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Anticipation of elbow joint perturbation shortens the onset time of the reflex EMG response in biceps brachii and triceps brachii

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Abstract

This study aimed to investigate the influence of the anticipation of a perturbation torque applied to extend the elbow joint on the onset time of reflex electromyogram (EMG) responses. A perturbation torque generated by an electromagnetic torque motor system was applied to the forearm of five subjects during trials. The trials were divided into an anticipated (AN) condition—perturbation torque applied after the auditory signal—and an unanticipated (UAN) condition—suddenly applied perturbation. To detect the reflex EMG response in the biceps brachii (Bb) and triceps brachii (Tb) muscles, a new method involving the discrete wavelet transform and outlier tests was used. We found that the onset time of the reflex response in both the muscles in the AN condition was significantly shorter than that in the UAN condition. The angle of transition from flexion to extension, which was induced by the reflex response of Bb, was also significantly smaller in the AN condition than in the UAN condition. The results indicate that the anticipation of an applied perturbation torque decreases the onset time of the reflex response in the Bb and Tb.

Introduction

When a joint is destabilized by a suddenly applied perturbation, the stability of the joint must be enhanced by the co-contraction activity of the agonist and antagonist muscles [2,18,19,20]. It is reported that the co-contraction activity is increased at the middle latency of the stretch reflex (MLR) in the agonist muscle [5,10,18], and that the supraspinal structure influences the MLR [17]. Further it is stated the change in the activity of MLR is found to be a greater extent in the upper limb than in the lower limb muscles [22]. The structure can contribute to the enhancement of joint stability. However, to successfully stabilize a joint, the early onset of co-contraction after the perturbation may be required.

It is reported that the anticipation of the upcoming perturbation reduces postural destabilization after the perturbation is applied [13]. When the onset of perturbation is anticipated, a motor command to resist it is preliminarily generated in the supraspinal structure before the perturbation is applied [4,14]. For example, the activities of the primary motor cortex and the neurons in the transcortical pathways are involved in pre-programmed reactions [14] that preliminarily generate a motor program to control the destabilized joint posture induced by a peripheral stimulus [4]. Hence, it is possible that the anticipation of the upcoming perturbation will generate a motor program to resist the perturbation; this program will reduce joint oscillation. However, studies that investigated the effect of anticipation on the reflex responses in both agonist and antagonist muscles only reported that the activity of the muscles increased during the MLR [3,5,10]. No studies have investigated the effect of anticipation on the onset time of the reflex response in both muscles.

It has been reported that the onset time of the stretch reflex response in the agonist muscle is shortened during motor imagery [16], indicating that the subjects feel that they are performing a certain movement without actually executing it. The result suggests that the activity of the primary motor cortex during the motor imagery is involved in decreasing the onset time of the reflex electromyogram (EMG) response. It is possible that subjects subconsciously imagine the image of the direction and level of the perturbation torque due to their anticipation of the perturbation. Therefore, it is expected that the anticipation of the onset of perturbation would also decrease the onset time of the reflex response in the agonist and antagonist muscles.

In this study, to evaluate the hypothesis that the anticipation of the onset of a perturbation torque decreases the onset time of the reflex EMG response in the biceps brachii (Bb) and triceps brachii (Tb) muscles, we analyzed the reflex response in these muscles by using a new method involving the discrete wavelet transform (DWT); this method is more reliable than the conventional methods used to detect onset times [21]. Additionally, outlier tests that are adapted to the notion that the first peak value that shows a statistically significant value against the background EMG (BGA) is considered as the onset of the reflex response were used.

