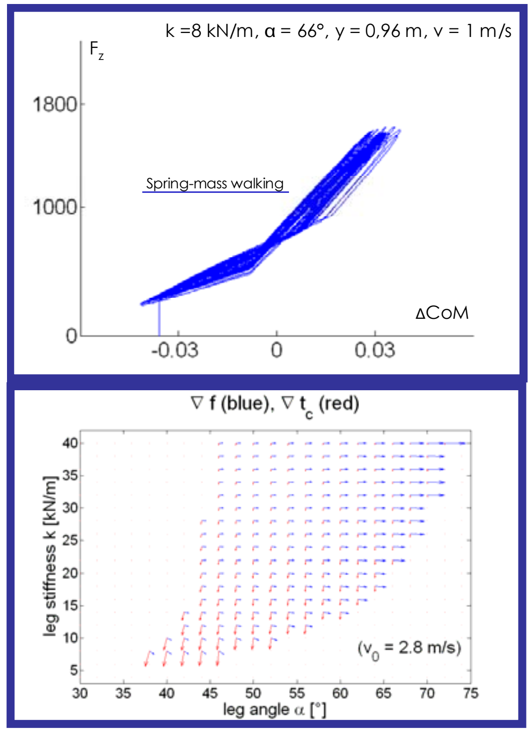


**Figure 1:** (Top) vertical force-length relation representing vertical stiffness of the spring-mass model for walking at 1m/s. (Bottom) gradients of step frequency (f) and contact time ($t_c$) within stable k-α solutions

## CONCLUSIONS

The assumption of spring-like leg behavior results in similar vertical force-length curves as observed in human walking. Several methods do exist for estimating leg stiffness. For a given forward speed, leg stiffness could be approximated by measuring only two parameters: step frequency and contact time. A detailed analysis of this method based on experimental data will provide deeper insights about the limits of this approach.

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## A telescoping inverted pendulum model directly applied to normal and pathological gait

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In clinical gait analysis, we strive to understand contributions to body support and propulsion as this forms a basis for treatment selection, yet the relative importance of gravitational forces and joint powers can be controversial even for normal gait. We hypothesized that an inverted pendulum model, propelled only by gravity, would be inadequate to predict velocities and ground reaction forces during gait (Buczek et al., Clinical Biomechanics, 21, 288-296, 2006). Unlike previous ballistic and passive dynamic walking studies, we directly compared model predictions to gait data for 24 normal children. We defined an inverted pendulum from the average center-of-pressure to the instantaneous center-of-mass, and derived equations of motion during single support that allowed a telescoping action. Forward and inverse dynamics predicted pendulum velocities and ground reaction forces, and these were statistically and graphically compared to actual gait data for identical strides. Results of forward dynamics replicated those in the literature, with reasonable predictions for velocities and anterior ground reaction forces, but poor predictions for vertical ground reaction forces. Deviations from actual values were explained by joint powers calculated for these subjects. With a telescoping action during inverse dynamics, predicted vertical forces improved dramatically and gained a dual-peak pattern previously missing in the literature, yet expected for normal gait. These improvements vanished when telescoping terms were set to zero. Because this telescoping action is difficult to explain without muscle activity, we believe these results support the need for both gravitational forces and joint powers in normal gait. Our approach also begins to quantify the relative contributions of each. A similar study of pediatric patients with cerebral palsy is in progress.

# DISCOVERY OF PENDULUM AND SPRING DYNAMICS IN THE EARLY STAGES OF WALKING*

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## INTRODUCTION

We propose that, during early practice toddlers are exploring their *dynamic resources* as they discover a range of solutions for 'getting from here to there.' Dynamic resources can be categorized as force-producing capabilities of muscle, the conservation mechanisms of soft tissues (i.e., the potential to store and return of elastic energy of muscles and tendons) and the conservation due to the energetics of the body within the gravitational field (i.e., the pendular transfers of kinematic and potential energy of the whole body and its segments). Emergent movement patterns reflect the individual's utilization of their available dynamic resources.

To capture the dynamic resources the body is modeled as an inverted pendulum with a global spring, driven by an escapement (EDIPS) (Holt et al. 2000). The purpose of the study was to determine if the profound improvements in gait in the earliest stages of walking was due to the discovery of the appropriate escapement estimated from the acceleration profiles of the body COM.

## METHODS

Seven toddlers who had just learned to walk (no more than 6 steps) walked overground and on seven monthly visits. Motion analysis was used to collect data on kinematics of each body segment (Peak Motus).

Center of mass for the whole body was calculated using a seven-segment model (Jensen, 1986). Angular acceleration of the COM around the ankle joint was calculated. Power was estimated by the power spectral density of the peak COM angular accelerations; time difference between initial foot contact and peak COM acceleration; Integrated COM angular acceleration amplitude during double support were calculated.

## RESULTS AND DISCUSSION

All children failed to display an inverted pendulum gait on the first visit. The spectral power was distributed across multiple frequencies suggesting multiple escapements. By the second visit, all subjects displayed a pendulum gait. The subject's dominant frequency was either at the step or stride frequency suggesting a single escapement.

After the first visit, peak acceleration of the COM occurred just after ground contact in which it would have the most adaptive propulsive effect (fig 1), and positive integrated COM angular acceleration amplitude (fig 2) further suggest an appropriately timed and directed escapement.

