Quantitative EMG analysis to investigate synergistic coactivation of ankle and knee muscles during isokinetic ankle movement. Part 1: time amplitude analysis

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Abstract

Synergy generally refers to the coordinated action of several motor elements to produce a specific motor task, either intentionally or automatically. One example is motor irradiation, a sudden spread of synergistic muscular coactivation resulting from a forceful single joint movement. To investigate this type of synergy pattern, a quantitative EMG approach was employed to characterize explicit neuromuscular synergy in the ankle–knee complex during maximal ankle isokinetic contraction. In the present study, isokinetic ankle contractions, both dorsiflexion and plantarflexion, at four different speeds (30, 60, 120, and 240 °/s) were studied in a normal adult population (N=11) to assess synergistic coactivation of the prime movers (tibialis anterior and gastrocnemius) and irradiated muscles (ipsilateral and contralateral rectus femoris and biceps femoris) of the ankle–knee complex. Electromyographic signals were collected with surface EMG electrodes and processed with traditional time-amplitude analysis to examine specific neural control strategies. The data generally supported several empirical assumptions common to neurological facilitation techniques. (1) Motor irradiation to the knee muscles due to ankle muscle isokinetic contraction was strongly directionally dependent. (2) Motor irradiation to the ipsilateral knee muscles due to ankle isokinetic contraction was speed dependent. (3) The prime movers demonstrated a similar control strategy, irrespective of different contraction speeds. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

An important feature of motor synergy is the action of the central nervous system to activate or suppress several related neuromotor pools to achieve a specific movement goal. Sometimes, motor neurons extraneous to the specific goal, either in another part of the body or in a different nerve territory, may be facilitated automatically in addition to the primary voluntary or semi-reflex movement. This accompanying facilitation is often referred to as motor irradiation [1]. A common example is the coactivation of the muscles at a proximal joint as a result of strenuous exercise of distal musculature. Zulch et al. attributed motor irradiation to an intermediate stage between pure reflex triggered action and volitional integrated movement from a motor control standpoint [24]. Frequently, motor irradiation is associated with fatigue resulting from sustained exercise, maturational reorganization or functional recovery of the motor system [23], or a variety of psychiatric and neurological disorders [10,14]. However, motor irradiation may also be extensively found in normal adults during some specific effort-related tasks [5,11]. Extraneous movements have been reported in non-homologous muscles, in either contralateral or ipsilateral limbs, during motor tasks such as sustaining target pressures using different fingers, or rapid and repetitive finger thumb alternation. Motor irradiation is not confined to motor tasks of the upper extremity but is also common to those of the lower extremity. Recent research has documented significant coactivation of knee muscle groups in the ipsilateral and...
contralateral lower limbs when even a minor isometric contraction of the ankle dorsiflexors was performed [2]. This observable presence of associated motor activity has raised relatively little attention in the field of neuro-motor control, whether it may serve as normal coordination for an unknown purpose or as something harmful to movement performance.

Neurophysiological mechanisms of motor irradiation are not well understood, nor are all related neural pathways confirmed. In spite of this limited comprehension, motor irradiation is of clinical interest and has been applied empirically in neurological rehabilitation as a means of providing facilitation of weakened muscles for the enhancement of mobility and stability of a volitional movement [7]. To our knowledge, there is no research documenting activation patterns of motor units during strenuous exercise with motor irradiation as an effect. In the present study, in particular focusing on knee muscle irradiation due to ankle isokinetic contraction, we hypothesized that the excitation patterns of the spinal motor pools caused by motor irradiation are asymmetric, dependent upon the ankle movement direction and speed. The selection of an isokinetic contraction was to approximate the principle of maximal resistance (MR), one of the most important elements in proprioceptive neuromuscular facilitation (PNF) when employed to facilitate weakened muscles.