Materials and Methods

Eleven male subjects (age range, 18–36 years) with no history of any overall nerve and orthopaedic disorders in their right arm participated in this study. Prior to the experiment, informed consent was obtained from all subjects. The experimental protocol was approved by the Ethical Advisory Committee of Hokkaido University. We used an electromagnetic torque motor system [1] with a built-in torque motor (5TK20CGN-A/5GN50K; Oriental Motor Co. Ltd.), torque sensor (SS-200 sample version and TS-2600; Ono Sokki Co. Ltd.), and potentiometer (CPP45B). Fig. 1A shows the experimental setup. The beam (inertial moment, 0.030 kg/m^2) on which the forearm was rotated in a horizontal plane was coupled to a motor shaft that was parallel to the vertical axes. The subjects were asked to sit on a customized seat that was placed to the left of the motor system; their trunks were then secured to the seat by the use of straps to ensure that their trunk and upper arm positions remained unchanged throughout the experiment. Although it is necessary to maintain the right forearms and hands of the subjects in the neutral position between the pronated and supinated positions to induce the reflex response in Bb, it was difficult to fix the forearm and hand to the beam in this position. Their forearms and hands were fixed to the beam in the pronated position by using a non-stretch tape and Velcro straps to align the centre of the elbow joint with the motor axis. When fixed to the beam, their forearms were at right angles to their upper arms. The initial right angle at the elbow joint was considered as 0°, i.e., the full extent of movement of the joint was –90°. Surface EMG signals were obtained from two major elbow joint muscles—Bb and Tb. The EMG signals were collected using bipolar electrodes with a built-in amplifier and band-pass filter (bandwidth: 20–450 Hz) (SX230; Biometrics Ltd; inter-electrode distance = 20 mm, gain: 1000). Since the maximum resistance of the shaft to the perturbation torque was 20 Nm, 50% (16 Nm) (Angle, AN: 9.78 ± 2.54 deg; UAN: 11.34 ± 1.66 deg; Angular velocity, AN: 126.48 ± 22.27 deg/s; UAN: 135.28 ± 12.19 deg/s) and 55% (18.5 Nm) (Angle, AN: 10.68 ± 1.33 deg; UAN: 11.23 ± 0.25 deg; Angular velocity, AN: 129.52 ± 14.38 deg/s; UAN: 134.68 ± 10.95 deg/s) of the maximum torque level that was measured when the beam fixed at 0° was applied to the elbow joint of each subject to evoke the reflex response in the Bb and Tb. Further, the actual level of the perturbation torque was equal to the sum of the reaction torque induced by the inertial moment of the forearm and beam as well as by the elbow flexor. The measured torque values changed due to a change in the angular acceleration about the forearm and beam. The torque, potentiometer, and EMG signals were digitized at 2 kHz and stored in a laptop computer (PowerBook G3, Apple Computer, Inc.) via an A/D converter (MacLab 8S; AD Instruments Co. Ltd.).

Prior to the trials, each subject practiced experiencing the torque intensity for various periods of time. Subsequently, the experimenter informed them that the perturbation torque should be applied on the forearm more than 50 times, and instructed them to begin the trials. The torque levels were not changed until the subject completed their trials for each torque level. In half the trials for each torque level, prior to the manual application of a perturbation, the subjects were manually given auditory signals as an announcement and/or a warning to indicate the application of the perturbation torque. Therefore, in these trials, the subjects were able to anticipate the applied perturbation (anticipated condition: AN condition). In the other trials in which no auditory signal was given, the subjects were unable to anticipate the perturbation (unanticipated condition: UAN condition). Although the experimenter attempted to maintain the time interval between the auditory signal and the moment of perturbation torque application, the time interval was 0.37 ± 0.07 s (mean ± standard deviations (SD)). The trials in the AN and UAN conditions for each torque intensity were performed in a random order. The subjects were also requested not to activate both Bb and Tb before the perturbation torque was applied and to resist the perturbation immediately after it was applied. To confirm the relaxation of both muscles, we examined the BGA (for 300 ms before applying the perturbation) displayed on a computer monitor. Emergence of the BGA was not observed (Bb, AN: 1.38 ± 0.21 mV; UAN: 1.35 ± 0.32 mV; Tb, AN: 1.76 ± 0.34 mV; UAN: 1.71 ± 0.23 mV). Subjects were asked to perform the trials with two torque levels, and these trials were continued until 15 reflex EMG responses were acquired in each condition for each torque level. These responses were determined by the measured EMG waveform displayed on the computer monitor. The trials in which the muscles were activated before the perturbation was applied were excluded. Thus, a total of 60 data points per subject were collected (15 (trials) × 2 (torque levels) × 2 (conditions)) and used in the next offline analysis.

