The Ankle and Hip Patterns from a Single Control Strategy

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BACKGROUND

Ankle & Hip Patterns:

- A seminal finding in the posture control literature is the existence of two fundamental patterns to maintain upright: the ankle and hip patterns.
- These patterns are thought to represent different motor programs that are selected to counteract the physical characteristics of the perturbation, implying different control strategies.

Sensory reweighting:

- Reweighting is the process through which the nervous system changes the "emphasis" of a particular sensory input due to neurological injury or when environmental conditions change.
- Reweighting is typically characterized through changes in gain

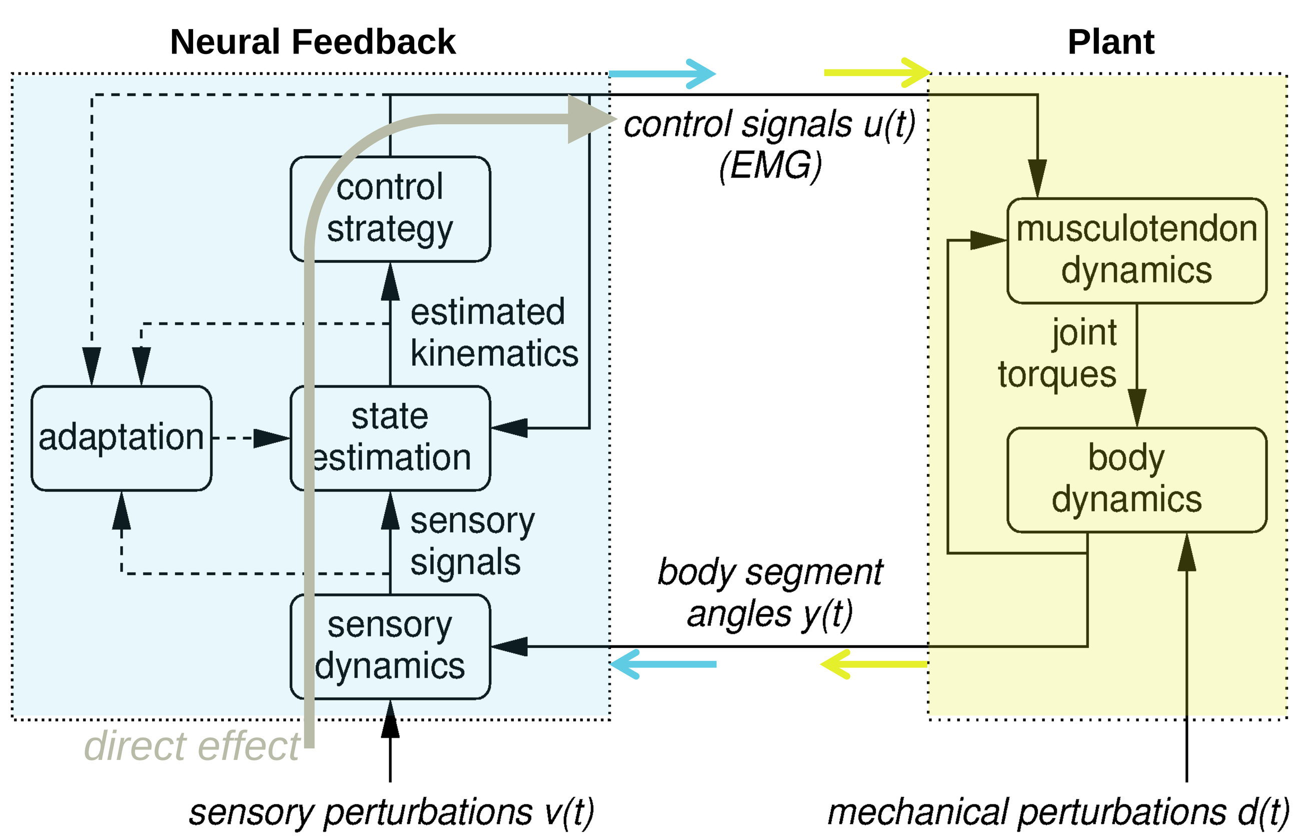
Postural control loop & Joint input-output method

- Open-loop mappings:

(a) Plant : form EMG signals to body segment angles

(b) Feedback : from body segment angles to EMG signals.

