Proprioceptive facilitation of muscle tension during unilateral and bilateral knee extension

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Key Words: Knee extension - Peak torque - Muscle stretch - Neuromuscular facilitation - Excitation - Storage of elastic energy

A B S T R A C T

The effects of double neuromuscular facilitation (DNF) in unilateral movements and of quadruple neuromuscular facilitation (QNF) in bilateral movements were studied in 42 physically active college age male subjects. Results showed a 10.4% significant increase of maximal knee extension torque output when unilateral extension was preceded by a knee flexion on an isokinetic exerciser and a 16.7% increase of maximal torque in the bilateral condition of simultaneous alternating flexion-extension when compared to the simultaneous extension movement. Consequently, the increased peak torque observed in the unilateral and bilateral experimental conditions in which knee extension was preceded by a knee flexion appears to be the result of a combination of neuromuscular influences and stored elastic energy.

INTRODUCTION

Proprioceptive impulses that enter the central nervous system from the muscles, tendons and joints play a vital part in normal voluntary movement. The force of muscle contraction depends largely on the number of activated motor units and, consequently, the use of facilitating mechanisms that originate from proprioceptors should be an integral part of strength training exercise regimens designed to achieve the strongest possible muscle contraction. This has been the case in the fields of physical medicine and rehabilitation where each of the more recognized neurophysiologically based exercise systems are characterized by a subset of specific sensory stimulation techniques capable of facilitating or inhibiting volitional muscular action (2, 3, 4, 9, 10). However, in the field of athletic training where increases in muscle force are considered to be important to improve performance very few studies have attempted to test the strength training protocols in which exercises are based on neuromuscular influences to achieve a greater muscle output.

Lagasse (14) and Morris (16) reported gains in muscle tension following a sudden stretch of the right quadriceps during a maximal bilateral isometric voluntary contraction. The contralateral unstretched muscle simultaneously decreased its output. These findings were explained by muscle spindles influences: following a sudden stretch, proprioceptors discharge impulses along Ia afferent fibers which, at the spinal level, make direct excitatory synapses on motoneurons of the stretched muscle. The Ia afferents also connect on inhibitory interneurons that synapse on and inhibit motoneurons of the antagonist muscle. The Ia afferents are also connected to interneurons that affect the motoneuron pool of the contralateral muscles. The opposite agonist is inhibited and the opposite antagonist is facilitated, as in the pattern of the well known crossed extension reflex. Facilitation of the stretched muscle and inhibition of its antagonist produce a higher agonist muscle

torque output, and this is in contrast to the contralateral muscles where there is a decrease in extensor muscle tension because of agonist inhibition and antagonist facilitation.

Other proprioceptive receptors at the muscle level are the Golgi tendon organs (GTOs) that act as autoregulated inhibitors to protect the muscle against excess of tension development. Excited GTOs discharge along Ib afferent fibers and synapse on interneurons at the spinal level. Interestingly, the evidence indicates that GTOs and muscle spindles have opposite effects. It is postulated that GTOs inhibit ipsilateral agonists and contralateral antagonists (5). Then, during a flexor muscle contraction, GTOs would facilitate the motoneuron pool of the extensors and, at the same moment, muscle spindles of the extensor muscles, stretched by the concentric contraction of the flexors, would also have a facilitation effect on the extensors motoneuron pool.

The present experiment was undertaken to examine whether facilitation influences from both types of proprioceptors can be summed or not. When comparing an extension movement with a flexion followed by an extension movement, an increase of maximal torque output in the latter condition would argue in favor of the double neuromuscular facilitation (DNF) hypothesis. Similarly, the quadruple neuromuscular facilitation hypothesis (15) would be supported by an increase of the maximal torque output in a bilateral alternating flexion-extension movement when compared to a bilateral simultaneous extension movement.