To detect the onset of the reflex response in the Bb and Tb, we used a new method that is based on the DWT and outlier tests. Previous studies on the detection of the onset time of the reflex response used the Daubechies, Coiflet, and Symmlet mother wavelets in the DWT [21,23]. A characteristic of the DWT is that the obtained signal is decomposed into multiple sub-signals by multi-resolution analysis. However, in the three types of DWT, not only the signal energy is mainly concentrated on multiple sub-signals but also the number of data points is reduced by half as the sub-signal is increased. Meanwhile, a characteristic of the spline wavelet is that the main signal energy is concentrated at only one level of sub-signals. Furthermore, the spline function uses a relatively easy technique for interpolating between adjacent data points; thus, the number of data points in the sub-signals obtained by the spline wavelet is identical to the original data [6]. Hence, we used the spline wavelet transform to decompose the measured EMG signal into seven sub-signals. Subsequently, we calculated the frequency domain of each level of the original signals by using the fast Fourier transform (FFT). As shown in Fig. 2A, the onset of the reflex response detected using level 4 signals had a higher amplitude than that detected by using signals of other levels. The frequency domain of the signals ranged from 50 to 120 Hz; this is consistent with those obtained in previous studies that demonstrated the frequency of EMG during movement [12]. We used level 4 signals for detecting the reflex EMG response by employing the following method. First, we created the baseline data group comprising the positive and negative peak values that periodically occurred during BGA since, as shown in the enlarged graphs in Fig. 2A, the amplitude of the BGA fluctuated slightly for the positive and negative values. Second, small fluctuations were also observed during the zero level EMG from the moment of perturbation application to before the onset of the reflex response, i.e., several positive and negative peaks were found during this period. Such fluctuations in EMG amplitude were also observed during the occurrence of the reflex EMG response; these fluctuations increased with time. Thus, we compared the peak values of the reflex EMG response observed 150 ms after the perturbation was applied with the fluctuations in the EMG signals during the BGA. Third, a peak value extracted from the values obtained after the applied perturbation was added to the baseline group; we then verified whether the added value was significantly different from that of the baseline group by using the Smirnov-Grubbs outlier test ($P < 0.05$). Finally, we considered that the earliest peak values varied significantly with the onset time of the reflex response. After computation, the onset times of the reflex response in the Bb and Tb muscles were compared between the AN and UAN conditions by using paired *t* tests ($P < 0.05$). Data are indicated as means ± SD in the text.

Results

Fig. 1B shows representative examples of the time series of the perturbation torque (top trace), angular displacement in the elbow joint (second trace), and the raw EMG data in Bb and Tb (third and bottom traces, respectively). The stretch reflex EMG response in the Bb muscle occurred at the moment at which the first peak occurred in the perturbation torque. Although the extension at the elbow joint began at the moment of the onset of the perturbation torque, the transition from extension to flexion occurred when the reflex response occurred in the Bb. The onset of the reflex response in the Tb EMG lagged behind that in the Bb EMG.

Fig. 2A shows representative examples of the waveform in the measured raw EMG signal, the seven sub-signals of the measured EMG signal decomposed by multi-resolution analysis of the DWT, and the frequency domain of each decomposed signal obtained by FFT. The left and right sides of the figure indicate the waveform in the Bb and Tb EMG, respectively. As described above, in the level 4 sub-signals that were used to detect the reflex response, the waveform during BGA was considerably smaller than that after the onset of perturbation, and the detection of the onset time of the reflex by using signals of this level was easier than that by using signals of other levels. Furthermore, the noise was centred on levels 1 and 2.

A paired *t* test revealed that the onset time of the reflex response in the Bb and Tb in the AN and UAN conditions was significantly different. As shown in Fig. 2B, the onset time of the reflex response in the Bb and Tb was shorter in the AN condition than in the UAN condition (Bb, AN:

0.049 ± 0.031 s; Bb, UAN: 0.059 ± 0.034 s; P < 0.01; Tb, AN: 0.070 ± 0.042 s; Tb, UAN: 0.094 ± 0.044 s; P < 0.01). These results may influence the angle of transition from extension to flexion in the elbow joint (Fig. 1B) induced by the reflex response in the Bb. We therefore tested the effect of the difference in the conditions on the kinematics of the elbow joint induced by the reflex response by using the paired *t* test. The extension-flexion angle was smaller in the AN condition than in the UAN condition (AN: –9.64 ± 5.97 deg; UAN: –13.98 ± 6.21 deg; P < 0.01).