(c) Direct effect : from the sensory perturbation to EMG signals



EXPERIMENT

Here we use…

- a multiple input-multiple output (MIMO) system for the feedback & plant
- standing on a normal support surface and standing on a short support surface
- two sensory perturbations & two mechanical perturbations

We ask…

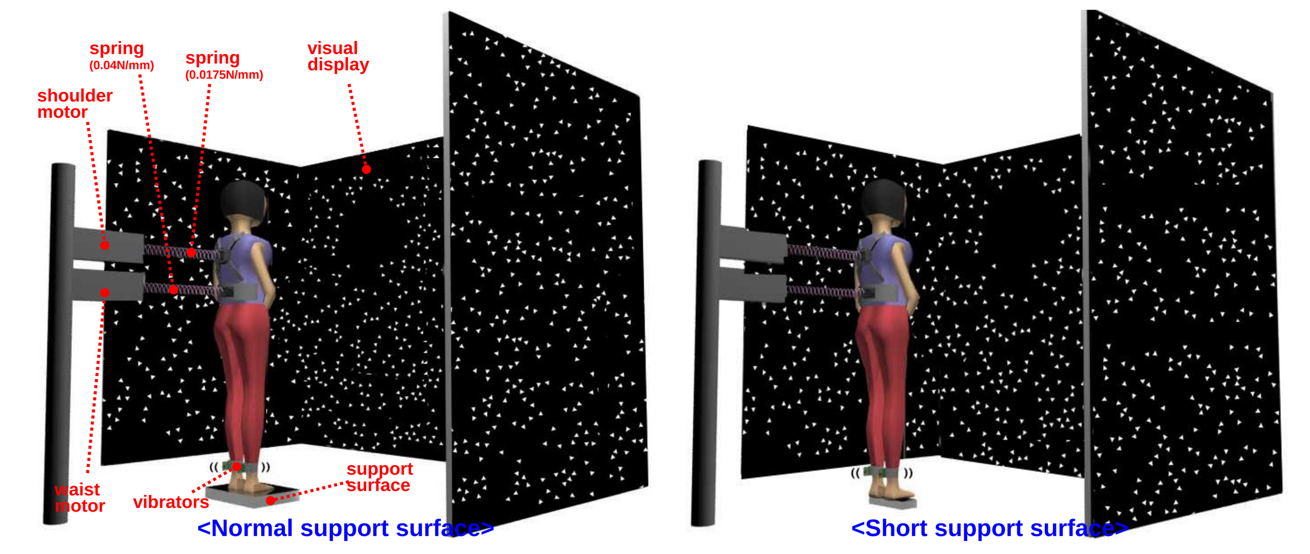
- What is the mechanistic basis for any changes in the behavior on normal support surface to short support surface?

1) The plant may be different between the two conditions?
   : The same muscle activation pattern may produce a different kinematic response because of the mechanical differences of standing on a short surface.
2) The feedback may be different?
   : A subject adopts a different control strategy on a short surface.
3) The direct effect of the sensory perturbation may be different?
   : The nervous system may re-weight the use of sensory information on a short surface.

METHODS

Subjects: 10 healthy young participants (22.3±3.0yrs, 175.0±13.7cm, 70.3±17.3kg)

Conditions: (240 sec/ trial, 5 trials in each condition)
-- Standing on a normal vs. a short support surface (50% foot length)
-- vision + vibration + shoulder perturbation + waist perturbation;



Kinematics: Leg segment angle & trunk segment angle (in the sagittal plane)

EMGs: Soleus, Tibialis Anterior, Gastrocnemious lateralis & medialis, Semitendinosus, Biceps Femoris, Vastus lateralis & medialis, Rectus Femoris, Erector spinae, Rectus Abdominus

Stimuli: *(uncorrelated signals)*
Vision:
-- filtered white noise with most power at frequencies < 5 Hz,
-- rotation around ankle joint
Vibration:
-- filtered white noise with most power at frequencies < 5 Hz,
-- 80Hz vibration at both Achilles' tendon by two vibrator motors
Mechanical perturbations:
-- based on position movement of linear motors
-- filtered white noise with most power at frequencies < 5 Hz,
-- spring constants: 0.04N/mm (waist), 0.0175N/mm(shoulder).

Analysis -- FRFs:

sway, plant, EMGs, direct effect of mech. prtb., mechanical perturbations, noise

$$Y(f)=P(f)U(f)+M(f)D(f)+N_y(f) \quad \text{(a.1)}$$

$$U(f)=F(f)Y(f)+S(f)V(f)+N_u(f) \quad \text{(a.2)}$$

EMGs, feedback, sway, direct effect of sensory prtb., sensory perturbations, noise

FEEDBACK	PLANT	DIRECT EFFECT
Solving (a.1):	*Solving (a.2):*	*Solving (a.1,2):*
$H_{du}(f)=F(f)H_{dy}(f)$	$H_{vy}(f)=P(f)H_{vu}(f)$	$H_{vu}(f)=F(f)H_{vy}(f)+S(f)$ $H_{dy}(f)=P(f)H_{du}(f)+M(f)$
Inferred Open-loop segment angle (y) to EMG (u)	*Inferred Open-loop EMG (u) to segment angle (y)*	*Inferred Open-loop direct-effect*
$F(f)=H_{du}(f)H_{dy}(f)^{-1}$	$P(f)=H_{vy}(f)H_{vu}(f)^{-1}$	$S(f)=H_{vu}(f)-F(f)H_{vy}(f)$ $M(f)=H_{dy}(f)-P(f)H_{du}(f)$

