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Reflex Modulation is Linked to the Orientation of Arm Mechanics Relative to the Environment

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Abstract

To successfully complete a motor task, it is necessary to control not only the kinematics and dynamics of a limb, but also its mechanical properties. In a multijoint task such as the control of arm posture, limb mechanics are directional, resisting external disturbances more effectively in certain directions than others. It has been demonstrated that feedforward neuromotor pathways can regulate these directional characteristics of the arm to compensate for changes in the mechanical properties of the environment. However, it is unclear if spinal reflex pathways exhibit a similar specificity. The present results suggest that the sensitivity of the human stretch reflex also can be tuned to adapt the mechanical properties of the arm in a task appropriate manner. We hypothesized that the orientation of arm mechanics relative to the mechanical properties of the environment would influence reflex adaptation. Two destabilizing environments, oriented relative to the mechanical properties of the arm, were used to test this hypothesis. These environments were simulated using a 3 degrees of freedom (DOF) robot, which also was used to perturb arm posture. The resulting reflexes, assessed by electromyograms recorded from 8 muscles, were found to modulate in accordance with how the environmental instability was oriented relative to the mechanical properties of the arm. Our results suggest that stretch sensitive reflexes throughout the arm are modulated in a coordinated manner corresponding to the orientation of arm mechanics relative to the environment.

Keywords

stretch reflex; endpoint stiffness; adaptation

I. INTRODUCTION

Endpoint stiffness describes the static forces generated by a limb in response to external perturbations of posture. As such, it completely describes the static mechanics of the limb as seen at the point of contact with the environment. The stiffness of a multijoint system is directional, having an orientation along which the limb is most resistant to postural perturbations. Stiffness in all directions can be regulated through changes in feedforward or

feedback motor commands. While feedforward commands can be refined through learning and adaptation, the adaptability of involuntary feedback mechanisms is less understood.

Strong evidence suggests that stretch reflexes contribute to the regulation of limb mechanics and stability. Stretch reflexes increase the stiffness of muscles and joints [1], and can coordinate activity across muscles in a limb [2]. Reflex sensitivity is not fixed, but adapts to environmental mechanics, increasing to compensate for decreased environmental stability [3]. Furthermore, many functional tasks have direction dependent stability requirements. For example, exerting forces against a screwdriver decreases limb stability in directions orthogonal to the driver, towards which buckling is possible, but not along the axis of the driver, which is extremely stiff relative to the arm. Feedforward motor commands can adapt to such direction dependent instabilities [4], but is it unclear if such specificity exists in reflex pathways providing feedback control.

The goal of this work was to investigate the specificity of stretch reflex adaptation. We hypothesized that multijoint reflexes would be modulated according to the orientation of arm mechanics relative to those of the environment. Such specificity would suggest that arm mechanics can be involuntarily tuned to the properties of the environment, extending current knowledge of the adaptability of reflex pathways. We examined changes in reflex sensitivity within muscles and reflex coordination across muscles as subjects interacted with environments that were aligned or orthogonal to the orientation of their maximum endpoint stiffness.

II. METHODOLOGY

A. Experimental Setup

Ten subjects, 26 – 41 years of age (8 males and 2 females), participated in the study. The protocol was approved by the Institutional Review Board at Northwestern University.

Subjects sat upright with the shoulders and waist secured to an immobile chair. Subjects held the right shoulder at $\sim 70^\circ$ abduction and $\sim 45^\circ$ flexion in the horizontal plane, with the elbow flexed to $\sim 90^\circ$ (Figure 1A). The hand and wrist were secured in a rigid cast, mounted to a custom gimbal that was attached to the force sensor of a 3DOF robot [HapticMaster; FCS Control Systems, The Netherlands]. The robot was used to control the mechanical properties of the environment and to apply perturbations to the arm. The latter were used to estimate the limb mechanics and to elicit stretch reflexes, as described below.

To account for compliance in the HapticMaster's drive mechanism, we redundantly measured endpoint displacement with an Optotrak motion analysis system [Optotrak 3020; Northern Digital, Waterloo, Ontario]; the endpoint of the arm was tracked using landmarks on the robot's gimbal.

