Neuromuscular control adaptation in gait due to injury: A motivating study using a simplified dynamic model

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Symposium on Control and Modeling of Biomedical Systems
April 22-23, 2010 · Urbana, IL, USA

Introduction:

Gait pathologies and injuries result in significant changes to the motion output [1], but the corresponding neuromuscular control changes are more difficult to measure or interpret [*e.g.*, 2]. The goal of this work is to motivate the study of neuromuscular control adaptation due to injury using a simplified dynamic model.

A fundamental hypothesis is the existence of isolated discontinuous changes in the actuation strategies deployed by the neuromuscular control system in response to continuous changes in musculoskeletal physiology. Such discontinuities are common in nonlinear systems and could have immediate implications to rehabilitation strategies for maintaining functional gait.

Methods:

The plausibility of this hypothesis is investigated using a spring-mass-damper system sharing certain features with gait (**Fig 1&2**, **Table 1**):

- periodicity · symmetry · coupled DOFs
- distinct phases of motion · contact

Model:

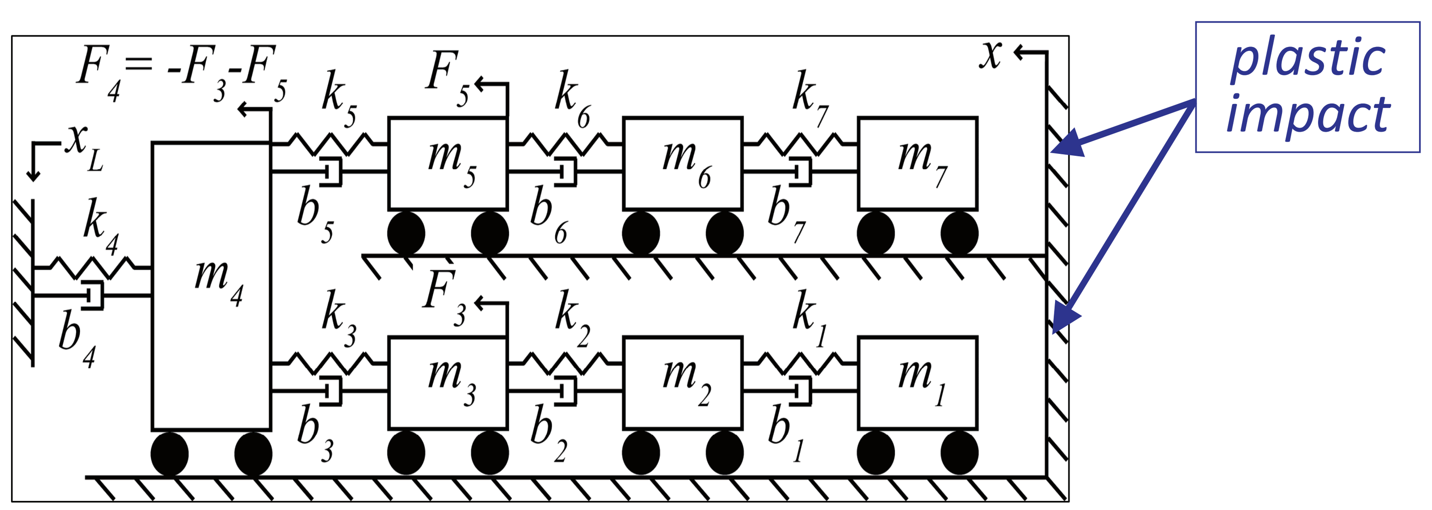

Fig 1: Coupled spring-mass-damper system

Table 1: Baseline parameters
(l = natural spring length)

Index	m_i	k_i	b_i	l_i
1, 7	0.15	2.5	1	0.5
2, 6	0.5	5	2	1
3, 5	1	1	1	1
4	1	2.5	5	1

Nonlinear spring constants emulate passive joint stiffness (adapted from [3], **Fig 2**)

