

THE CONTROL STRATEGY FOR HUMAN LOCOMOTOR ADAPTATION CHANGES WITH PRACTICE FROM OPTIMAL FEEDBACK CONTROL TO NOISE REDUCTION

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INTRODUCTION

Humans have more degrees of freedom than necessary to complete a motor task. For example, there are many combinations of leg joint torques that result in the same ground reaction force (GRF) produced by a leg. Previous research on motor control of hopping indicates that humans exploit this redundancy by structuring variance of joint torques to minimize variance in peak GRF [1]. Also, when adapting joint angles to reaching in a force field, subjects do not reduce variance in joint angles uniformly [2]. Rather, they selectively decrease only the variance that affects the endpoint goal. These studies are consistent with optimal feedback control, a theory that the nervous system reduces variability only in dimensions that affect the task goal [3]. However, adaptation is poorly understood in bouncing gaits like hopping, and analysis of how joint torques are coordinated to minimize changes in endpoint force has never been applied to locomotor adaptation. Here, subjects hopped while trying to match their peak GRF to a target provided by visual feedback. The purpose of this study is to understand how humans exploit redundancy by changing their coordination of leg joint torques as they adapt to an increase in peak GRF. In order to assess this on a hop-by-hop basis, we focus on individual joint torque deviations, rather than variance, projected along and orthogonal to the intended goal in operational space. We expect subjects to reduce only the joint torque deviations that affect GRF as they adapt to a new target GRF. Specifically, we hypothesize that subjects will adapt peak GRF to the explicit target GRF and that they will reduce non-goal equivalent deviations in joint torques while deviations that do not affect peak GRF will remain unchanged.

METHODS

Protocol: Eleven subjects gave written, informed consent in accordance with the Georgia Tech IRB. Each subject did 11 30-second, 1-legged hopping trials at 2.2Hz. Visual feedback appeared as two bar graphs on a screen: one target bar and a second feedback bar displaying the peak GRF of the previous hop. Subjects were instructed to match the height of the second bar to the target bar height, but were not told that some feedback would be shifted as to require a change in force output. Four sets of trials were presented in the following order:

- 2 trials without visual feedback to find an average peak GRF to use as the target in control trials
 - 2 trials with unperturbed feedback (control)
 - 4 adaptation trials with feedback shifted down by 10% of the target
 - 3 de-adaptation trials with unperturbed visual feedback
- Data were filtered with a 10Hz, low-pass, Butterworth filter

Analysis: This analysis is designed to determine if the local variables – joint torques – coordinate to stabilize the goal variable – peak GRF – at the target GRF. The kinematic

Jacobian was found using joint angles ($\vec{\Theta}^r$) averaged over the last 30 hops of each set, a reference time in which peak GRF had reached a steady value. The kinematic Jacobian was converted to the kinetic Jacobian $J(\vec{\Theta}^r)$ as previously described [4]. The null space $\vec{\epsilon}$ was found using Equation 1.

$$0 = J(\vec{\Theta}^r) \cdot \vec{\epsilon} \quad (1)$$

Projecting the difference between joint torques at each time point onto the null space gave the deviations parallel (\vec{X}_{\parallel}) and perpendicular (\vec{X}_{\perp}) to the UCM.

$$\vec{X}_{\parallel} = \sum_{i=1}^{n-d} \vec{\epsilon}_i^T \cdot (\vec{X} - \vec{X}^r) \vec{\epsilon}_i \quad (2)$$

$$\vec{X}_{\perp} = (\vec{X} - \vec{X}^r) - \vec{X}_{\parallel} \quad (3)$$

where n = local degrees of freedom = 3 and d = global degrees of freedom = 1.

Averaging these deviations over number of hops (N) and normalizing across degrees of freedom gave non-goal-equivalent (NGED) and goal-equivalent deviations (GED). The normalized difference between these two values is the single cycle index of deviation structure (SCIDS), which provides a way to compare NGED and GED structure across subjects for each hop cycle with a single metric.

$$NGED = \sum_{i=1}^N \vec{X}_{\perp} / d \quad (4)$$

$$GED = \sum_{i=1}^N \vec{X}_{\parallel} / (n-d) \quad (5)$$

$$SCIDS = (GED - NGED) / \|\vec{X} - \vec{X}^r\| \quad (6)$$

where $\|\vec{X} - \vec{X}^r\|$ = magnitude of torque error.

Magnitude of torque error, SCIDS, GED and NGED were calculated at peak GRF by averaging each value across the 5% of the hop cycle surrounding where peak GRF occurred. The changes in these values and GRF error within each trial were further evaluated by averaging first and last 10 hops of each trial and comparing them with 1-tailed, paired t-tests.

RESULTS AND DISCUSSION

The hypothesis that subjects would adapt peak GRF to the target was partially supported. Subjects decreased GRF error in the first three adaptation trials, but error eventually reached a non-zero steady state (Figure 1). This may be due to the difficulty of reaching a 10% increase in peak GRF while maintaining a frequency of 2.2Hz or conflict between visual feedback and proprioception. A negative GRF error decreased to zero within the first de-adaptation trial, indicating that the adaptation to increased peak GRF that had occurred had washed out quickly.

