REFLEX CHANGES DURING ANTICIPATORY POSTURAL ADJUSTMENTS PRECEDING VOLUNTARY ARM MOVEMENTS IN STANDING HUMANS*

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INTRODUCTION

Human stance may be modeled biomechanically as an inverted pendulum pivoting about the ankle joint [1]. It has a high center of mass (COM) and a small support base at the feet, so the pendulum is fundamentally unstable as gravity acting at the COM will cause it to topple over. Studies of quiet stance have shown that the center of vertical pressure (COP) at the feet is displaced to maintain the vertical projection of the COM slightly anterior to the ankle joint [2]. In summary, relaxed human posture is unstable, with constant sway.

The ankle muscles have been identified as the prime effectors of controlling sway. Electromyographic (EMG) recordings from the triceps-surae (TS) complex show that they actively contract in quiet stance [3] producing torques to counteract gravity. There has been much debate about the mechanisms responsible for controlling this muscle activity. It is thought that postural sway is minimized by the resistance provided by a combination of the *passive* mechanical visco-elastic properties of the ankle muscles, tendons and ligaments [1] and *active* control from the central nervous system (CNS) incorporating vestibular, visual and proprioceptive information [4]. Furthermore, it has been postulated that *active* CNS control involves both feedback (reactive) [4, 5] and feedforward (predictive) mechanisms [6].

The feedback mechanism of primary postural significance is the stretch reflex. Muscles when stretched will initiate a reflex arc that that will cause them to contract and return to resting length. It is thought that the TS stretch reflex plays an important role in the control of sway by counteracting forward lean [7]; studies have shown that it can contribute significant stiffness (i.e. resistance to sway) to the pendulum [8] and that it can possibly be centrally modulated [9] independently of passive contributions.

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On the other hand, the core idea behind feed-forward mechanisms is that the CNS uses anticipatory control to maintain stability and employs strategies optimized on the basis of past experience [6]. In situations where the body is required to deal with large dynamic changes in stability, the existence of feed-forward postural control mechanisms has been widely accepted. A number of authors have shown that for a range of voluntary arm, trunk or leg movements, there are anticipatory postural adjustments (APA) , in which specific motor programs of postural muscles precede activation of the focal muscles required for the task at hand[10, 11].

To date, no one has examined how the stretch reflex changes during the APA. The aim of our study was therefore to quantify stretch reflex changes in the TS during the APA phase of a voluntary unilateral arm raise. This task has been used repeatedly for postural control studies, in which the TS complex is stretched during the initial phase of the APA.

METHODOLOGY

Experimental Apparatus

Figure 1 shows a typical subject on the experimental apparatus made up of four main components.

A. A custom-built bilateral electro-hydraulic actuator comprising of two rotary foot pedals equipped with load cells, potentiometers and torque sensors, was used to apply a short perturbation to the right leg.
B. A custom-built adjustable aluminum frame housed a visual cue (light emitting diode-LED), an audio cue (piezoelectric buzzer) and a movement target (Double Pole Double Throw Switch).
C. A desktop 8 channel differential EMG system (*Delsys Bagnoli*) was used to record muscle activity from the main postural muscles of both legs (Soleus, Lateral and Medial Gastrocnemius, and Tibialis Anterior) and the

primary focal muscle involved in the task (Right Arm Anterior Deltoidus).

D. Arm kinematics were measured using a single-axis inclinometer (*Microstrain FAS-G*) fixed to a splint (*Formedica Ergo-forme*) on the right wrist and oriented orthogonally to the radial bone. Elbow flexion was prevented using a custom-made cast.

