Neuromechanical adaptations in joint stiffness when hopping with a SL-AFO

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The human body is modeled to behave like a spring-mass system during bouncing gaits such as running and hopping.\textsuperscript{1-4,21,23} The leg’s stiffness influences:\textsuperscript{2,3,5-7}
- peak ground reaction force
- ground contact time
- center of mass displacement
- stride frequency
- “stiffness is the primary control variable in motor behavior.” \textsuperscript{9}
Basic Science Question:

Understand how local control variables are adjusted to maintain stable global tasks.\textsuperscript{11, 19-20}

during hopping leg stiffness (global task) is modulated at the ankle (local variable) with different pertubations:\textsuperscript{5-6,8}

[Farley et al, 1998]
Significance

Basic Science Question:

- Understand how local control variables are adjusted to maintain stable global tasks. \(^{11, 19-20}\)

- During hopping leg stiffness (global task) is modulated at the ankle (local variable) with different perturbations: \(^{5-6,8}\)

- An elastic element in series

[Ferris et al, 1997]
Significance

Basic Science Question:

Understand how local control variables are adjusted to maintain stable global tasks. ¹¹, ¹⁹-²⁰

- during hopping leg stiffness (global task) is modulated at the ankle (local variable) with different pertubations:⁵-⁶,⁸
  - an elastic element in series
Significance

- Basic Science Question:
  - Understand how local control variables are adjusted to maintain stable global tasks. \(^{11, 19-20}\)

- During hopping leg stiffness (global task) is modulated at the ankle (local variable) with different perturbations: \(^{5-6,8}\)

- An elastic element in parallel \(^{5}\)

[Ferris et al, 2006]
Hypothesis

**Hypothesis A:** When a spring is added in parallel to the leg to create a *plantar-flexor* torque, the effective leg stiffness will stay the same, but the biological ankle stiffness will *decrease*.

**Hypothesis B:** When a spring is added in parallel to the leg to create a *dorsi-flexor* torque, the effective leg stiffness will stay the same, but the biological ankle stiffness will *increase*.
Subjects‡:
- Inclusion Criteria: no major muscular or skeletal injuries, or neurologic conditions
- 10 Total: 6 Male, 4 Female
- Avg. Weight: 61.34 Kg (11.16) Avg. Age: 25.4 y/o (2.46)

Protocol:
- 3 conditions*: AFO, AFO w/ PFA, AFO w/PFR
- 3 frequencies for each condition**: 2.2 Hz, 2.4 Hz, and 2.8 Hz
- 3 trials for each condition-frequency combination
- 10 sec of hopping on Right Leg for each trial when frequency is reached
- ~30 hops were analyzed per condition

* 3 trials taken at preferred frequency with no AFO
** 3 trials taken at 2.2Hz with no AFO
‡INDEPENDENT VARIABLES

Instrumentation used: Vicon Motion Capture system, AMTI Force Plate, Konigsberg 8-channel bi-polar EMG, and an Omega Force Transducer

Statistical Methods
- Three-Way AVOVA: Repeated Measures
- Post-Hoc: Bonferroni
General Procedures:
Data Analysis

Dependent Variables:

**Leg stiffness** = Linear Regression ($\Delta \text{vGRF} / \Delta \text{COM}$)
- Units: N / m
- vGRF (from Force plate)
- COM = $\int \int \text{vGRF}/m\ dt^2$

**Total Joint stiffness** = Linear Regression ($\Delta \text{M} / \Delta \theta$)
- Units: Nm / rad
- M (inverse kinematics)
- $\Delta \theta$ (from Vicon)

**Orthosis Ankle Stiffness** = Linear Regression ($\Delta F_{FT} \times d_{sp} / \Delta \theta$)
- Units: Nm / rad
- $F_{FT}$ (force transducer)
- $d_{sp}$ (geometric model of spring moment arm)

**Biological Ankle Stiffness** = Total Ankle Stiffness – Orthosis Ankle Stiffness
- Units: Nm / rad
Normalized Leg Stiffness (N = 10)

- AFO
- PA-SLAFO
- PR-SLAFO

2.2 Hz: P = .745
2.4 Hz: P = .103
2.8 Hz: P = .762
Normalized Total Ankle Stiffness (N=10)

- AFO
- PA-SLAFO
- PR-SLAFO

P = .065

P < .001

P = .002

Normalized values at different frequencies:
- 2.2 Hz: 0.933, 0.904, 1.010
- 2.4 Hz: 1.067, 1.057, 1.149
- 2.8 Hz: 1.360, 1.292, 1.480
Study Limitations

- AFO may not be universally designed for all subjects
- Spring length predetermined for all subjects, rather than for each person
- Spring stiffness predetermined for all subjects rather than for each person
- Inclusion criteria for data was: Hopping $f \pm 3\%$; $f \propto k^2$ which implies $k$ may vary $\pm 9\%$
Leg stiffness was maintained within a frequency, though it is not mechanically necessary to do so.\textsuperscript{3,7} Therefore it is shown that the global task (leg stiffness) is maintained under new perturbation paradigm; i.e., with a dorsi-flexor torque.

To maintain an invariant effective leg stiffness with this perturbation requires that compensation is occurring at one or more of the joints – though which one it is has yet to be deciphered since it does not appear to be entirely at the ankle.
Application

- Further insight into a rehabilitative modality achieved
  - With variable assistance/resistance we can work toward therapeutic AFOs

- More sophisticated rehabilitation devices could be made effectively. $^{14-18}$
  - Compliance of device (e.g. a PLS-AFO or GRF-AFO) could directly impact the effective stiffness of the joint it is being applied to.

Mehrholz et al, 2005
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References


Use of EMG

- Physiological Check:
  - “joint stiffness” varies with muscle activation\(^5\)
  - variations to be expected with the main flexors/extensors surrounding the ankle and knee

Ferris et al, 2006
SL-AFO