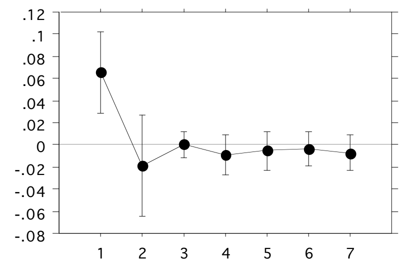


**Figure 1**: Time difference between initial contact (Tic) and peak acceleration of COM (Tpa) (y-axis), and the testing sessions (monthly after visit 1) (x-axis).

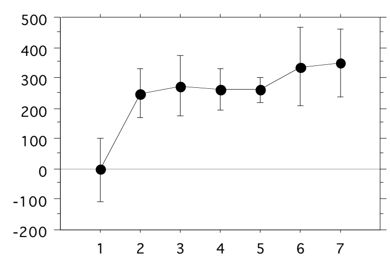


**Figure 2**: Integrated peak angular acceleration of the COM (y-axis), and the testing sessions (x-axis)

## CONCLUSIONS

The parallel between the passive dynamic walking robots with footswitch-driven actuators of the ankle plantar flexors (Collins, 2005) and the current findings for children's locomotion are remarkable and exemplify the rich potential for collaborations between disciplines in the research on locomotor systems that are passively driven. In anticipation, we would emphasize the power of anatomical constraints in human design in optimizing and stabilizing the locomotor system that could be instantiated in robotic design. Conversely, the simple switch used in design of passive robots may be informative of the simplicity with which human neural control of locomotion might be achieved.

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# An integrative view on legged locomotion obtained from the bipedal spring-mass dynamics

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## A view that separates walk-run dynamics

Do walking and running share similar dynamics? In the classical picture, they do not; rather, it is assumed that the two gaits reflect two contrasting mechanical concepts of legged locomotion: walking is considered as vaulting over stiff legs; and running, as rebounding on compliant legs with intermittent flight phases [1].

These two concepts are idealized by the inverted pendulum model for walking and the simple spring-mass model for running. Both models much advanced our understanding of legged locomotion; but they also showed that whereas rebounding on compliant legs well explains the dynamics observed in running, stiff-legged vaulting cannot truly reproduce that of walking [2].

This discrepancy is mainly related to the double support, which, because it requires leg compression, can not be addressed with an inverted pendulum. Indeed, more complex models that (partially) include the double support describe the dynamics of walking much closer than the inverted pendulum model [2]; conceptually, however, compliant leg behavior remained to be regarded as additional but not essential to the walking motion.

## A model that contradicts the classical view

In contrast to this classical view, we could recently show that not stiff but compliant legs are essential to obtain walking mechanics [3]: with the simplest walking model that includes leg compliance, a bipedal spring-mass model, we could reproduce the characteristic walking dynamics that result in the observed small vertical oscillation of the body and the observed out-of-phase changes in forward kinetic and gravitational potential energies (left and center panel in Figure 1).

This result challenges classical views about walking efficiency and the origin of the walk-run transition, which both are based on the stiff-legged motion as mechanical concept underlying the walking gait. It moreover demonstrates that the dynamics of walking and running can be united within one mechanical concept that is based on compliant leg behavior (Figure 1).

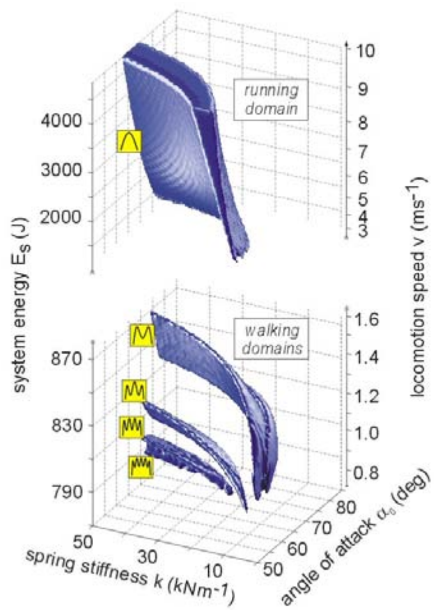


**Figure 2**: Parameter domains for stable locomotion include steady-state dynamics that, from fast to slow speeds, range from the single-peak running pattern to an infinite number of multi-peak walking patterns.

## A view that integrates walk-run dynamics

But the bipedal spring-mass model not only combines walking and running dynamics in one simple but compelling mechanical template, it also suggests that both gaits are just two members out of a family of stable solutions to legged locomotion that share similar dynamics (Figure 2).

This integrative view on the walk-run dynamics may change our intuition about legged locomotion, for instance, about the origin of gait transitions. Moreover, it could trigger the development of (nearly) passive dynamic robots that walk and run.

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## Acknowledgements

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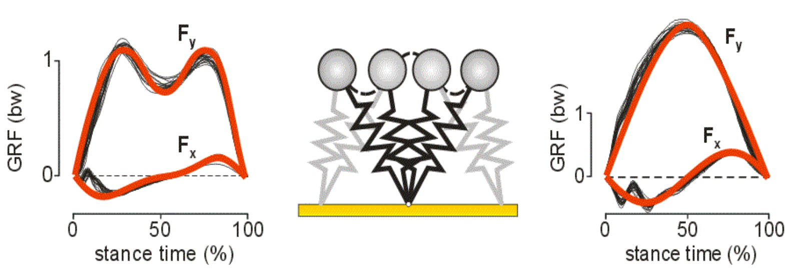


**Figure 1**: The bipedal spring-mass model (center) explains walking (left) and running dynamics (right). Thick red lines: ground reaction forces (GRF) predicted by the model; thin lines: experimental GRF traces (Fx and Fy: horizontal and vertical GRF measured in body weight, bw).