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Regulation of Multijoint Stretch Reflexes During Interactions with Stiff and Compliant Environments

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***Abstract*—The purpose of this study was to examine how multijoint stretch reflexes are modulated during interactions with stiff and compliant environments. Reflex responses were elicited using a 3D robotic manipulator to perturb arm posture in the three degrees of freedom relevant to functional behaviors. The robot applied controlled displacements and simulated environments with different stiffnesses. Stiff (10kN/m) and compliant (10N/m) environments were used. Perturbation characteristics were matched across environments. Reflex responses were monitored using surface electromyograms from 8 upper limb muscles. Data were collected from 9 subjects. Significant stretch reflex responses were observed in all muscles and these were significantly modulated by the environmental stiffness. This modulation was due to increased levels of background muscle activity in the compliant environment and to increased reflex sensitivity at matched levels of muscle activation. These results suggest that the neuromotor control system uses both feedforward and feedback mechanisms to compensate for changes in environmental compliance.**

I. Introduction

THE human motor system regulates arm mechanics to produce stable postures during interactions with a variety of environmental loads. These mechanics are regulated by controlling the actions of multiple muscles within the arm using both spinal and supraspinal pathways. Single joint studies have demonstrated that stretch reflex contributions to arm mechanics vary with task and can increase to compensate for environmental loads with low stability [1, 2]. This suggests that stretch reflex modulation is a fundamental component of motor function, but the extent of this modulation has yet to be investigated during multijoint tasks. The purpose of this study was to examine how multijoint stretch reflexes vary with changes in environmental stiffness. Our hypothesis was that reflexes modulate to compensate for decreased environmental stiffness and that this modulation is appropriate for maintaining whole limb stability.

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II. Methods

Experiments were conducted on 9 subjects using protocols approved by the Northwestern University IRB.

A. Equipment

Stretch reflex responses were elicited by perturbing each subject's dominant arm with an instrumented 3 degree of freedom (DOF) robotic manipulator. [HapticMaster; FCS Control Systems, The Netherlands]. The HapticMaster uses an admittance control algorithm which allows it to simulate a range of virtual environments [3]. In these experiments, the device was configured as a critically damped second order system with a 3D isotropic stiffness of 10 N/m (COMPLIANT) or 10kN/m (STIFF). As a reference, the endpoint stiffness of the human arm is on the order of 100N/m for low levels of voluntary muscle activity. [4].

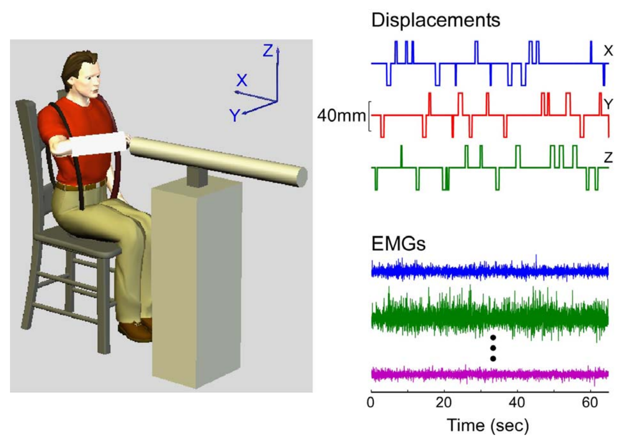

Fig. 1. Robotic manipulator, coordinate system and perturbations for all experiments. EMGs show typical raw data used in the subsequent analyses.

Subjects were attached to the robot using a custom fitted fiberglass cast. The cast fixed the wrist in a neutral position and extended approximately one-third of the distance from the wrist to the elbow. A low mass, custom gimbal mounted between the end of the robot and the cast ensured that the robot applied pure forces and no moments to the arm.

Randomly occurring ramp-and-hold perturbations with an amplitude of 30mm and a velocity of 500mm/sec were applied along the three orthogonal axes illustrated in Fig. 1. Perturbation amplitude and velocity were matched in the stiff and compliant environments using a prefiltering algorithm that compensated for the limb mechanics and the simulated environmental stiffness. An example of the accuracy of this match is illustrated in Fig. 2.

