The Dynamic Effect of Muscle Activation on Knee Stiffness

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***Abstract*—Adapting limb mechanics in a task and environment dependent manner is one component of human motor control. Joint mechanics have been extensively studied under static postural conditions, but less so under time-varying movement conditions. The limited studies that have investigated joint mechanics during movement, have found a drop in joint stiffness during movement, however the source of this decrease in stiffness remains unknown. Here in this paper we investigate whether time-varying muscle activation, which occurs during volitional movement, can lead to the drop in stiffness seen during movement. We found that under time-varying isometric conditions stiffness dropped when subjects transitioned from extension to flexion and vice-versa, a phenomenon that could not be explained by simply superimposing extension and flexion contractions. These findings suggest that dynamics of muscle activation may be responsible for the complex pattern of stiffness changes seen during simple movements. Furthermore, these results imply that EMG-based estimates of stiffness, which work well for steady-state postural conditions, will need to be augmented to account for the highly non-linear relationship between muscle activation and stiffness before they can also be used to estimate stiffness during dynamic contractions.**

I. Introduction

Adapting limb mechanics in a task and environment dependent manner is one component of human motor control. This component is especially valuable when interacting with unpredictable environments, such as walking on a rocky surface. A detailed knowledge of how our limb and joint mechanics change in a variety of tasks and environments not only increases the base of knowledge of human motor control but may also provide insight into altered regulation of limb mechanics that may occur after injury.

While joint mechanics have been extensively studied under postural tasks, fewer studies have investigated the modulation of joint mechanics during movement. Joint impedance—a key mechanical property that dynamically relates the torque produced in response to a position perturbation [1]—has been shown under static postural conditions to vary with both the position of the joint [2, 3] and the torque about the joint [2-4], both of which change dramatically with movement. A limited number of studies have found that joint impedance decreases during movement [5, 6] but none have systematically investigated what possible mechanisms contribute to the observed modulation of impedance.

One mechanism that will contribute to joint impedance is changes in muscle stiffness—the static component of the impedance—that concurrently occur with muscle activation [7]. It has been well established that joint stiffness increases with increasing absolute joint torque [2-4], however this holds under static postural conditions where the measured torque reflects the active force produced by the muscles, an assumption that is not valid during movement. Others, including work from our lab, have predicted impedance based on electromyographic (EMG) activity [4, 8]. However these predictions were made under static postural conditions. Thus it remains unknown how joint impedance varies dynamically with varying muscle activation.

In this paper we determined whether the dynamics of time-varying muscle activation lead to the decrease in joint impedance seen during movement. Furthermore, we investigated whether a linear dynamic model could be used to predict stiffness from EMG recording during time-varying behavior as it had been done during posture. We accomplished this by measuring stiffness during a dynamic isometric torque matching task. We found that the dynamic isometric muscle activations did produce a pattern of stiffness modulation similar to that seen during movement, suggesting voluntary muscle activation is the major source of stiffness modulation seen during movement. However, the EMG-stiffness relationship was highly non-linear and further investigation is required to produce a generalizable model that can predict stiffness from EMG under time-varying conditions.

II. Methods

A. Subjects

3 males ranging in age from 29–33 years old participated in the experimental. All subjects gave informed consent to the experimental protocol, which was approved by Northwestern University's Institutional Review Board.

B. Apparatus

A schematic of the experimental setup is shown in Fig. 1. Subjects' right legs were attached to an electric rotary motor via a custom made cast. The knee was aligned with center of rotation of the motor, allowing for only flexion and extension of the knee. The upper portion of the right leg was

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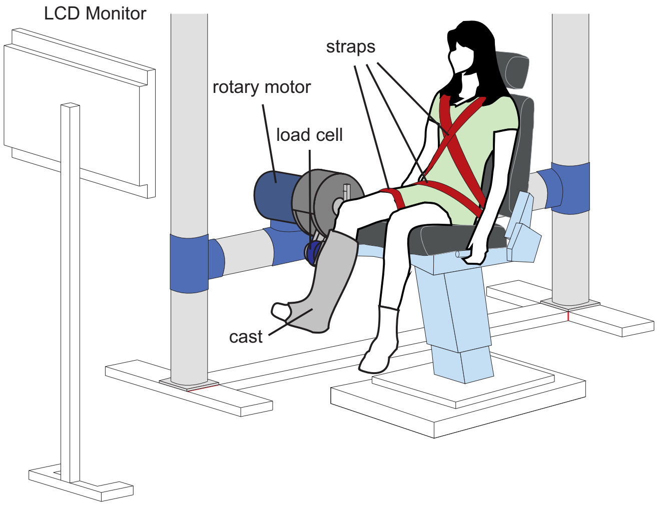