U(f), V(f), *D(f)* and *Y(f)*: Fourier transforms of *u(t)*, v(t), *d(t)* and *y(t)*.
$H_{du}(f)$: Closed-loop 2-by-2 matrix FRF from mechanical perturbations to EMG signals.
$H_{dy}(f)$: Closed-loop 2-by-2 matrix FRF from mechanical perturbations to body segment angles.
$H_{vy}(f)$: Closed-loop 2-by-2 matrix FRF from sensory perturbations to body segment angles.
$H_{vu}(f)$: Closed-loop 2-by-2 matrix FRF from sensory perturbations to EMG signals.
F(f): Open-loop FRF of feedback
P(f): Open-loop FRF of plant
S(f): Open-loop FRF characterizing the direct effect of the sensory perturbations on the EMG signals
M(f): Open-loop FRF of characterizing the direct effect of the mechanical perturbations on the body segment angles

RESULTS

- Identification of feedback & direct-effect (Error bars denote bootstrap standard errors)
- Identification of plant & direct-effect (Error bars denote bootstrap standard errors)

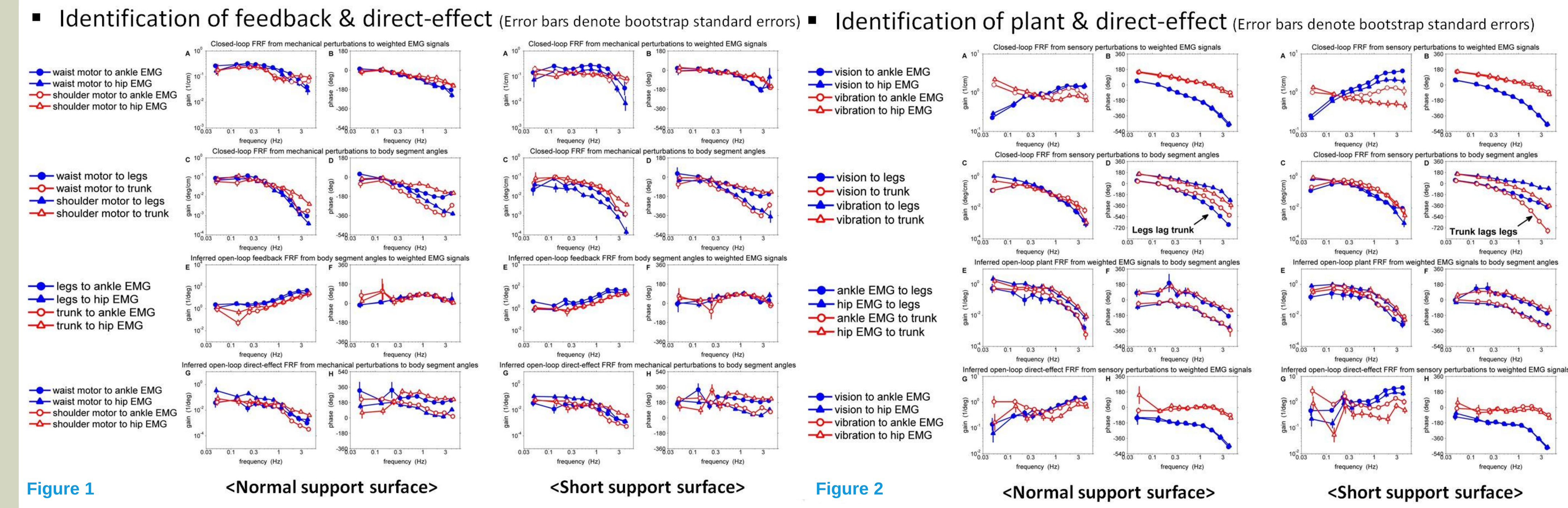


Figure 1 <Normal support surface> <Short support surface> Figure 2 <Normal support surface> <Short support surface>