2. Methods

Eleven healthy adult subjects (9 males, 2 females, mean age =30.2 years old, range =24–38 years old) were examined in this study. Subjects were selected from a pool of volunteers at the University of Texas at Austin. All subjects were university students without a history of any neuromuscular diseases in the past. All subjects had normal full ankle range of motion (roughly ankle dorsiflexion 0–30° and plantarflexion 0–45°), and provided informed consent according to the guidelines set forth by the Department of Health and Human Services concerning the protection of human subjects.

2.1. Test administration

A Biodex dynamometer (Biodex Medical System, Shirley, NY) was used to provide the distal effort protocols for the ankle muscles. Each subject performed two modes of ankle isokinetic contraction (dorsiflexion and plantarflexion) with four different angular velocities, slow (30°/s), intermediate (60 and 120°/s) and fast (240°/s), randomly ordered across subjects. The movement range covered the entire comfortable range of motion of subject’s ankle joint (roughly plantarflexion 45° to dorsiflexion 30°). The subject was seated in the dynamometer chair with the dominant hip at 90° flexion and the knee stabilized at 45° flexion (Fig. 1). The subject’s dominant foot was tightly fixed in the footplate of the dynamometer. The ankle joint of the subject was aligned with the axis of the dynamometer. The contralateral knee, fixed by an adjustable knee brace, was kept at 45° with the hip flexed at 135° and the ankle in a comfortable neutral position. The seating position was a standard position for testing ankle isokinetic movement in the Biodex system. The reference angle (0°) in this case corresponded to the ankle’s neutral position. All testing was conducted with the subject’s hands placed by the hips.

Practice sessions were allowed for subjects to become familiar with performing isokinetic exercise in the Biodex. The isokinetic mode, similar to MR of the proprioceptive facilitation technique in principle, was chosen because it is artificially constrained so that maximal voluntary effort was possible during the whole movement session. Subjects were asked to produce their maximal concentric efforts at the ankle joint isokinetically for three trials at each of the fixed preset velocities. Between trials was a rest period of at least 3 min so that fatigue was prevented. There were a total of twenty four individual trials for each subject in the testing protocol including two directions of ankle isokinetic exercises (dorsiflexion and plantar flexion) with each performed at the four speeds. EMG activities from the ipsilateral tibialis anterior (TA) and medial gastrocnemius (GS), and both ipsilateral and contralateral rectus femoris (RF) and biceps femoris (BF) were recorded using preamplified bipolar surface electrodes (Iomed, Inc., electrode spacing 2.5 cm; diameter 1.1 cm, a gain of 380 and a
CMRR of 102 dB) placed on the long axis of each muscle and centered over the muscle belly.

Torque, ankle angle, and ankle angular velocity were sampled at 60 Hz and stored in the relay computer-1 (Intel 386 SX) which was connected directly to the dynamometer. Prior to digitization, the EMG was conditioned using an analog band pass filtering distribution box with cut off frequencies set at 6 and 500 Hz. The EMG signal was sampled at 1 kHz with a data acquisition card (AT-MIO16, National Instruments) in a relay computer-2 (PowerMac 7100/66). All EMG data collected in the experiment were stored on a ZIP floppy disk (Iomega Inc.) controlled by LABVIEW 4.0 (National Instruments, Austin TX) for processing. The torque, the velocity, and the power were computed at each degree of the ROM to establish the kinetic records for each test condition. The EMG signal was processed off-line to extract useful physiological features as described below.