Discussion

The stretch reflex response can be separated into three distinct components. The first component is the short-latency response (SLR) that involves a monosynaptic pathway from Ia afferents to the motoneurons (duration, 40–60 ms after the perturbation). The second component is the MLR that has a long latency and a more complex origin that may involve the supraspinal pathways (duration, 60–80 ms). The third component is long-latency response (LLR) that occurs occasionally (duration, 80–100 ms). Here, the onset time of the stretch reflex EMG response in Bb in the AN and UAN conditions occurred during the SLR, and the onset time was more advanced in the AN condition than in the UAN condition. The onset time in the Tb was also more advanced in the AN condition than in the UAN condition; furthermore, the onset time was during the MLR in the Bb in the AN condition and during the LLR in the Bb in the UAN condition. The results indicate that a situation wherein an upcoming perturbation is predictable allows a decrease in the onset time of the reflex response. Furthermore, as described above, the BGA was not observed in either the Bb or Tb. This indicates that the reduction in the onset time of the reflex response is caused by factors other than muscular force and/or activation, e.g., some kind of neural factor in the central nervous system and/or brain might contribute to the change in motoneuron excitation.

In contrast to these results, many previous studies have reported that supraspinal activity contributes to the LLR. For example, the reflex response via the transcortical loop that is associated with the generation of motor commands such as those involved in the central set and voluntary activities contributes to the modulation of the LLR gain [17]. Motor evoked potentials (MEPs) that are elicited by transcranial magnetic stimulation (TMS) and that artificially mimic the generation of a motor command within the primary motor cortex (M1) modulated only the gain of the LLR EMG [7,15,25], even if the TMS intensity was conditioned not to evoke muscle activity [25]. In early studies [7,15], because a constant period was required to transmit an afferent signal from a stretched muscle to a homogeneous muscle via the motor cortex, the motor activity in the motor cortex contributed to the LLR. Although a later study [25] explained that the activity of the motor cortex was enhanced when the afferent signal was transmitted from the stretched muscle through the motor cortex, the factor inhibiting the SLR and MLR was unknown. However, it was reported that in cats, the electrical stimulus of the medullary enhanced the activity of the inhibitory interneurons; thus, the interneurons inhibit motoneuron activity [26]. Hence, in previous studies that investigated the relationship between the reflex response and MEPs, the functional activity of the interneurons might have been responsible for the inhibition of the earlier two reflex responses, and thus, the supraspinal activity might not be reflected in the SLR.

Recently, Li et al [16] showed that the onset time of the reflex EMG response was shortened during motor imagery, i.e., the results showed the possibility of a relationship between the onset time of the reflex response and supraspinal activities. They also reported that when the muscle was activated before the perturbation was applied, the onset time of the reflex response was identical to that during motor imagery. Based on the results, they suggested that the pre-activation of the muscle probably enhanced the spinal motoneuron and interneuron excitations to sub-threshold levels; thus, the factor responsible for shortening the onset time of the reflex response would be the imagery-related sub-threshold activity of the neurons. Indeed, the level of motoneuron excitation increased during motor imagery [9], and the interneurons were also influenced by the motor command generated in the supraspinal centres such as the M1 and the premotor cortex [8,11]. Moreover, the firing rate of the interneurons varies with the status of preparation for perturbation [24]. In this study, the anticipation of the applied perturbation torque might also excite the motoneurons and interneurons to sub-threshold levels as well as elicit neural activation during motor imagery; thus, the excitation might shorten the onset time of the reflex response in the agonistic muscle.