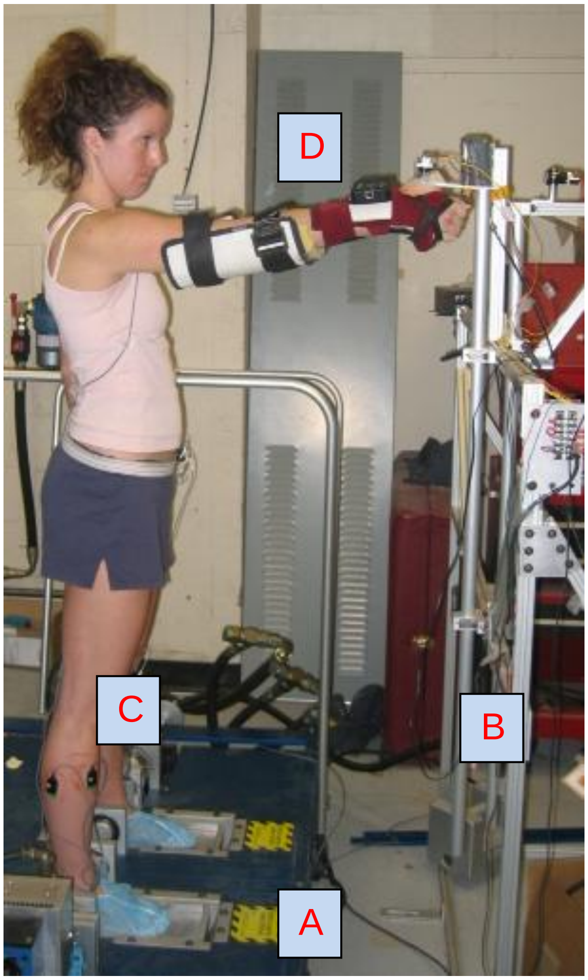

Figure 1. Side-on view of a typical subject executing a voluntary arm movement while standing on the actuator. **A.** Bilateral electro-hydraulic actuator fitted with two foot pedals and torque, position and load transducers. **B.** Aluminum target frame holding visual and audio cues, torque feedback meter and target switch. **C.** EMG surface electrodes on postural and focal muscles. **D.** Inclinometer used to measure arm angle.

<u>Experiment Control</u>

A real-time controller executed on a personal computer (XPCTARGET-*Mathworks Inc.)* controlled the rotary pedal and light signals via digital and analog input/output cards. A second personal computer fitted with data acquisition cards (*National Instruments 4472*) acquired and stored the EMG, ankle torque, and kinematic data. This computer also housed a custom-built graphical user interface (GUI) which allowed the experimenter to monitor or modify certain experimental parameters during the task.

<u>Experiment Protocol</u>

<u>Defining the operating point:</u> Subjects were instructed to stand on the two foot pedals maintaining relaxed stance. Subjects had visual feedback of the torque at each foot with two analog voltmeters attached to the frame in front of them. The torque applied to each rotary shaft was monitored for a period of 20 seconds. The GUI was used to set this torque level as a baseline, along with a modifiable tolerance level to act as the operating point for the initiation of each trial.

<u>Movement paradigm</u>: Subjects were instructed to hold down a 0-5V switch (double pole double throw) strapped to the right thigh with their inner palm to initiate the trial. The torque at each foot was monitored for a period of 2 seconds by the controller, during which time subjects were required to maintain torque levels within the defined operating point. Satisfaction of this requirement resulted in the onset of a 10ms beep from a piezoelectric buzzer, followed by the illumination of a LED on the target frame. Subjects were instructed to react to the visual cue, executing a quick unilateral right arm raise to hit the target switch with their right fist. After a 5 second rest period, subjects depressed the thigh switch to repeat the task. In an initial practice period, subjects executed a number of trials (25-30), until a consistent repeatable movement could be executed. To this end, reaction times (delay between light onset and release of thigh switch) and movement times (delay between release of thigh switch and depression of target switch) were monitored using the GUI. Once the subject had achieved a desirable pattern, data collection was initiated.

<u>Perturbed trials</u>: In approximately 75% of the trials, a small pulse displacement (0.025 radians, 20 ms wide) was applied to the right ankle at a random delay (from 800ms-1400ms) relative to the piezoelectric buzzer.

<u>Control trials</u>: In approximately 25% of the trials, no perturbations were applied. These trials gave estimates of changes in EMG and muscle torques purely due to the dynamics of the movement.