Muscle activity was monitored using surface electromyograms (EMGs). Disposable dual electrodes [Noraxon USA Inc., AZ] recorded muscle activity in the anterior [AD], medial [MD], and posterior deltoid [PD], pectoralis major [PC], biceps brachii [BI], the long [TLO] and lateral head of triceps [TLAT], and brachioradialis [BRD]. EMG signals were amplified with a Bortec AMT-16 measurement system [Bortec Biomedical, Calgary, AB] with high- and low-pass cutoff frequencies of 10 and 1,000 Hz. All EMG signals were anti-alias filtered using 5th order low-pass Bessel filters with a cutoff frequency of 500 Hz. They were then sampled at 1.25 kHz by a 32-channel, 18-bit data acquisition system [NI 6289; National Instruments, Austin, TX]. EMG data were re-sampled at 1 kHz before processing.

B. Protocol

Data collected in a preliminary session were used to quantify limb mechanics for each subject. Subjects applied 10 N (in the $\pm X$, $\pm Y$, and $\pm Z$ directions, Fig. 1A) to the HapticMaster, which applied 35s, 3D stochastic displacement perturbations (Fig. 1B) to the arm [5]. Force data were recorded by the robot, and displacement data were recorded by the robot and OptoTrak. Nonparametric system identification techniques were used to estimate endpoint impedance, later parameterized using stiffness (K), viscosity, and inertia [5]; Because this study was concerned with postural control, the simulated mechanical environments were oriented relative to the endpoint stiffness. Stiffness can be depicted graphically using an ellipsoid [5] (Fig. 2A). The long axis of the ellipsoid illustrates the direction in which the limb is most stiff. This orientation was consistent across all subjects (Fig 2B).

Experiments were designed so that subjects interacted with two destabilizing environments, oriented relative to their maximal endpoint stiffness; maximal stiffness was generally along a 3D axis from the center of the humerus to the hand (Fig. 2B). Directional instabilities were created by programming the HapticMaster to simulate a negative spring acting along a 3D line. As subjects moved their hand away from the neutral point of the virtual spring, the robot pushed the hand further with a force proportional to the distance between the hand and the neutral point. Movements were constrained to the axis of the spring, which was either aligned or orthogonal to the primary axis of the ellipsoid; the orthogonal alignment was aligned with the secondary axis (Fig. 3A). Subjects interacted with each environment for half of the experiment. The order was randomized. The magnitude of negative stiffness was equal in both environments. Negative stiffness ranged from 250 N/m to 600 N/m; these values were adjusted for each subject and always were greater than the magnitude of the second axis of endpoint stiffness, as measured in the preliminary session.

The subjects' task was designed so that identical endpoint forces were applied in both environments. Subjects were asked to maintain the nominal posture and to apply a target force, given real-time feedback of both. Target forces were 0N, and 5N and 10N away from the body (along the primary axis of stiffness) and to the right (along the secondary axis). After holding the target for 0.5–1.5 s, a ramp-and-hold perturbation was applied (Fig. 3B). Subjects were instructed not to react to perturbations. The ramp's velocity was 400 mm/s and its duration was 100 ms. 60 perturbations were applied at each target force, 10 per perturbation direction.

Two sets of perturbations were tested. First, in the primary experiment (N=10) perturbations were applied in three orthogonal ($\pm X$, $\pm Y$, and $\pm Z$) directions [3] to determine if arm mechanics relative to the environment induced reflex adaptation within muscles. Next, in a control experiment (N=4) custom perturbations were applied along the primary and secondary axes of stiffness. This allowed us to examine modulation in muscle groups linked to the orientation of the primary and secondary axes of stiffness. Target forces, target hold times, and perturbation directions were randomized.