2.2. Data analysis

Off-line EMG signal analysis included removal of any linear trend from the raw EMG, calculating the root mean square of the detrended EMG, and statistical analysis of the mean EMG RMS across different experimental sessions. Signal processing and statistical analysis were completed using MATLAB v. 5.2 (Mathworks Inc.) and spss for Windows v.7.0 (SPSS Inc.), respectively. Preliminary processing removed the linear trend of the raw EMG signal prior to the time-amplitude analysis. The detrended EMG signals were represented in the form of a root mean square (RMS) with a window of 25 ms. Repeated measures two way ANOVA and chi-square statistics were used to compare differences in the mean EMG RMS of the coactivated knee antagonist pairs (ipsilateral/contralateral RF and BF) during ankle isokinetic contraction at the four different speeds. The main interests of this analysis were EMG RMS differences: (1) among the four angular speeds; (2) between contralateral and ipsilateral muscles; and (3) between the two different directions (plantarflexion and dorsiflexion) of the ankle isokinetic contractions of the irradiated muscles. The first two issues were examined by repeated measures two way ANOVA with mean EMG RMS as a dependent variable. The third was examined using a chi-square statistic with the occurrence frequency of the irradiated muscles that was defined as the number of knee muscles exhibiting a significant irradiated activation (mean EMG RMS 3•standard errors of background activity) in all populations. In addition, to compare the muscle activation level of the prime movers, mean EMG RMS of the TA and GS muscles at different contraction speeds were analyzed using one way repeated ANOVA. The level of significance was 0.05. In this study the probability of extraneous contamination between the contralateral muscle groups was assumed to be insignificant.

3. Results

One of the major findings of the present research was two different irradiation patterns in the knee muscles for ankle isokinetic dorsiflexion and plantarflexion. Fig. 2 shows the occurrence frequency of activated knee muscles in the whole testing population in two different modes of isokinetic movements. A chi-square test indicated that the occurrence frequency of the irradiated response was strongly dependent on ankle movement direction ($\chi^2(3) = 11.878, p<0.01$). In other words, the irradiated patterns, induced by the two modes of ankle isokinetic movements, were directionally dependent. Corresponding to the second and the third hypotheses, related major findings of this research were significant velocity dependence and asymmetry of the knee irradiated response. In this part, only two major irradiated responses, mean RF EMG RMS during dorsiflexion and mean BF EMG RMS during plantarflexion, were examined based on three averaged trials at each of four different contraction speeds. Fig. 3 shows the mean value of the EMG RMS of the RF during ankle dorsiflexion, and statistical analysis of the mean values. Repeated measures two way ANOVA showed that the RF mean EMG RMS depended on both limb and ankle contraction velocity ($p<0.01$). Post hoc comparison indicated that only the ipsilateral limb demonstrated a significant velocity effect ($F(3,24)=8.56, p=0.000$). In the ipsilateral limb, mean RF EMG RMS at 30°/s was

![Fig. 2. Occurrence frequency of irradiated knee muscle activity in the whole testing population during slow isokinetic ankle movements (30°/s). (IRF: ipsilateral rectus femoris, IBF: ipsilateral biceps femoris, CRF: contralateral rectus femoris, CBF: contralateral biceps femoris).](image-url)
the largest for all the contraction speeds and statistically different from that in the contralateral side \((F(1,8) =7.17, p=0.028)\).

The finding in the BF during isokinetic plantarflexion was similar to that in the RF during isokinetic dorsiflexion. ANOVA showed the mean EMG RMS of the BF during ankle plantarflexion was different between limbs \((F(1,10) =22.91, p<0.05)\) and dependent on ankle contraction velocity \((F(3,30) =12.48, p<0.05)\) with significant interaction of two factors \((p<0.05)\). Post hoc comparison indicated that mean EMG RMS of the ipsilateral limb had decreasing trend as ankle contraction velocity increased \((F(3,30) =14.69, p=0.000)\), and the mean EMG RMS of the ipsilateral BF at slower contraction speeds at both 30°/s \((F(1,10) =11.05, p=0.008)\) and 60°/s \((F(1,10) =6.02, p=0.034)\) were significantly larger than those of the contralateral BF. Fig. 4 displays a summary of the mean EMG RMS of the BF during isokinetic ankle plantarflexion. Unlike the irradiated muscle activation patterns, repeated measures of one way ANOVA of the EMG RMS of the prime movers did not demonstrate any significance with respect to the contraction speed during dorsiflexion and plantarflexion \((p>0.05)\). Table 1 shows the mean, standard deviation, and \(F\) test results of the mean EMG RMS of the prime movers during ankle isokinetic contraction at four different contraction speeds.