Although previous studies reported that the anticipation of an upcoming perturbation torque affects the change in the amplitude of reflexive co-contraction [3,5,10], no studies reported the effect of the anticipation on the onset time of the reflexive co-contraction. We found that the onset time of the reflex response in Tb, which acts as an antagonist, was faster in the AN condition than in the UAN condition, particularly when the onset of the reflex occurred during the MLR in the Bb in the AN condition. The difference in the onset time of the reflex response in the antagonist muscle between the conditions is reflected in the co-contraction activity with the agonist muscle, i.e., the difference influences the modulation of joint stiffness. Hence, the postural destabilization of the joint that is induced by perturbation is probably influenced by the onset time of the reflex response in the antagonist muscle. Furthermore, the joint stiffness modulated by the reflex co-contraction increased during the MLR in the agonist muscle when both the agonist and antagonist muscles were pre-activated before the onset of the perturbation torque [2,10,18]. Our results indicated that the onset time of the reflex activity of the antagonist muscle was equal to the period of the MLR in the agonist muscle in the AN condition. This could be explained by the possibility that the increased activity of the supraspinal centre that was induced in anticipation of the upcoming perturbation torque enhanced the excitation of the motoneurons and interneurons associated with the antagonistic muscle.

The advanced onset time of the reflex response in the Bb and Tb in the AN condition was reflected in the change in the kinematics of the elbow joint after the perturbation was applied (Fig. 1B). In particular, the observation that the extension-flexion angle in the AN condition was less than that in the UAN condition indicates that the anticipation of an upcoming perturbation will control the destabilized joint posture.

In summary, the anticipation of an applied perturbation torque decreases the onset time of a reflex response in agonistic and antagonistic muscles.

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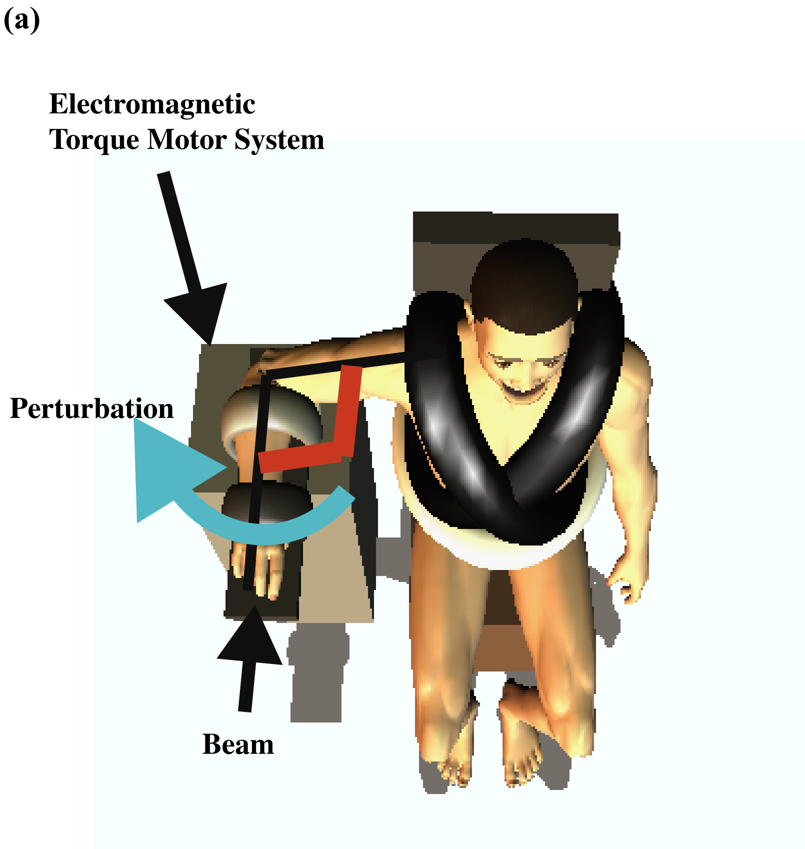
Figure legends

Fig. 1. (A) Experimental setup. (B) Representative data for perturbation torque, angular displacement of the elbow joint, and raw EMG data for the Bb and Tb; the data was obtained from a representative subject. The perturbation torque was applied at 0 s.