METHODS

The subjects were 42 physically active male undergraduate student volunteers. Their mean age, height and weight were 21.1 (± 1.5) years, 173.9 (± 4.4) cm and 70.3 ± (6.3) kg, respectively. Each subject participated in three testing sessions held 24 hours apart. There was no habituation period prior to testing. On each session, subjects executed three trials of each of the four experimental conditions: (1) a left unilateral knee extension (UE) from 90 to 180 degrees, (2) a left unilateral knee flexion immediately followed by a knee extension (UFE), range of motion being from 180 to 90 and back to 180 degrees, (3) a right and left bilateral simultaneous knee extension (BE) with both legs extending from 90 to 180 degrees simultaneously, and finally (4) a bilateral alternating simultaneous knee flexion and extension (BFE), the right limb moving from flexion (90°) to extension (180°) and back to flexion (90°) and the contralateral left limb moving simultaneously from extension to flexion and back to extension. There were five minutes of rest between each experimental condition and the order of treatment conditions was balanced across subjects to attenuate sequence effects. Intervals of 30 seconds were interspersed between trials. The duration of each trial was 0.5 second for UE and 1.0 second for UFE, BE and BFE experimental conditions. On each trial subjects were instructed to perform maximal speed muscle contractions.

For all experimental conditions, left knee maximal peak torque output was monitored by a microprocessor controlled dynamometer for testing human muscle function (Omnitron system I). The test device allowed the user to perform a movement or series of movements against a resistance provided by the machine via a rotating lever arm system in isokinetic as well as in isometric modes. By means of a hydraulic cylinder, the unit provides double concentric resistance allowing the measurement of knee extension and flexion muscle functions. A dedicated microprocessor system was used to monitor position and force on the Omnitron system. Angular position was measured from the signal obtained from a precision angular encoder. A graded pressure transducer that

sensed the pressure in the cylinder was used for force and torque measurements. An accurate crystal timer was also part of the Omnitron hardware. The velocity of muscle contraction was calculated from the time base and positional information. Peak torque output scores and muscle contraction velocity were displayed on a small screen positioned in front of the subject.

The hydraulic cylinder could be adjusted to provide 11 different isokinetic resistance levels. In the present study, resistance level number 6 was selected because it provided an average angular velocity of muscle contraction equal to 179.3 °/s ($\pm$ 5.1). Because the Omnitron System I allowed for the measurement of only one knee, a second cylinder with its lever arm, similar to the first one, was joined to the apparatus to provide resistance for the right knee flexors/extensors. The addition of a second cylinder was required for testing under the BE and BFE bilateral muscle work experimental conditions.

RESULTS

As seen in Table 1, maximal left knee extension torque output varied considerably from day to day for the four experimental conditions. The ANOVA between days yielded significant ($p<.01$) increases in maximal torque output for all experimental conditions. Post-hoc comparisons by Duncan's multiple range test revealed that maximal knee extension peak torque output was significantly lower on day 1 ($p<.05$) but remained stable between days 2 and 3 for all experimental conditions ($p>.05$). Consequently, only data from days 2 and 3 were used in the subsequent statistical analyses which were conducted to evaluate the difference between unilateral extension (UE) and unilateral flexion/extension (UFE) and the difference between bilateral simultaneous extension (BE) and bilateral alternating simultaneous flexion and extension (BFE).

As seen in Table 1 and displayed in Figure 1, the average maximal knee extension peak torque output for days 2 and 3 was 81.1 Nm ($\pm$ 12.1), 89.5 Nm ($\pm$ 11.9), 71.2 Nm ($\pm$ 12.9) and 83.1 Nm ($\pm$ 11.2) respectively for the UE, UFE, BE and BFE experimental conditions. The ANOVA conducted to test the difference in peak torque output between the two unilateral conditions (UE and UFE) yielded a signifiant ($p < .01$) F-ratio. In the bilateral experimental conditions, the results of the ANOVA indicate that maximal knee extension peak torque output was significantly ($p<.01$) lower for BE than for BFE.