According to the results in these time-amplitude analyzes, four major findings emerged based on EMG RMS.

1. The irradiated muscle patterns of the knee muscles were different between isokinetic ankle plantarflexion and dorsiflexion. (2) The slower contraction speeds (30 or 60°/s) of ankle isokinetic movements generally induced a more significant irradiated response in the knee muscles.

3. The ipsilateral irradiated response of the knee muscles was significantly larger in amplitude than the contralateral one. (4) No speed effect was discovered in the prime movers during ankle isokinetic contraction.

4. Discussion

This study examined a simple motor task requiring voluntary dynamic motor activity at only the ankle joint from eleven subjects with evident ankle–knee coacti-
vation. With potentially confounding factors such as age, neurological status, and handedness controlled, all subjects demonstrated patterned synergistic coactivation. The features of this synergism, quantitatively characterized with surface EMG based on time-amplitude analyses, including directional dependence, speed dependence, asymmetry, and control strategy, are discussed in the context of theoretical and clinical implications.

4.1. Directional synergistic coactivation

The first hypothesis of this research, that synergistic coactivation patterns of the knee muscles are different between isokinetic dorsiflexion and plantarflexion, was strongly supported. Examined by chi-square test, two independent activation patterns for isokinetic dorsiflexion and plantarflexion, in terms of occurrence frequency, were identified. In general, isokinetic ankle plantarflexion led to knee flexor irradiation, in contrast to knee extensor irradiation during isokinetic ankle dorsiflexion. Some occasional individual variations appeared in this experiment, including RF coactivation during plantarflexion or BF coactivation during dorsiflexion. However, those variations were relatively insignificant in activation magnitude and less frequent in occurrence as compared to the primary coactivated muscles. The findings of a directional synergistic coactivation of the ankle–knee complex are in accordance with the idea of task dependent motor irradiation [16,18]. To our knowledge, no known mechanisms could satisfactorily explain this direction dependent response. Within a given hemisphere, subdivisions of the motor cortex are connected to adjacent subdivisions upon which interlimb or intralimb integration for a movement is based [21]. It is possible that motor cortex activations involve in a different population of the corticospinal fibers with different degrees of activation among interneurons that connect various spinal motor pools with respect to the task command. From a biomechanical standpoint, patterned motor irradiation may help in optimizing joint stability, despite possibly impeding movement dexterity. A strenuous isokinetic dorsiflexion in the distal ankle joint could mechanically lead to a resultant flexion torque in the proximal knee joint. It is possible that the RF irradiates correspondently to counter the disturbing flexion torque on the knee joint. Similarly, isokinetic plantarflexion could also bring about a preferential motor irradiation of the bicep femoris. As a matter of fact, inherent in the neuromuscular system, proximal motor irradiation due to distal movement is likely to serve a stability purpose.

4.2. Speed dependent synergistic coactivation

The second hypothesis of this research, that synergistic coactivation of the knee muscles is dependent on the contraction velocity of the ankle joint, was largely supported. According to the statistical analysis, regardless of the movement direction of the ankle joint, slower contraction induced a significantly larger irradiated activity of the RF in dorsiflexion as well as of the BF in plantarflexion on the ipsilateral side. These results were not unexpected, according to the torque-velocity characteristics of a joint [6,19] and muscle mechanics based on the Hill model [8]. During concentric contraction, an inverse relationship between the moment and the velocity has been described for both single and two joint muscles [3]. In spite of maximal voluntary contraction of ankle movement, in reality, the moment output in a slow isokinetic contraction speed is greater than that in fast isokinetic contraction. According to the stability criterion, greater moment output in the ankle joint correspondingly results in greater coactivation of the knee joint muscle for stability from a biomechanical standpoint. Therefore, the extent of the irradiated response of the knee muscles, in terms of mean EMG RMS, was significantly larger during slower ankle isokinetic movement. However, in this study, the speed dependence of the synergistic coactivation seemed insignificant among higher contraction speeds (60, 120, and 240°/s) in some irradiated muscles. This might be because the relative differences of torque output among speeds decreased and subjects might not be able to reach a preset speed because of biomechanical constraints such as limited range of motion for ankle joint acceleration [20]. Additionally, a speed-independent response on the contralateral side might possibly be due to additional inhibitory mechanisms involved in contralateral influences. This idea is further discussed in the next section.