Figure 1. Schematic of experimental apparatus

immobilized by tightly securing a strap around the thigh and the torso was immobilized with straps across the shoulder and body. Electric and mechanical safety stops were placed at either end of the subjects' range of motion. Knee position, torque and EMGs—rectus femoris (RF), vastus lateralis (VL), vastus medialis (VM), biceps femoris (BF), semitendinosus (ST), and lateral (LG) and medial (MG) heads of the gasctrocnemius—were filtered at 500 Hz and recorded at 2.5 kHz.

C. *Procedure*

To estimate the contribution of changing muscle activation to joint stiffness independently of any other changes to stiffness that may occur during movement, we designed a paradigm to estimate knee stiffness during dynamic isometric muscle activation. Subjects were instructed to match a torque target, while the rotary motor—which was configured as a stiff position servo—imposed small position perturbations. These perturbations consisted of a pseudo-random binary sequence (PRBS) with a switching time of 0.15 s and amplitude of 0.06 rad. Subjects performed 4 trials of three different torque matching tasks, each lasting 180s. The three torque matching tasks were: an extend-relax trial, a flex-relax trial and an extend-flex trial. In each trial subjects alternated between the two states (e.g. extension & flexion) every 2 seconds aided by auditory feedback.

D. *Analysis*

1) *Alignment of data*

Accurately estimating knee impedance using an ensemble algorithm requires that the behavior be as repeatable as possible in each realization, thus alignment was critical. The data was aligned by minimizing the squared error between the voluntary torque of each segment and the average voluntary torque. In addition to shifting each segment, only the best segments were used for further analyses. The best segments were defined as those whose minimum squared error was in the lower 80% of the ensemble and whose knee position/torque standard deviation fell within 10%–90% of the ensemble.

2) *Estimation of knee impedance*

Knee impedance was estimated using the multi-segment algorithm we developed in our lab [9]. At each time point the joint impedance **h***(t)* was estimated using the aligned position and torque traces by computing an impulse response function (IRF) using the following equation

$$\mathbf{h}(t) = \Delta t^{-1} \mathbf{\Phi}_{\mathbf{xx}}(t)^{-1} \mathbf{\Phi}_{\mathbf{xy}}(t) \qquad (1)$$

where

$$\mathbf{\Phi}_{\mathbf{xy}} = \left[\phi_{xy}(t,0) \quad \phi_{xy}(t,1) \quad \cdots \quad \phi_{xy}(t, M2 - M1)\right]^{\mathrm{T}}$$

$$\mathbf{\Phi}_{\mathbf{xx}} = \begin{bmatrix} \phi_{xx}(t - M1, 0) & \cdots & \phi_{xx}(t - M2, M1 - M2) \\ \vdots & \ddots & \vdots \\ \phi_{xx}(t - M1, M2 - M1) & \cdots & \phi_{xx}(t - M2, 0) \end{bmatrix}$$

Δt is the sampling interval (0.01 s), *M1* and *M2* are the minimum and maximum lag (-0.12 & 0.12 s), and ϕ_{xx} and ϕ_{xy} are the multi-segment auto-correlation of the position and cross-correlation between the position and the torque respectively. The multi-segment correlations were computed by

$$\phi_{xx}(t,k) = \frac{1}{NR(t)} \sum_{r=1}^{R(t)} \sum_{i=t-N/2+T(t,r)}^{t+N/2+T(t,r)} x(i-k,r)\, x(i,r) \qquad (3)$$

where *x(i,r)* is the position (or torque) at time *i* and segment *r*, *N* is the length of the window over which joint impedance estimates were generated (0.05 s), *T(t,r)* is the timeshift determined from the alignment procedure, and *R* is the number of segments used at that time.