DISCUSSION

Day-to-day variance

As seen in table 1, maximal knee extension torque varied significantly ($p<.05$) between days 1 and 2, but remained stable from day 2 to day 3 for all experimental conditions. Furthermore, the trend for treatment effects was the same on each day. The differences observed between days 1 and 2 reflect the instability of this measurement, the lack of familiarization with the device and corroborate previous findings by Kroll (13) who reported that a significant improvement in maximal isometric strength from day 1 to day 2 might represent an increase in muscular strength due to the combination of a training effect and of a learning effect from one test session to the other. The training effect reflects the increase in the capacity of each muscle fiber to exert more tension, while the learning effect focuses on the adaptability of the central nervous system that activates more fully the agonist muscles while their antagonists are inhibited (13). These invalidating factors needed to be controlled before the measured variables could reach an acceptable level of reliability, which was attained on day 3 as demonstrated by the non significant F-ratios for all experimental conditions between days 2 and 3. Consequently, only data from days 2 and 3 were retained for the subsequent statistical analyses.

Unilateral versus Bilateral Extension Movements

The observed reduction in maximal knee extension torque during the bilateral extension condition (BE) as compared to the unilateral condition (UE) corroborates findings reported in the literature. Ever since the classical work of Patrizi (18), Claparède (7) and Rimathé (19), muscular work output has been known to be approximately 30% higher when one limb works alone as compared to its work done simultaneously with the contralateral limb. Despite the fact that this information was published several decades ago, the neurophysiological mechanisms responsible for this phenomenon have been difficult to pinpoint. Vandervoort et al (22) proposed the dispersion of the motor command to

explain the activation of a lower number of motor units. Interaction between cerebral hemispheres and/or spinal reflex influences have been considered by Ohtsuki (17) who also demonstrated that the bilateral deficit was reduced or abolished when isometric contraction of a muscle group in one limb was simultaneous with isometric contraction of its contralateral antagonists. This finding contradicts the motor command dispersion proposal and the suggestion of Kelso et al (11) who stated that the motor system was solving the different activation problems by activating all the muscles as a unit. There undoubtedly is an inhibitive mechanism which is active during bilateral simultaneous agonist contractions, and more or less passive or absent during the reciprocal condition of agonist and contralateral antagonist contractions. Moreover, training in a simultaneous mode (both knee extensors contracting at the same time) as opposed to an alternate mode (simultaneous contraction of knee extensors of one leg and knee flexors of the other leg) has been shown to influence the bilateral deficit and the action of this mechanism (20).

Unilateral Movements

The 10.4% significant difference in maximal knee extension peak torque output between unilateral flexion/extension (UFE) and unilateral extension (UE) conditions could be explained either by the use of stored elastic energy or by neuromuscular influences. Several studies (1,12) have shown that skeletal muscles can perform greater positive work if the immediately preceding experimental condition is characterized by a lengthening of the muscles. Elastic energy stored (6) in the lengthening muscles can be reutilized in a subsequent shortening contraction. As compared to the UE experimental condition in which knee flexion was absent, the 10.4% increase in maximal knee extension peak torque output observed for the UFE experimental condition could be the result of the utilization of the available elastic energy stored in the knee extensors during the knee flexion phase.

Speculatively, these results could also support the double neuromuscular facilitation hypothesis (15) which states that during an isotonic muscle contraction, the contracting muscle is inhibited by its own GTOs and by the muscle spindles of its stretched antagonist. Simultaneously, facilitation from both types of receptors is acting on the resting antagonist muscle and the consequences of such proprioceptive influences are that the agonist muscle becomes less excitable while its antagonist increases in excitability. Since these effects can last for at least three seconds (8,14), a motor command arriving from higher motor control centers on the antagonist muscle motoneuron pool during that time interval results in the recruitment of a higher number of motor units and the generation of a correspondingly higher muscle torque output. During the UFE experimental condition, the maximal knee extension peak torque output was higher than during the UE condition which could be the result of facilitatory influences from both the GTOs of the knee flexors and the muscle spindles of the extensors, influences that could be attributable to the preceding knee flexion movement.