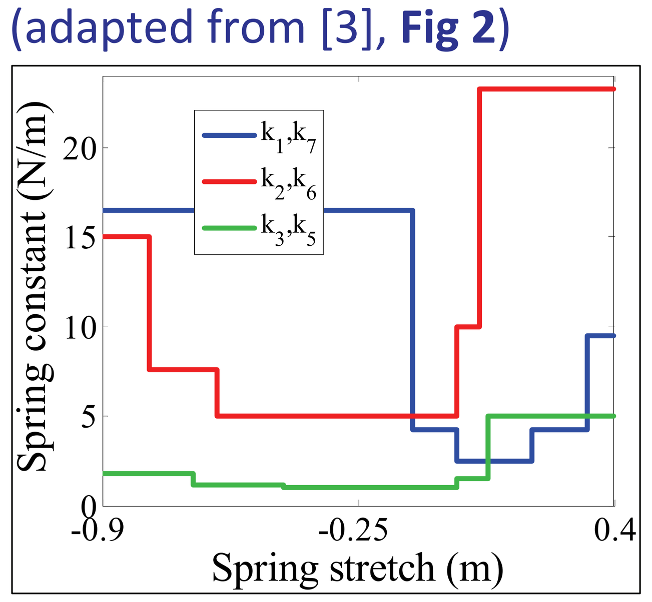

Fig 2: Flexion / extension spring stiffening parameters

Given the periodic forcing

$$F_i(t)=A_{i,1}\cos\left(2\pi t+\phi_{i,1}\right)+A_{i,2}\cos\left(4\pi t+\phi_{i,2}\right)$$

for $i\in\{3,5\}$, and $F_4=-F_3-F_5$,

· aside: this forcing creates input similar to hip torque acting between pelvis and thighs

the state-space equations of motion are then of the form

$$\frac{d\boldsymbol{x}}{dt}=\boldsymbol{A}_\sigma\boldsymbol{x}+\boldsymbol{F}(t)$$

where the first 7 components of $\boldsymbol{x}$ are the positions of $m_1,\ldots,m_7$, and the remaining 7 are the corresponding velocities. The coefficient matrix $\boldsymbol{A}_\sigma\in\mathbb{R}^{14\times14}$ depends on the contact conditions, $\sigma\in\{1,2,3,4\}$, and the forcing is provided by $\boldsymbol{F}(t)$.

Implementation:

The procedure to investigate control adaptations due to 'injury' relies on numerical analysis and cost function optimization.

A reference periodic solution is identified (via *ode15s*) such that the motion of the lower masses is identical to that of the upper masses after a temporal shift of half a period.
– with values in Table 1, Fig 2, x_L = 3 (left wall), and $F_3=20\cos(2\pi t)$; $F_5=20\cos(2\pi t+\pi)$ –

Perturbation is implemented by increasing k_6 and b_6 in 0.05 increments up to a total change of 2, corresponding to a fully developed 'injury,' and by subsequently reducing these parameters back to their reference values.

After each parameter change, optimization is applied (via *fmincon*) to tune the forcing parameters $A_{i,j}$ and $\phi_{i,j}$ to minimize the cost function described below applied to the asymptotic steady-state response.

Goal function:

$$H=50H_{clearance}+H_{sym}\text{, where}$$

$$H_{clearance}=\left|H_{target}^{(1)}-H^{(1)}\right|+\left|H_{target}^{(7)}-H^{(7)}\right|,$$

$H_{target}^{(n)}$, $H^{(n)}$ are maximal limit points of baseline and current x_n trajectories, respectively, and

$$H_{sym}=\int_{t_0}^{t_0+T}\max\left\{\left|x_1(t)-x_7(t-T/2)\right|-0.001;\ 0\right\}dt$$

over one steady state period, T.