The stiffness was computed by integrating the impedance IRFs.

III. Results

The main purpose of this study was to determine whether changing muscle activation can lead to a decrease in stiffness as seen in movement conditions. For both the extend-relax task and the flex-relax task, the stiffness increased when subjects extended/flexed and returned to resting when they relaxed (Fig. 2). However, when subjects

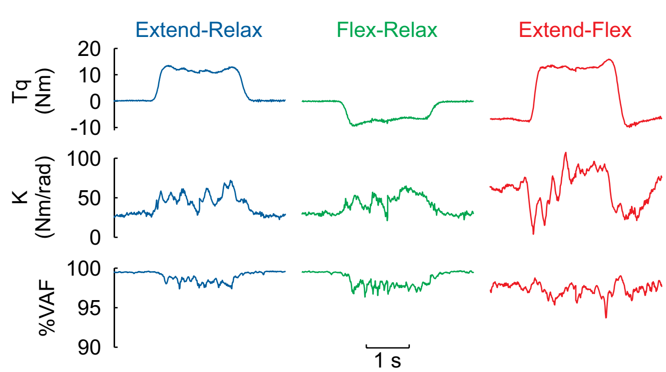

Figure 2. Voluntary torque (*Tq*), stiffness (*K*) and percentage of variance accounted for (%VAF) estimated in the three dynamic isometric torque matching tasks for one subject.

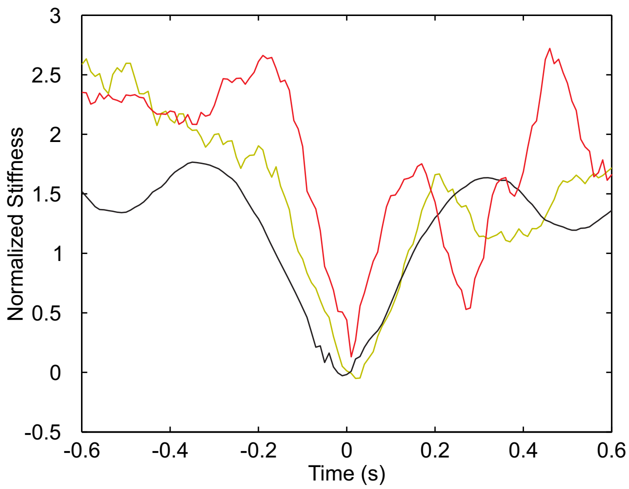

Figure 3. Normalized stiffness for all three subjects for transition from flexion to extension estimated during extend-flex task. Stiffness was normalized to passive resting levels while time zero corresponds to time of transition.