Bilateral Movements

As was the case for the unilateral experimental conditions, the 16.7% significant difference in maximal knee extension peak torque output observed between the two bilateral experimental conditions (BE and BFE) could be explained either by the use of stored elastic energy or by neuromuscular influences. As compared to the BE experimental condition in which knee flexion was absent, the 16.7% increase in maximal knee extension peak torque output observed for the BFE experimental condition could be the result of the utilization of the available elastic energy stored (6) in the knee extensors during the knee flexion phase.

Neuromuscular influences, acting on the contralateral motoneuron pools (5,14) and which are more complex during bilateral movements could, speculatively, also explain the increase in maximal knee extension peak torque output observed during the BFE experimental condition. In the bilateral simultaneous extension condition (BE),

proprioceptive effects are acting against each other: the GTOs of the left extensors inhibit these muscles and facilitate the right extensors while the GTOs of the right extensors inhibit the right extensors and facilitate the left extensors. The same pattern emerges when considering the effects of muscle spindles from the stretched flexors. On the other hand, during the bilateral alternating flexion/extension movement (BFE), the facilitation effects are more important. During right knee extension, the GTOs of the right extensors facilitate the right flexors and the left extensors, while the muscle spindles of the right flexors also facilitate the right flexors and the left extensors. At the same time, during left knee flexion, the GTOs of the left flexors facilitate the left extensors and the right flexors; concurrently, the muscle spindles of the left stretched extensors also facilitate the left extensors and the right flexors. At the end of the simultaneous right knee extension and left knee flexion, at the onset of the subsequent simultaneous right knee flexion and left knee extension, the motoneuron pools of the right flexors and of the left extensors would receive a quadruple facilitating influence. Consequently, the motor commands would immediately be more effective as evidenced by the 16.7% increase in maximal knee extension torque output during the BFE experimental condition.

In the present study, the 10.4% and 16.7% differences between the two unilateral and the two bilateral experimental conditions observed in maximal knee extension peak torque output could be attributed to the double and quadruple neuromuscular facilitation principle (15). However, since the highest knee extension peak torque output was obtained when knee extension was preceded by a knee flexion in both unilateral and bilateral conditions, consideration must be given to the facilitatory effects of the elastic energy stored in the muscles as a plausible mechanism (6). In a recent investigation, Sinkjaer et al. (21) evaluated the respective contribution of the reflex component and of the elastic energy component to the mechanical response to stretch in normal ankle dorsiflexors. If their findings, which indicated that

approximately half of the mechanical response to stretch is due to a reflex mechanism, can be applied to the results of the present investigation, it could then be suggested that the increased peak torque output observed in the unilateral and bilateral experimental conditions in which knee extension was preceded by a knee flexion could be the result of a combination of neuromuscular influences and stored elastic energy. In conclusion, strength training protocols utilized in the field of athletics to improve human performance should consider in their design the combined facilitatory effects of neuromuscular influences and stored elastic energy.

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SUPPLIERS

Hydra-Fitness Omnitron 1, Hydra-Fitness Industries, Belton, Texas.

TABLE 1

Means and standard deviations of Maximal Knee Extension Peak Torque Output on Days 1, 2 and 3 (N = 42)

	TESTING DAYS			
	1	2	3	Average of days 2 and 3
Unilateral Extension	73.7(±12.4)	80.8(±10.1)	81.4(±9.8)	81.1(±12.1)
Unilateral Flexion/ Extension	83.2(±11.1)	90.7(±10.9)	88.3(±12.2)	89.5(±11.9)
Bilateral Extension	63.9(±11.0)	70.6(±10.1)	71.8(±9.4)	71.2(±12.9)
Bilateral Flexion/ Extension	73.5(±13.1)	81.6(±12.4)	84.6(±10.4)	83.1(±11.2)