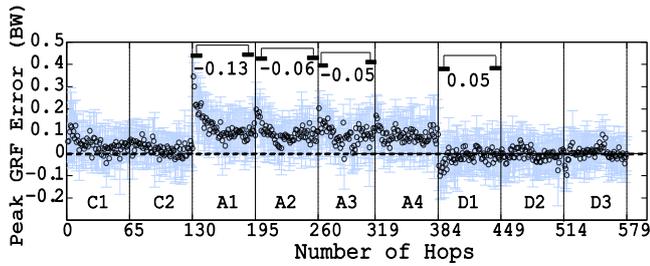


Figure 1: Peak GRF error averaged across all subjects. Significant differences denoted by connected bars with difference below (C - control set, A - adaptation set, D - de-adaptation set)

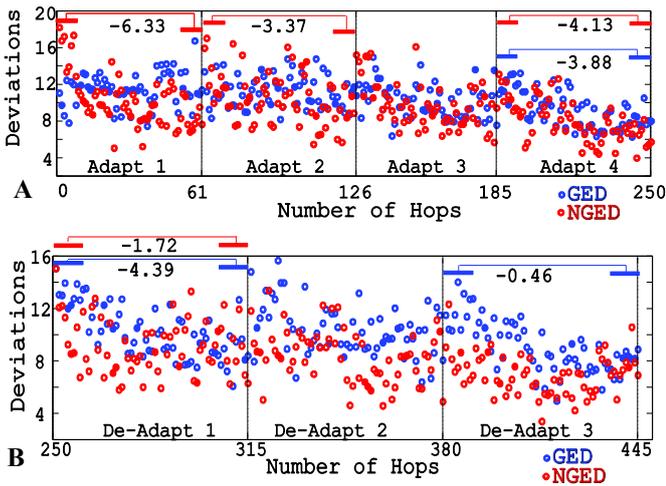


Figure 2: NGED and GED at peak GRF, averaged across all subjects for adaptation trials (A) and de-adaptation trials (B). Significant differences denoted by connected bars with difference below.

In the first and second adaptation trials, NGED decreased significantly at peak GRF while GED remained unchanged (Figure 2A). This supports the hypothesis that the nervous system reduces only the torque deviations that affect peak GRF. However, in the last adaptation and first de-adaptation trials, there was no preference to reduce only deviations that affect peak GRF, as GED, NGED (Figure 2) and magnitude of torque deviations (data not shown) all decreased significantly while SCIDS was unchanged (Figure 3). This indicates a change in strategy from optimal feedback control in early adaptation to noise reduction in late adaptation. This change in strategy occurred in the last adaptation trial, once GRF error was no longer being reduced. It appears that subjects relied on optimal feedback control to move closer to the target peak GRF. Once they had gotten as close to this goal as possible, they begin fine-tuning joint torques. The purpose of this fine-tuning could be to minimize energy expended. Previous research shows that, as subjects adapt to even simple arm reaching tasks, metabolic cost decreases in late adaptation, after the largest reductions in error have already occurred [5]. However, further research into muscle activity and metabolism during hopping is necessary to better understand how energy minimization is involved.

In de-adaptation, subjects used only a noise reduction strategy. The first and third de-adaptation trials have

significant reductions in total error, and none of the adaptation trials showed changes in SCIDS. Reduction of GRF error fully occurred within the first de-adaptation trial, which was the only de-adaptation trial in which NGED decreased. Also, de-adaptation trials had lower peak GRFs than adaptation trials, so reducing signal-dependent noise contributed to this total noise reduction [6].

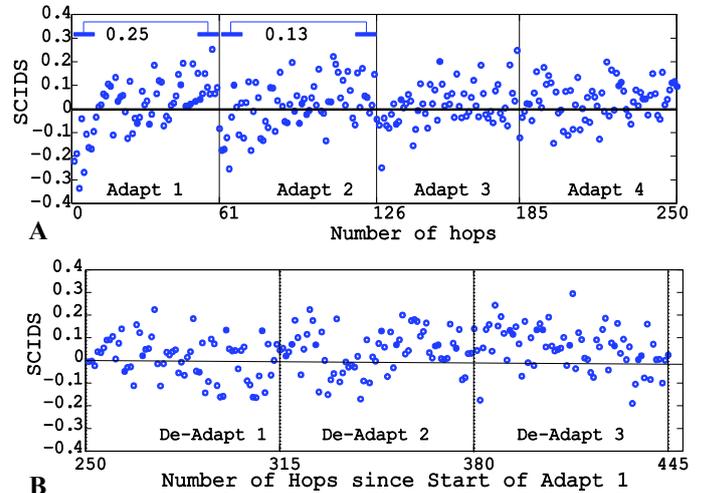


Figure 3: SCIDS at peak GRF, averaged across all subjects for adaptation trials (A) and de-adaptation trials (B). Significant differences denoted by connected bars with difference below.

CONCLUSIONS

In this study, we show for the first time how local joint torques change on a cycle-by-cycle basis to allow peak GRF adaptation in locomotion. Subjects selectively reduced only non-goal equivalent torque deviations in early adaptation when peak GRF error was decreasing, but reduced all torque deviations in late adaptation when peak GRF error had stabilized. This indicates a switch from an optimal feedback control strategy to a noise reduction strategy. Noise reduction in late adaptation may be designed to minimize energy costs after error has been reduced as much as possible. This study suggests different roles for joint control strategies that are utilized depending on task level performance.

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