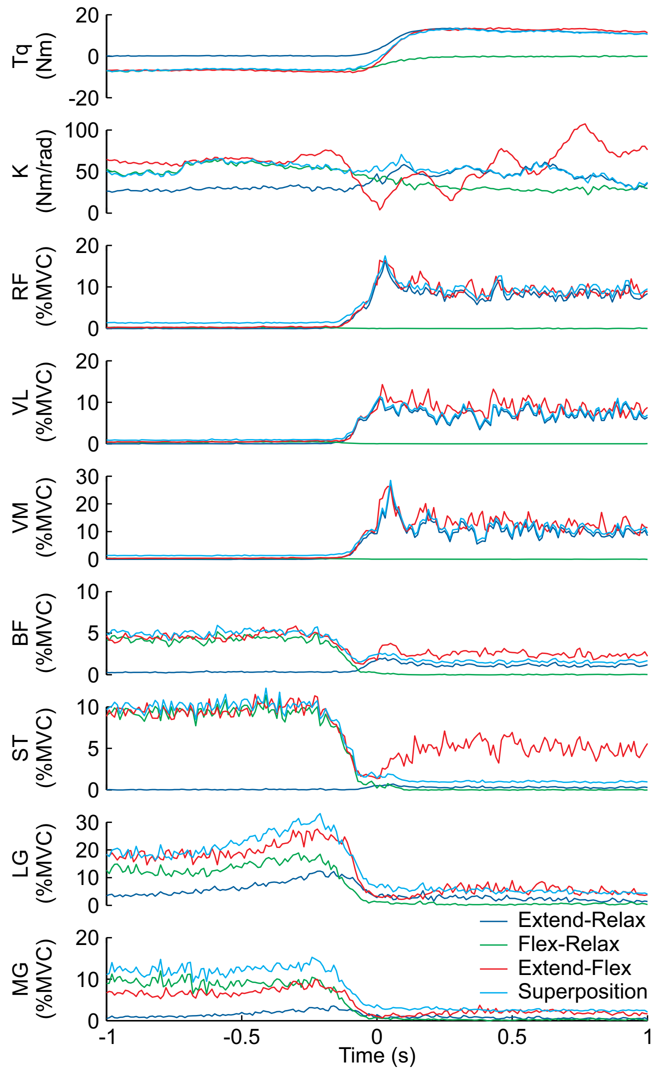

Figure 4. Voluntary torque (*Tq*), stiffness (*K*) and EMGs estimated and recorded for the three dynamic isometric torque matching tasks (blue = extend-relax, green = flex-relax, red = extend-flex) as well as the superposition of the extend-relax and flex-relax trials (cyan) for one subject.

alternated between flexion and extension, stiffness dramatically decreased as they switched between the torque levels, even dropping lower than relaxed levels for the flexion to extension transition. This can be seen in Fig. 3, which shows that for all three subjects stiffness dropped from between 1.5–2 times passive resting levels to below half resting passive stiffness, prior to returning to levels greater than passive resting stiffness.

To further explore the drop in stiffness associated with switching from flexion to extension, we compared the torque, stiffness and EMG data from all three dynamic isometric torque conditions aligned to the rising edge of increasing torque (Fig 4). In addition, the three torque conditions were compared to the superposition of the flex-relax and extend-relax. Doing so resulted in a superposition torque that was nearly identical to that in the extend-flex condition. Despite the nearly identical torque profiles, the flex-extend condition showed a drop in stiffness at the time of the transition from flex to extend whereas the superposition maintained a nearly constant stiffness level. EMG recordings showed no difference in the activity in the extensors (RF, VL and VM) between the extend-flex condition and the superposition. While the activity in the flexors was greater in knee flexors (ST and BF) during the extend-flex condition, this increase occurred after the transition—during the extension phase of the task—thus is not likely the source of a decrease in stiffness seen during the transition. Rather this increased activity of the flexors during the extension phase is merely some co-contraction that also explains the increased stiffness seen later on in the extension phase of the extend-flex condition.

IV. Discussion

A number of studies, including our own, have begun to investigate how impedance changes during movement [5, 6, 10]. While there is evidence that stiffness drops during movement the origin of this decrease in stiffness was unclear. Based on the findings presented here, we posit that the decrease of stiffness below passive resting levels, is due to alternating patterns of extension and flexion that occur during the cyclic movement. As was shown in our previous work [10], a large drop in stiffness during movement occurs right as subjects switch from flexion to extension, mirroring the decrease seen in the extension-flexion task shown in this study.

A second conclusion arising from the findings presented here is the strong non-linearity in the EMG-stiffness relationship. Previous studies have developed models that can effectively predict stiffness based on EMG recordings [4, 8]. These methods are valuable to predict stiffness during functional tasks where estimation is not possible, as well as potentially a means for the user to control the stiffness of a powered prosthetic device. These current methods do not work during movement, but this is not surprising as they are static methods and do not account for the dynamics of muscle activation. We hoped to be able to extend these methods to time-varying conditions by estimating the dynamic relationship between EMG and stiffness. However, the results presented here show that a simple linear dynamic model cannot accurately predict stiffness. This is demonstrated by the finding that the stiffness during the extend-flex condition is vastly different from the superposition of simple flex and extend tasks. Thus, to accurately predict stiffness during dynamic time-varying conditions, many more patterns of muscle activations need to be run so that a generalizable model can be produced or, preferably, a better understanding of the mechanisms underlying the observed behavior, which would allow for a model that would be generalizable to any conceivable pattern of muscle activity.

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