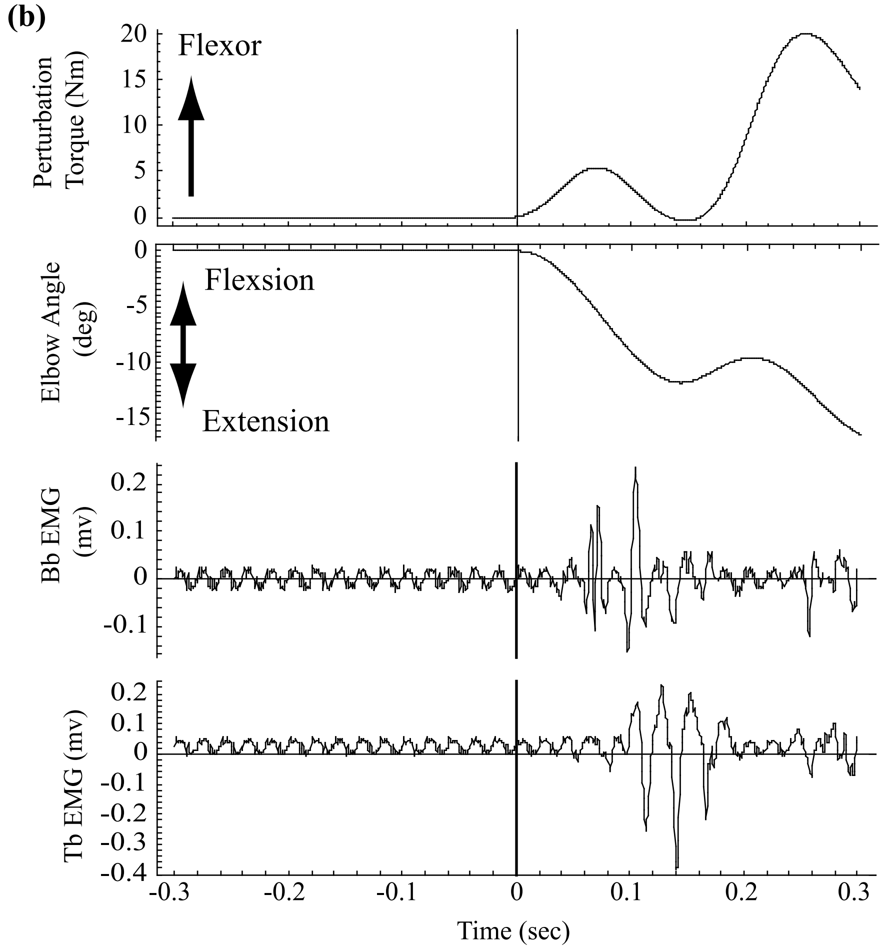
Fig. 2. (A) Schematic representative data for the waveform of the seven sub-signals of the measured EMG signal decomposed by multi-resolution analysis performed using the discrete wavelet transform and the frequency domain of each decomposed signal obtained by FFT. The left-hand side of the figure shows the decomposed EMG data and the frequency domains of the EMG signals for the Bb; the right-hand side of the figure shows these values for the Tb. As the decomposition level increased, the frequency domain decreased. The longitudinal axis through

each decomposed graph for each muscle indicates that a perturbation torque was applied. Enlarged signals are shown at the bottom of the figure. Arrows shown in both the level 4 sub-signals and the enlarged signals indicate the onset time of the reflex response. It is apparent that the onset time of the reflex response was faster in the Bb than in the Tb. (B) The onset time of the reflex EMG response in the Bb (Top trace) and Tb (Bottom trace). Error bars represent standard error of each mean value. ** indicates a significant difference ($P < 0.01$) between the AN and UAN conditions.