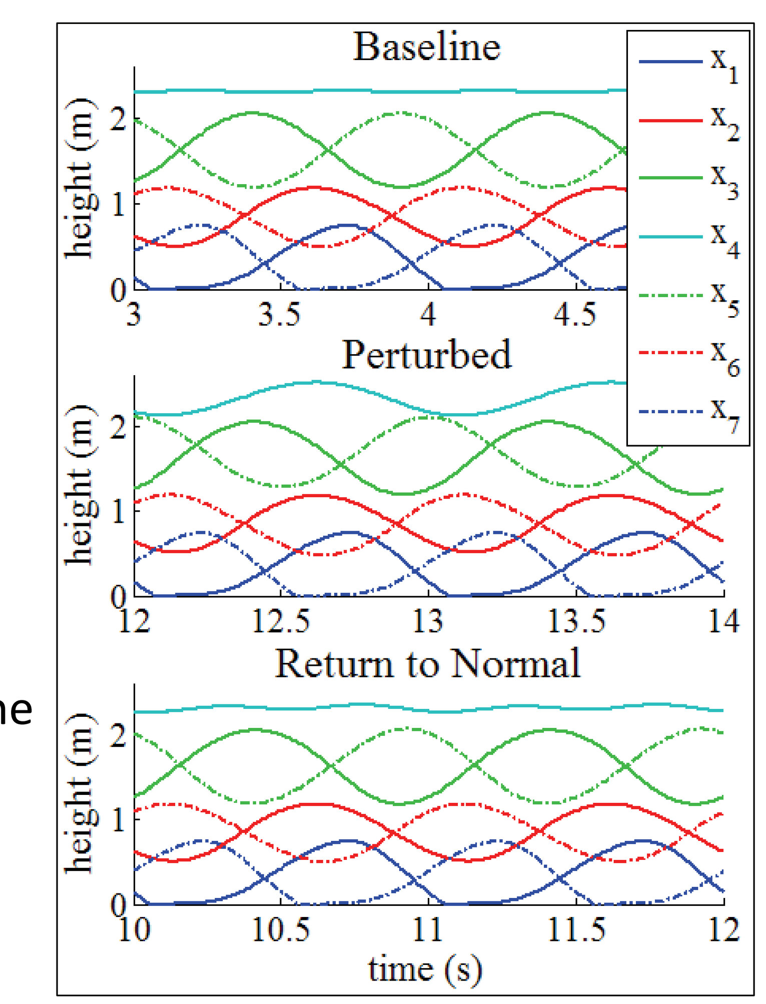

Fig 3: State trajectories

Results:

The resulting perturbed and returned-to-normal state trajectories compare well with the baseline system (**Fig 3**) but the forcing change is readily apparent (**Fig 4**).

Fully perturbed:

$F_3=20.93\cos(2\pi t)+1.90\cos(4\pi t+0.54)$

$F_5=21.58\cos(2\pi t+2.62)+2.08\cos(4\pi t+3.00)$

Return to baseline:

$F_3=20.15\cos(2\pi t)+3.27\cos(4\pi t+1.28)$

$F_5=19.91\cos(2\pi t+3.09)+3.40\cos(4\pi t+2.57)$

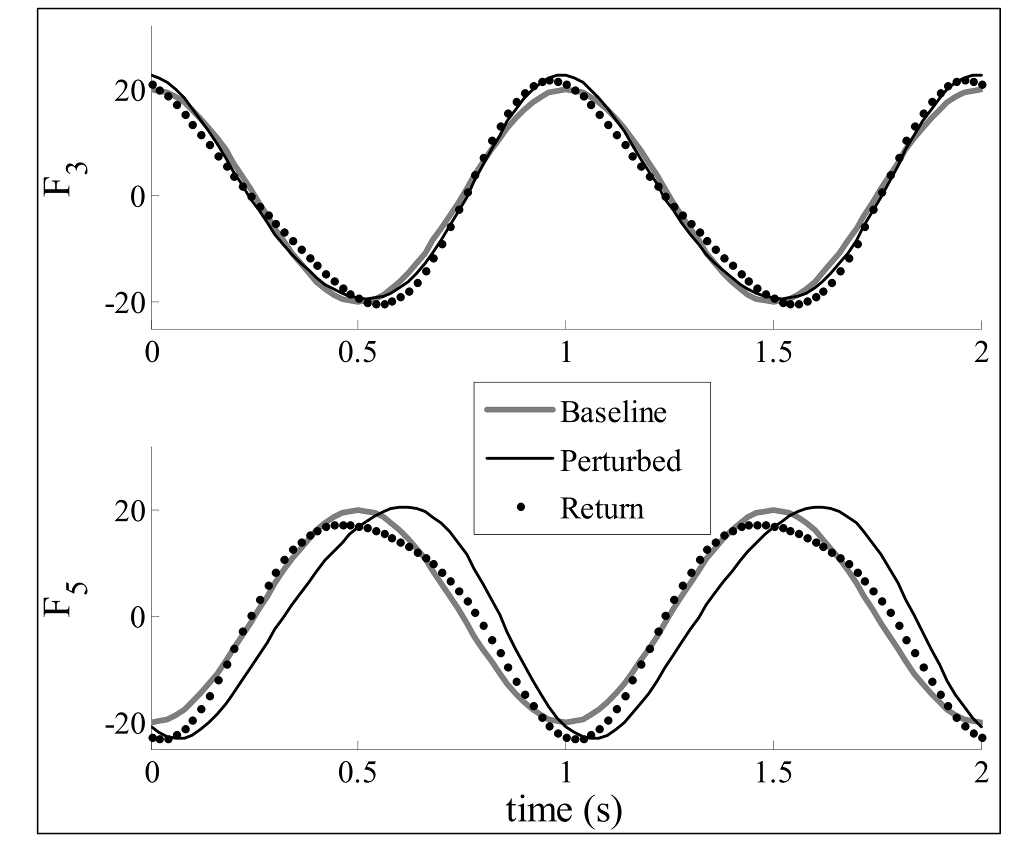

Fig 4: Forcing results for baseline, fully perturbed, and returned to baseline systems

Discontinuities were present in the forcing magnitudes throughout the parameter variation, including a hyster-esis effect in the second forcing mode (**Fig 5**).

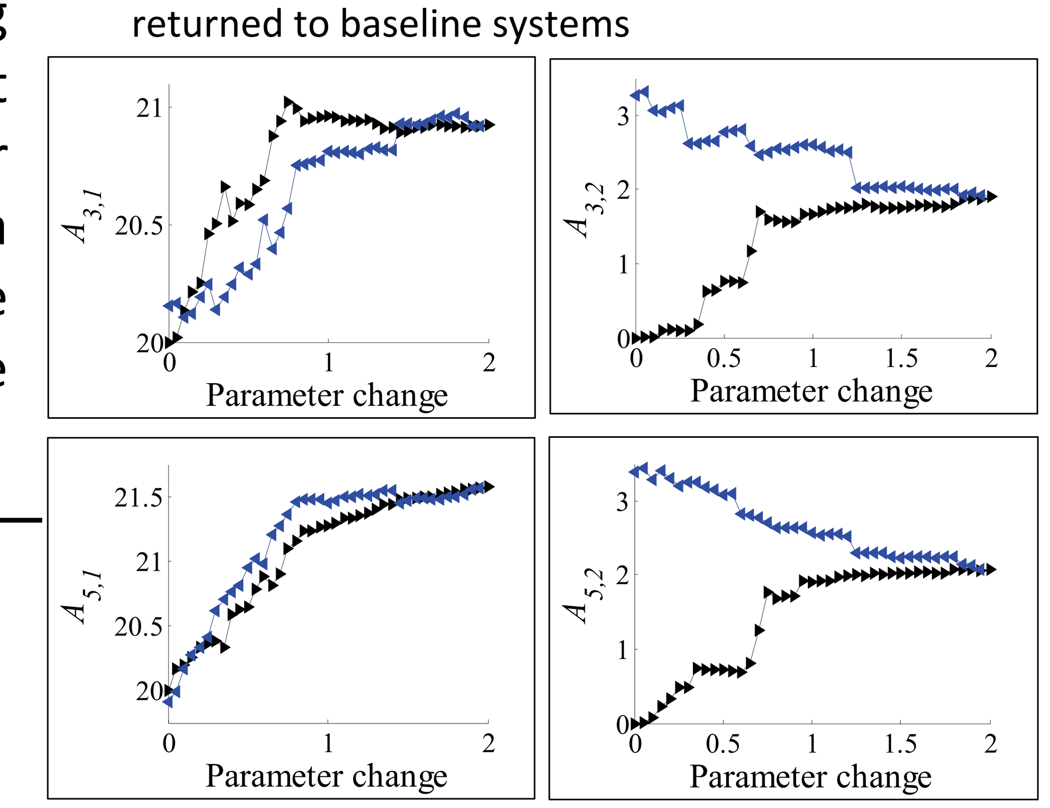

Fig 5: Forcing amplitude changes throughout iterations to and from perturbation

Discussion:

- Hysteresis demonstrates ability to settle on alternative control strategy during healing or rehabilitation
  - Second mode is needed to maintain symmetry of asymmetric system, but it did not "turn off"
- Discontinuities suggest certain phases of healing could lead to abrupt control changes.
  - Plausible since the musculoskeletal system is highly redundant with infinite possibilities to produce gait [4]

Acknowledgements:
National Science Foundation grant #0727083

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4. Bernstein, N. *The Coordination and regulation of movements*, Pergamon, 1967.