Perturbed and control trials were randomized. In total, each subject executed 350-400 trials during the experiment. A mandatory 2 minute rest period was provided every 5 minutes to minimize the effects of fatigue. A total of 7 subjects were tested.

ANALYSIS & RESULTS

Control trials

Figure 2 shows the mean response from the control trials of a typical subject. Individual trials were aligned to the movement onset (red line) using the rising edge inputs from the thigh switch as movement onset markers. The soleus EMG is shown to represent the TS complex. The onset of the APA (green window) is evident from the inhibition of the soleus, indicated by the arrow in Fig. 2D. This was followed by activation

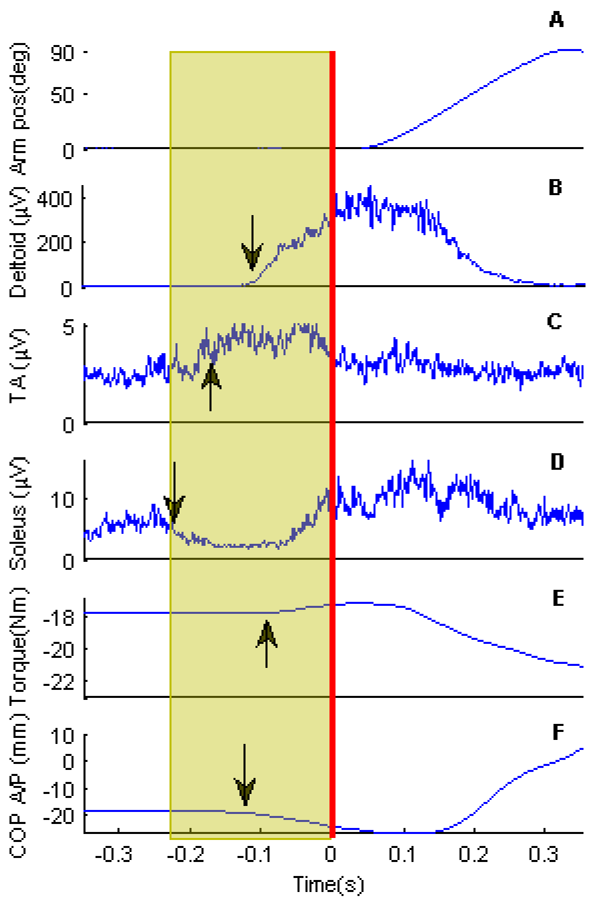

Figure 2. Ensemble averaged data from the control trials of a typical subject. Arm position (**A**), focal (**B**) and postural muscle (**C, D**) EMG's, ankle torque (**E**) and COP (**F**) are shown aligned on movement onset (red line). The APA region is indicated by the green window. Arrows indicate start of changes in each variable.

of the agonist TA, and lastly the activation of the anterior deltoid muscle responsible for the arm movement. This led to a backward shift in the COP and a small forward ankle torque response. These changes all preceded the actual movement of the arm, as shown by the arm position (Fig 2A), with movement onset occurring at time zero. This general pattern was consistent across subjects.

Perturbed trials

Figure 3 shows a representative perturbation trial from a typical subject. The position signal was used to determine the onset of the pulse (arrow in Fig 3B). The perturbation elicited a sharp reflex response in TS EMG (arrow indicating EMG peak in Fig 3C with LG used as a representative muscle). Note that the reflex EMG will subsequently cause a reflex torque response. The reflex torque responses were not analyzed at the time of writing and hence are not illustrated here. Since background changes in EMG also occur during the APA (e.g. Fig 1C and 1E), the mean background EMG in a 15-20 ms window after pulse application was also recorded for each trial (red window in Fig 3C).