TABLE I
RECORDED MUSCLES

Muscle	Abbreviation	Action
Deltoid: Anterior	AD	Shoulder flexor
Deltoid: Medial	MD	Shoulder abductor
Deltoid: Posterior	PD	Shoulder extensor
Pectoralis Major	PM	Shoulder adductor, flexor
Latissimus Dorsi	LD	Shoulder extensor, adductor
Biceps Brachii	BI	Elbow flexor, Shoulder flexor
Triceps Brachii: Long head	TRI_long	Elbow extensor Shoulder adductor, extensor
Triceps Brachii: Lateral head	TRI_lat	Elbow extensor
Brachioradialus	BRD	Elbow flexor

Electromyograms (EMGs) were recorded from 8 muscles in the perturbed arm (Table 1). These represent the major single and multijoint muscles at the elbow and shoulder, which can be recorded reliably using surface EMGs.

All data were synchronized by a common sampling clock.

B. Protocols

The basic experimental protocol involved applying endpoint displacement perturbations to the subjects arm and recording the corresponding reflexively evoked changes in muscle activity. All measurements were made in the stiff and compliant environments to determine if the multijoint stretch reflex was modulated to compensate for changes in environmental stiffness.

Each experimental trial lasted for approximately 65s and consisted of 7 perturbations in each of the 6 measurement directions (±displacement along each axis). During each trial, subjects were required to maintain a constant endpoint force by pushing or pulling against the manipulator along the X-axis (Fig. 1), while not responding the imposed endpoint perturbations. Flexion forces (+X) were directed in towards the body and extension (-X) forces away from the body. Subjects were provided with 3D visual feedback of the voluntarily generated endpoint force to assist in this task. Endpoint forces of 0%, 5% and 10% of the maximum voluntary contraction (MVC) were examined. Each experimental condition was repeated twice.

C. Analysis

EMGs were rectified and averaged for each perturbation direction and experimental condition. The average response between 50-100ms following perturbation onset was used to quantify reflex magnitude. This latency is thought to correspond to reflexes mediated via multi-synaptic, and possibly supraspinal, pathways.

III. RESULTS

Fig. 2 shows typical average reflex responses elicited from a single subject. All data were collected while the subject was extending the arm along the negative X-axis at 5%MVC. Thick lines correspond to data collected in the compliant environment and thin lines to the data collected in the stiff environment. Perturbations are shown at the top of the figure and EMGs below. The yellow shaded area indicates the portion of data over which means were computed for subsequent analysis. For this condition, there was a large increase in the elicited reflex response when subjects exerted forces in the compliant environment.

All muscles exhibited significant reflex modulation in the compliant environment. Group results for four representative muscles are shown in Fig. 3. Data points indicate the change in the elicited stretch reflex between the two environments. Positive changes correspond to increased reflex responses in the compliant environment. Data are represented as a percentage of the background muscle activity. Different types of modulation were observed in different muscles. For example, the long head of the TRI exhibited significant modulation only when stretched during voluntary extension. In contrast, BRD reflex responses were significantly enhanced during stretch and release. Some muscles, such as the AD, exhibited both increased and decreased modulation in the compliant environment. For the perturbation directions shown in Fig. 3, the reflex response in this muscle was enhanced during stretch diminished during release.

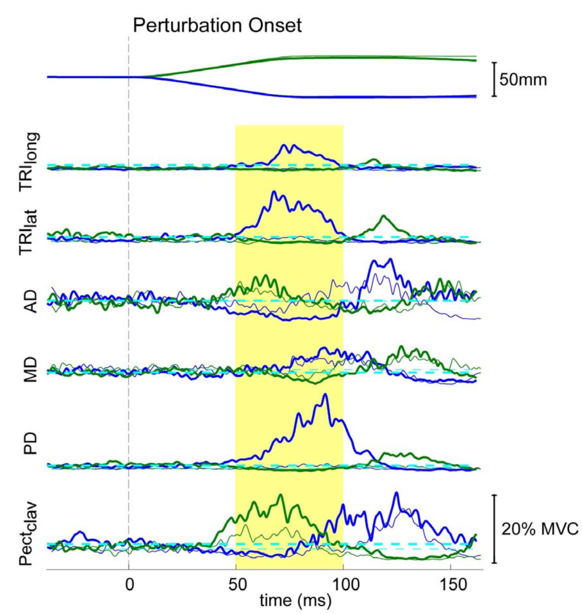

Fig. 2. Typical average reflex responses. Data from a single subject. Perturbations applied along the +ve (green) and –ve (blue) X-axis when subject was pushing away from the body (negative X-axis) with a force of 5% MVC. Thin lines correspond to reflexes elicited in stiff environment and thick lines to those elicited in compliant environment.