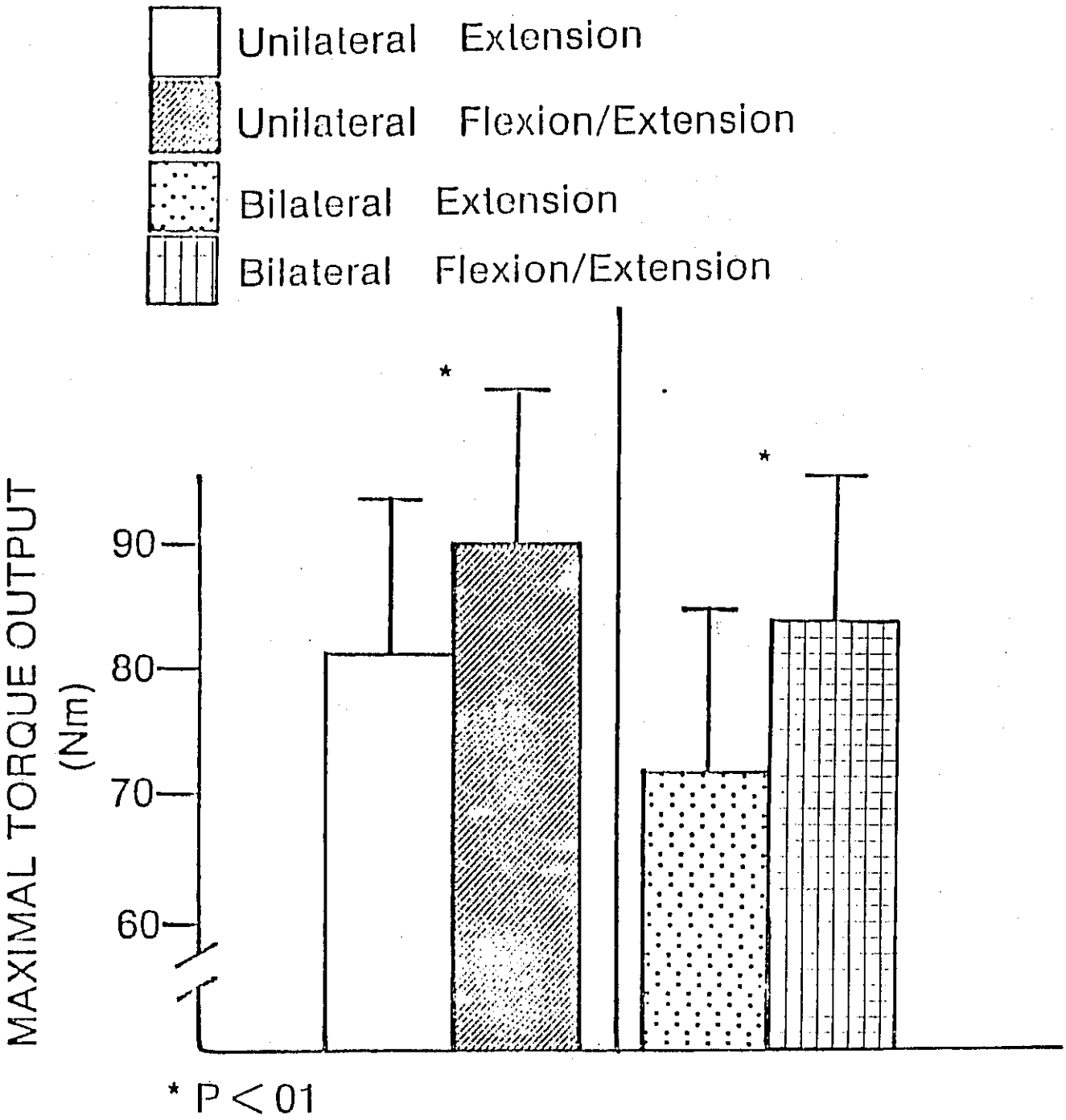

Figure 1. Maximal left knee extension torque output under different experimental conditions of neuromuscular facilitation.