4.3. Asymmetric synergistic coactivation

The third hypothesis of this research, that differences exist between ipsilateral and contralateral motor irradiation due to ankle isokinetic movement, was generally supported. It has been reported that motor irradiation could spread from one side to the other, “homolateral activation” [2,5,16]. Notwithstanding a limited understanding of motor irradiation and numerous hypothetical underlying mechanisms, two possible explanations based on neurophysiological findings are: (1) transcallosal facilitation, scattering coactivation of both hemispheres in the cerebral space by well-known crossing fibers in the corpus callosum [1], and (2) spinal bifurcation, a split of the pyramidal tract in the brainstem [12,13]. Our results from surface EMG support the first concept of the transcallosal facilitation because of typical homolateral responses of knee irradiated muscles in both limbs during plantarflexion, though the extent of irradiation in both sides was different. The relatively insignificant irradiation in the contralateral limb suggests the spread of activation to contralateral structures in the brain (ipsilateral) is naturally more limited because of several unidentified inhibitory mechanisms in
the cerebrum [21]. In addition to neural activity in the brain, Kanouchi et al. [9] pointed out that the ipsilateral motor cortex and ipsilateral uncrossed corticospinal tract play a major part in the generation of motor irradiation. In normal subjects, approximately 85–90% of pyramidal fibers decussate in the medullary pyramid and constitute the lateral corticospinal tract. In contrast, only about 10–15% of the fibers remain uncrossed to continue in the anterior corticospinal tract [15]. Functionally, the asymmetrical synergistic activation can also be explained by our stability criterion in that stabilization for the ipsilateral knee joint due to ankle perturbation (isokinetic movement) is necessary, instead of the contralateral knee joint. Hence, the rather significant muscle activity recorded in the ipsilateral knee muscles can be expected. As all subjects were right dominant and right ankles were examined, it is not irrational to consider this to be an effect of handedness [11]. Nevertheless, it seems unlikely. Most research regarding handedness has reported greater homolateral motor irradiation associated with the use of the non-preferred limb [4,19], unless some special tasks are performed like finger placement [16]. However, all subjects in this study voluntarily contracted the dominant ankle muscles, yielding a larger ipsilateral irradiated knee responses.

5. Conclusions

Muscle weakness and loss of coordination could be a result of segmental or multiple injuries of the neuromuscular system. Stimulation of the proprioceptive system by PNF has long been considered a promising treatment to attain a greater motor response and to re-educate impaired muscles [17,22]. The empirical use of mass movement patterns induced by motor irradiation to restore integrated motor functions has been characterized in this study. The main findings and corresponding clinical implications of the present investigation are: (1) the directional dependence of the motor irradiation during ankle isokinetic movement in part agrees with the use of patterned movement to produce a better response, the central idea of the PNF technique. (2) Speed related motor irradiation of the knee muscles indicates that a better facilitation of the proximal limb muscles is achieved at constant slower ankle speed with MR applied on the distal joint. In this regard, the use of PNF with MR applied to subjects could not be made more useful by requiring fast contraction. (3) Asymmetric motor irradiation due to distal effort favors facilitation of the ipsilateral proximal joint muscles. All of these findings may relate to the maintenance of knee joint stability during isokinetic ankle movement.

References

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