In some trials, increased cocontraction was used to compensate for the increased environmental compliance. For example, Subject A in Fig. 4 exhibited a large increase in background muscle activity when exerting forces in the compliant environment. Since changes in background muscle activity influence stretch reflex gain, comparisons of reflex excitability in the stiff and compliant environments must be made at matched levels of background activation. This was achieved by linearly interpolating the reflex responses obtained between the 5% and 10%MVC contractions in both environments and comparing responses only when there was overlap in the background activity within this interpolated range. Comparisons were made at the midpoint of the overlap range, as indicated for Subject B in Fig. 4.

Significant reflex modulation at matched levels of background muscle activity was observed in all monitored muscles (minimum $p<0.05$). Examples for two perturbation directions in two muscles are shown in Fig. 5. Data during voluntary flexion and extension was grouped for this analysis.

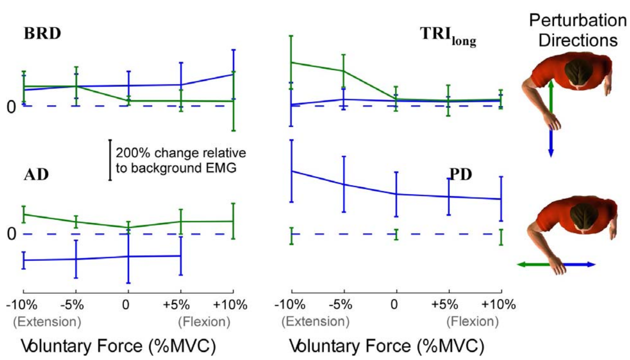

Fig. 3. Group results for change in reflex response with environmental stiffness across all levels of voluntary activation. Positive change indicates increased response in compliant environment. Only conditions with a significant response in at least two subjects are shown. Error bars indicate 95% confidence intervals. Colors indicate perturbation direction.

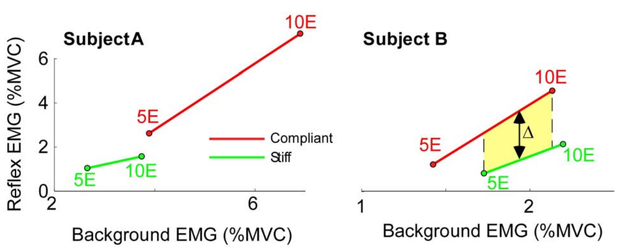

Fig. 4. Examples of how reflex responses and background muscle activity were modulated to compensate for increased environmental compliance. Number (5,10) indicates level of voluntary activation and letter (F,E) the direction (flexion or extension). Results for Subject B indicate how overlap regions were used to estimate reflex responses at matched levels of background activity. See text for details.

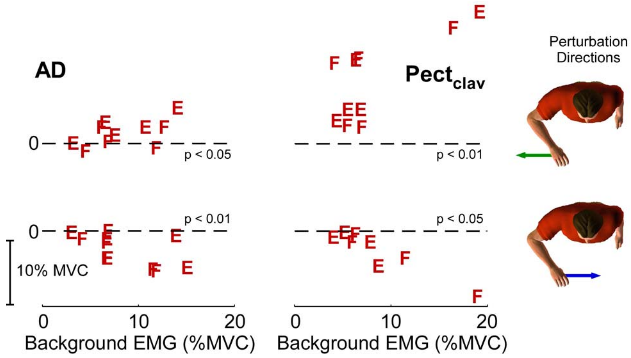

Fig. 5. Examples of estimated reflex responses at matched levels of background activity in the stiff and compliant environments. Data from flexion (F) and extension (E) trials is grouped. Significance levels computed using signed rank test. Positive values indicate increased reflex responses in the compliant environment.

IV. Conclusions

Our results demonstrate that the multijoint stretch reflex is modulated to compensate for changes in environmental stiffness. These changes reflect not only an increase in background muscle activation due to increased cocontraction, but also an increase in reflex sensitivity.

Even when net forces and torques are matched, maintaining arm postures in a stiff environment is a fundamentally different task than maintaining postures in a compliant environment. When operating in a stable environment that is much stiffer than the human arm, the neuromuscular control system does not need to provide limb stability. However, when stability is not provided by the environment, it must be regulated explicitly. Our results demonstrate that this regulation can involve changes in both feedforward and feedback pathways. The feedforward mechanisms were observed as changes in background muscle activity; the feedback mechanisms were observed as increased stretch reflex sensitivity at matched levels of background activation within an individual muscle.

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