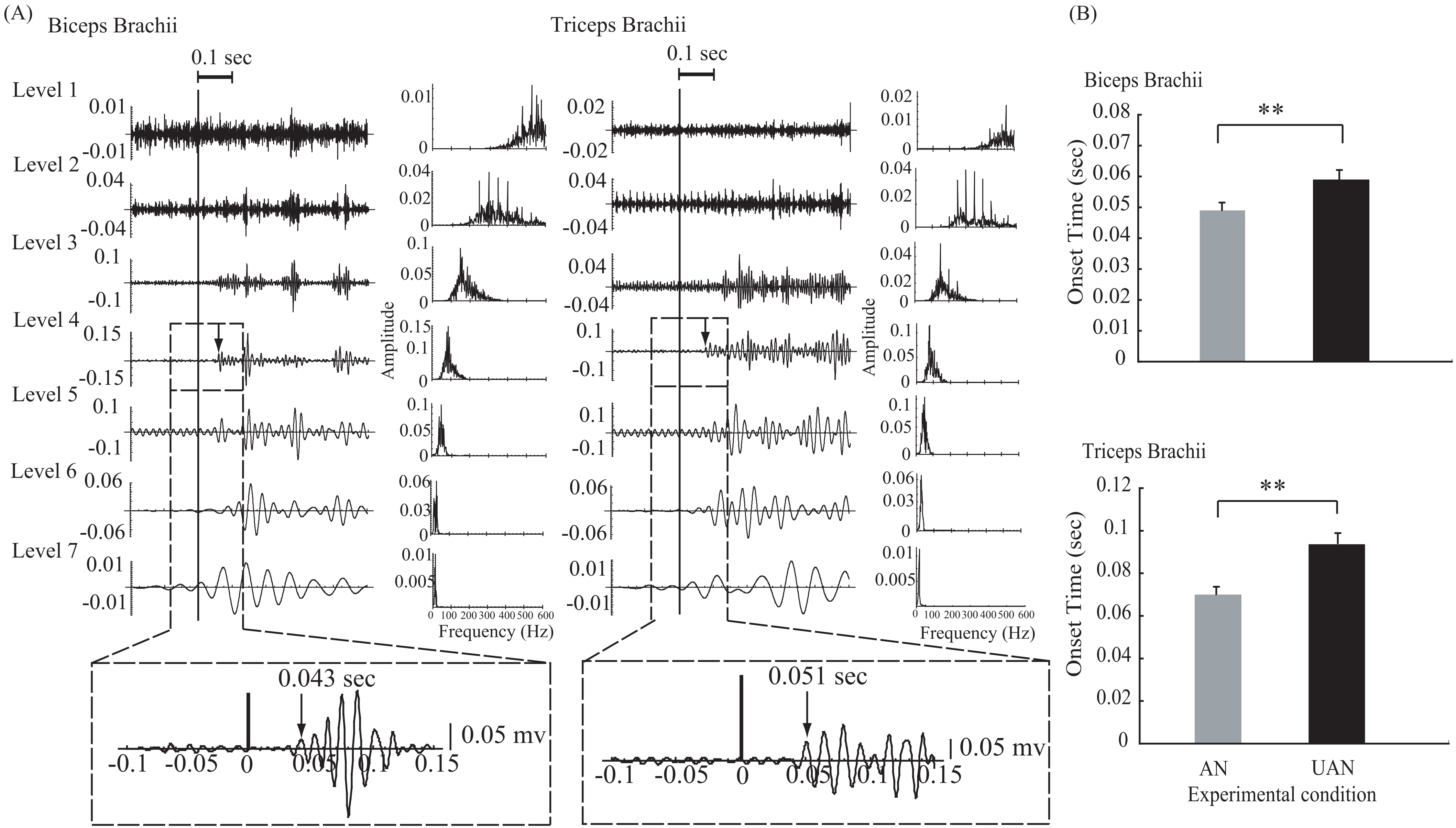
Fig.1



(a)
Electromagnetic
Torque Motor System
Perturbation
Beam



(b)
Perturbation
Torque (Nm)
Flexor
Elbow Angle
(deg)
Flexion
Extension
Bb EMG
(mv)
Tb EMG (mv)
Time (sec)


(A)
Biceps Brachii
Triceps Brachii
0.1 sec
Level 1
Level 2
Level 3
Level 4
Level 5
Level 6
Level 7
Amplitude
Frequency (Hz)
0.043 sec
0.051 sec
0.05 mv
(B)
Biceps Brachii
Triceps Brachii
Onset Time (sec)
**
AN
UAN
Experimental condition