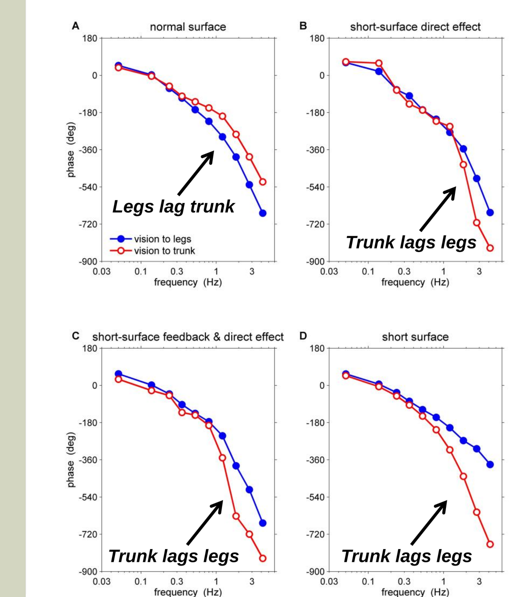


Figure 3

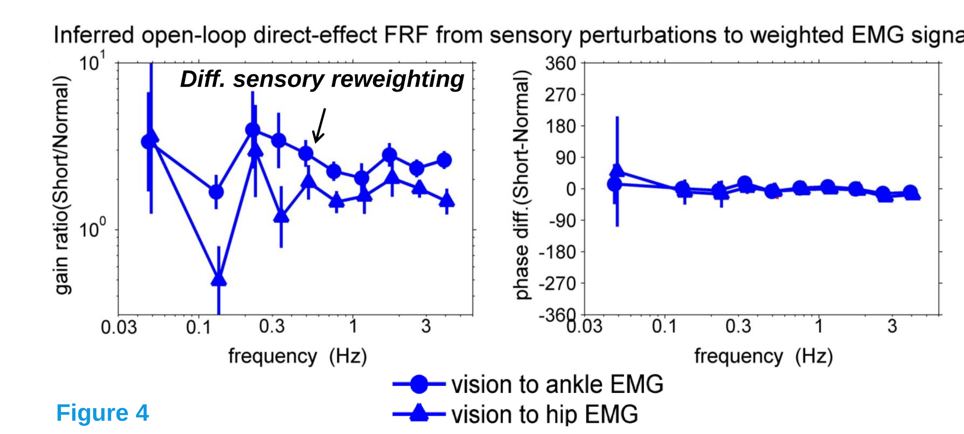


Figure 4

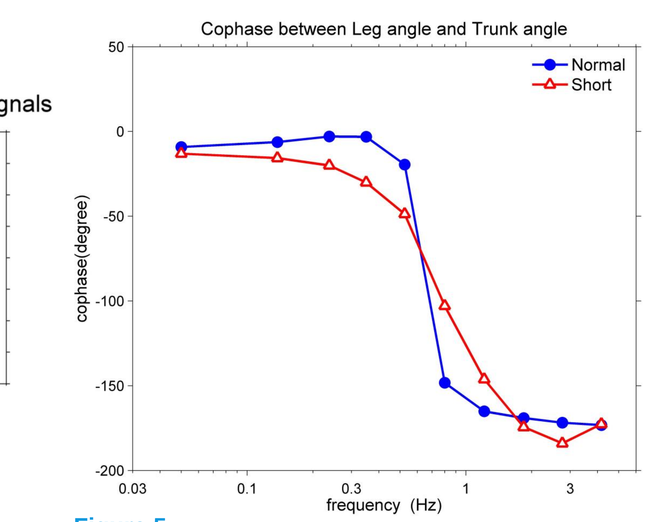


Figure 5

- Feedback FRF showed no differences between surface conditions (Figure 1).
- The most striking difference between the two conditions occurred in the phase of the closed-loop kinematic responses to the visual perturbation (Figure 2C, D).
  - On the normal support surface, as frequency increases the legs' response begins to lag behind the trunk's response.
  - In contrast, on the short support surface it is the trunk that lags behind the legs.
- Plant? Feedback? or Direct effect? (Figure 3)
  - The change in the direct effect by itself increases the phase lag of the trunk at high frequencies so that the trunk now lags behind the legs (Figure 3B).
  - The change in the plant from Figure 3C to Figure 3D decreases the phase lag of the legs at high frequencies, further increasing the lag of the trunk behind the legs.
- The sensory upweighting was greater for ankle EMG than for hip EMG from the visual perturbation (Figure 4).
- The shift from in-phase to anti-phase sway showed a gradual change for the standing on the short support surface (Figure 5).

CONCLUSIONS

Our analysis suggests that condition differences in both the direct effect and the plant, but not the feedback, contribute to the condition differences seen in the closed-loop responses of the legs and trunk to the visual perturbation.

Subjects upweight vision while standing on a short supporting surface, possibly because their ankle proprioceptive information is less reliable.

Moreover, we found that upweighting is greater for ankle EMG than for hip EMG, suggesting that sensory reweighting differs across actuators.

The similar feedback under both surface conditions suggests that standing on the short supporting surface does not change the control strategy.

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