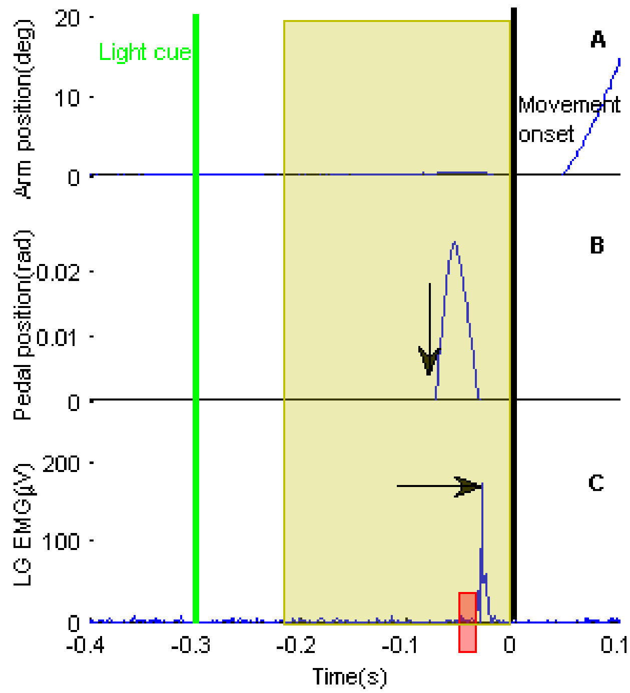

Figure 3. A typical perturbation trial. The pulse (panel B) was applied to the right leg eliciting a reflex EMG (panel C). Mean background EMG was recorded in a 15-20 ms window after pulse onset (red window- panels C).

Reflex EMG modulation

Perturbations were applied at different delays relative to the movement onset to measure the variation in the reflex before, during and after the APA. For each trial, the instantaneous time at which the reflex occurred was recorded. The data were then grouped into 25ms wide bins according to the relative delay between pulse and movement onset. For each bin, mean values and standard errors for reflex and background EMG and torque were computed. Bins which contained less than 5 trials were excluded.

Figure 4 shows the variation in the TS reflex (A) and background (B) EMG using the soleus as a representative muscle, from a typical subject. The individual trial values are indicated by the scatter plots, while the mean estimates and standard errors from each bin are shown by the overlying trend lines. Both profiles follow a biphasic pattern with an initial decrease followed by an increase. Background changes (Fig 4B) were similar to those obtained during control trials (Fig 1C), and reflex changes modulated with a similar time course (Fig 4A).

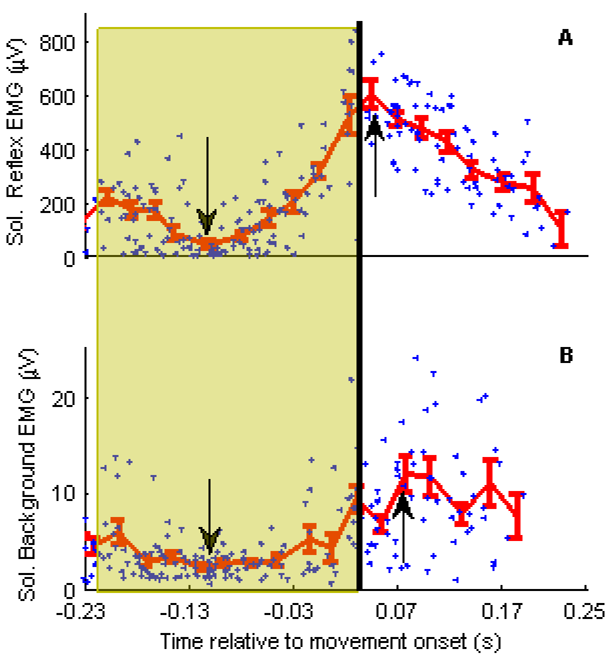

Figure 4. Time variation of the reflex (**A**) and background (**B**) soleus muscle activity during the APA. Mean values are averaged over 25 ms bins and shown in overlying fits. Downward arrows highlight the inhibition, while upward arrows highlight the up-regulation of the respective parameters.

CONCLUSIONS

EMG results indicate that the sensitivity of the stretch reflex at the TS is modified during the APA phase of a voluntary movement, such that it is initially down-regulated at the beginning of the APA phase and subsequently up-regulated close to movement onset. Furthermore, we found that reflex and background muscle activity co-varied during the APA, with no significant delay. Our findings do not support the idea that reflexes might be centrally modulated independently of muscle activity.

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