C. Analysis

EMG data for each muscle were processed by removing the mean, normalizing to the EMG recorded during a maximum voluntary contraction (MVC), rectifying, and finally averaging across a condition. Voluntary EMG was subtracted and reflexes were quantified as the mean EMG over 50–100 ms after perturbation onset [3]. We hypothesized that reflex sensitivity within muscles would be modulated according to the orientation of the environmental instability relative to the orientation of the limb mechanics. Comparisons of reflex sensitivity must be made at matched levels of voluntary EMG. This is because differences in the size of reflexes recorded at different levels of voluntary EMG could be due to either the difference in background EMG or a change in reflex sensitivity [6]. Thus, reflexes were recorded at multiple

force levels in both environments. As reported previously, reflex magnitude was modeled as a function of voluntary EMG and compared across environment only when there was overlap in the voluntary EMG recorded in both environments [3].

Since perturbations simultaneously stretched multiple muscles throughout the arm we also examined patterns of reflex coordination. To accomplish this we used PCA/ICA, a two-stage technique shown to produce robust estimates of muscle coordination [7]. According to

$\vec{E} = \sum_{i=1}^N c_i \vec{w}_i$, this analysis reduced reflex EMGs (E) across muscles to N eight-muscle coordination patterns (w_i) multiplied by scalar activation coefficients (c_i). First, N was determined by applying PCA to reduce reflex data to the least number of orthogonal components that accounted for > 90% of the data variance. Next, ICA was applied to the reduced data to determine the independent components (ICs; w_i). We hypothesized that any reflex modulation within muscles could be described either by changes in coordination patterns (w_i) across environments or by changes in the activations (c_i) of similar patterns across environments.

III. RESULTS

A. Reflex Modulation in Different Environments

During interactions with both environments at least one of the $\pm X$, $\pm Y$, and $\pm Z$ perturbations elicited a significant reflex response (>3 SD voluntary EMG) in each muscle. Changes in reflex magnitude across the environments were most consistent in response to $\pm Y$ perturbations. Figure 4 shows typical responses. Reflex magnitude within muscles was dependent on the orientation of the environment with which the subject interacted. In the orthogonal environment the stretch response to $\pm Y$ perturbations was significantly increased in all muscles except for AD and PC ($p < 0.05$; paired t-test; group data). Typical modulation can be seen for the BI, TLO and PD in Fig. 4.

The observed reflex modulation within muscles was due to changes in reflex sensitivity, not changes in voluntary EMG. This was determined by comparing reflex EMG at matched levels of voluntary EMG [3]. At matched background EMG, interactions with the orthogonal environment induced significantly increased stretch responses to $\pm Y$ perturbations in all muscles except for AD and PC ($p < 0.05$; paired t-test).

The observed changes in reflex sensitivity were strongest and most consistent in response to $\pm Y$ perturbations. Significant changes in reflex sensitivity were observed in the stretch response of six muscles for $\pm Y$ perturbations, two muscles for $\pm Z$ perturbations, and for one muscle for $\pm X$ perturbations. Across all muscles, interactions with the orthogonal environment induced stretch responses that were $73.2 \pm 49.9\%$ greater for $\pm Y$ perturbations, $26.2 \pm 18.4\%$ greater for $\pm Z$ perturbations, and $5.2 \pm 25.9\%$ greater for $\pm X$ perturbations. Because Y perturbations tended to be roughly aligned to the orientation of the orthogonal environment, this suggests that the orthogonal environment may have induced preferential reflex modulation.

B. Patterns of Reflex Coordination

The greatest modulation within muscles was observed in response to perturbations that were most closely aligned with the orthogonal instability. Therefore, we performed a control study in which perturbations were aligned exactly along the first and second axes of stiffness. This allowed us to examine modulation in muscle groups with reflexes elicited by perturbations along each of the destabilizing environments. Increased reflex activity across the muscle groups responding primarily to orthogonal perturbations, but not to other directions, would suggest

preferential tuning. Conversely, increased activity in all muscle groups would simply imply a global increase in reflex sensitivity throughout the arm.

PCA/ICA provided robust estimates of the underlying patterns of reflex activity for these data. Four ICs (Fig. 5) were required to account for more than 90% of the reflex variance. The components of each IC represent the relative activation of each muscle; the magnitude of each IC is normalized to 1.0. ICs were similar across subjects and environments, which is consistent with our previous findings [3]. Each IC was named according to the most prominent individual muscles within the IC.

The activation of the first three ICs in Fig. 5 was strongly linked to specific perturbation directions. For example, the ‘elbow+shoulder’ flexion and extension ICs were most active in response to perturbations in the orthogonal direction (Fig. 6B). The ‘shoulder flexion’ IC was most active in response to inward perturbations along the aligned direction (Fig. 6A).

Changes in the activations of the first three ICs were tuned to the mechanical properties of the environment. This can be seen in Figure 6B by the large, significant changes in the activation coefficients of the ‘elbow+shoulder’ flexion and extension ICs. Alternatively, no significant modulation was observed for the ‘shoulder flexion’ IC, the IC most active during perturbations aligned with endpoint stiffness. Note that the modulation that occurred in Figure 7A was for ICs that were not the main contributors to the reflexes elicited by aligned perturbations.

IV. CONCLUSIONS

Our results suggest that stretch sensitive reflexes can be tuned to the mechanical properties of the environment and how those mechanical properties are oriented relative to the arm. Specifically, we found that reflex responses were greatest in response to perturbations directed along an environmental instability. With reference to the example of using a screwdriver that was provided in the *Introduction*, our results would lead us to expect that stretch sensitive reflexes would be preferentially tuned to respond to perturbations orthogonal to the axis of the driver. Such tuning of the involuntary response to postural perturbations may represent an important mechanism by which the neuromotor system can rapidly adapt the mechanical properties of the arm to the mechanical constraints of a newly experienced task. For example, the reflex modulation presented here occurs upon immediate exposure to a new environment and does not appear to adapt to lengthy exposure to the same environment, however this could not be tested rigorously from the collected data; the perturbations, the exposure to each environment, and the target forces applied by the subjects were randomly timed across subjects.

Although our results demonstrate a clear modulation of the coordinated response to perturbations of multijoint posture, there are limitations to the present study. First, increased reflex responses only were observed during interactions with the orthogonal environment. This may reflect the fact that the tested instabilities were similar in magnitude to maximal endpoint stiffness, corresponding to the direction of the aligned environment. Hence, significant reflex modulation may not have been necessary for interactions with the aligned environment. The second limitation is that we have yet to quantify the reflex contributions to endpoint stiffness. Hence, although reflex sensitivity increases in a manner that is consistent with a task appropriate regulation of limb mechanics, the influence of that increased sensitivity on those mechanics remains to be quantified. Our ongoing experiments address both of these issues.

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Fig. 1.

(A) 3D robot and experimental setup. (B) Typical stochastic perturbation used to estimate upper limb endpoint stiffness in 3D. An endpoint force target was presented to subjects at 5 s (dashed line).

Fig. 2.
(A) Stiffness ellipsoid for a single subject. Principal axes are numbered. (B) Primary and secondary axes of stiffness for all subjects.

Fig. 3. (A) Destabilizing environment,. Thick and thin arrows denote forces applied by the HM and virtual walls, respectively. (B) Typical trial. The subject voluntarily stabilized the arm while holding the target force for the time denoted by the dashed lines. A single perturbation was then applied.

Fig. 4.

Reflex EMGs from a single subject in a restricted set of muscles. EMGs were elicited by the displayed displacements. Thin and thick traces are data obtained during interactions with the aligned and orthogonal environments, respectively. Dashed lines denote perturbation onset.

Fig. 5. Reflex ICs estimated from control data. Error bars were determined using a bootstrap analysis with 100 repetitions. Asterisks (*) denote $p < 0.05$. Bars are mean $\pm$ 95% confidence intervals.

Fig. 6.

Activation coefficients of the estimated ICs during interactions with both environments (ALI & ORT). Data were estimated from reflexes obtained while subjects applied 0N to the robot. Perturbations aligned with the **(A)** first and **(B)** second axes of stiffness are shown by arrows. Asterisks (*) denote $p < 0.05$. Bars are mean $\pm$ 95% confidence intervals. Control data were also collected with endpoint forces of 10N in the aligned and orthogonal direction and were consistent with this figure.