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ORIGINAL ARTICLE

Kyle T. Ebersole · Terry J. Housh · Glen O. Johnson
Tammy K. Evetovich · Douglas B. Smith
Sharon R. Perry

The effect of leg flexion angle on the mechanomyographic responses to isometric muscle actions

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Abstract The purpose of this investigation was to examine the effect of leg flexion angle on the relationship between mechanomyographic (MMG) amplitude and isometric torque production. Adult males ($n = 9$) performed isometric muscle actions of the leg extensors at 25, 50, 75, and 100 percent maximal voluntary contraction (%MVC) on a calibrated CYBEX 6000 dynamometer at 25, 50, and 75° below full extension. A piezoelectric MMG recording device was placed over the mid-portion of the rectus femoris. At 25° of leg flexion, the MMG amplitude increased to 100%MVC. At 50 and 75° of leg flexion, however, MMG amplitude increased to 75%MVC, and then did not change significantly ($P > 0.05$) between 75 and 100%MVC. These findings indicate that the MMG amplitude-isometric torque relationship is joint angle specific and may be the result of leg flexion angle differences in: (1) muscle stiffness, or (2) motor unit activation strategies.

Key words Mechanomyography · Isometric muscle actions · Rectus femoris

Introduction

The amplitude of a mechanomyographic (MMG) signal quantifies the low-frequency oscillations of contracting skeletal muscle fibers (Barry 1987; Frangioni et al. 1987; Barry and Cole 1988, 1990; Zwarts and Keidel 1991; Stokes and Cooper 1992; Orizio 1993). Barry and Cole (1990) and Orizio et al. (1993, 1996) have suggested that the lateral oscillations are generated by: (1) a gross lateral movement of the muscle at the initiation of a contraction that is generated by non-simultaneous activation of muscle fibers, (2) smaller subsequent lateral oscillations occurring at the resonant frequency of the muscle, and (3) dimensional changes of the active muscle fibers. The MMG amplitude, however, is influenced by many factors including muscle stiffness, fiber type, tension, length, mass, intramuscular pressure, the viscosity of the surrounding medium, and the motor unit firing frequency (Barry 1987; Frangioni et al. 1987; Barry and Cole 1988; Orizio et al. 1989; Barry and Cole 1990; Marchetti et al. 1992; Orizio 1993).

A number of studies (Orizio et al. 1989; Maton et al. 1990; Stokes and Dalton 1991a,b; Zwarts and Keidel 1991; Stokes and Cooper 1992; Smith and Stokes 1993; Esposito et al. 1996; Matheson et al. 1997) have utilized incremental isometric muscle actions to determine the relationship between MMG amplitude and force. These investigators have reported that the MMG amplitude is linearly (Stokes and Dalton 1991a,b; Zwarts and Keidel 1991; Stokes and Cooper 1992; Smith and Stokes 1993) and non-linearly (Orizio et al. 1989; Maton et al. 1990; Stokes and Cooper 1992; Smith and Stokes 1993; Esposito et al. 1996; Matheson et al. 1997) related to isometric force production. Stokes and Dalton (1991a) suggested that the linear relationship between isometric force production (20–100 percent of maximum voluntary contraction; %MVC) and the amplitudes of the MMG ($r = 0.98$) and electromyographic (EMG) measurements from the rectus femoris (RF) at 90° of leg flexion ($r = 0.99$) indicate that the MMG is reflective of motor unit activation patterns. It has also been reported that for the biceps brachii (Orizio et al. 1989) and RF (Matheson et al. 1997) muscles, the MMG amplitude increased up to approximately 80%MVC and then decreased from 80 to 100%MVC. A plateau or decrease in the MMG amplitude between 80 and 100%MVC may reflect a reduction in muscle fiber oscillations due to the fusion of motor unit twitches at high firing frequencies or high levels of muscle stiffness (Esposito et al. 1996; Matheson et al. 1997; Orizio et al. 1989, 1993). Thus, the relationship between MMG amplitude and isometric force may be influenced by motor unit activation patterns, motor unit firing frequency, and/or muscle stiffness. Furthermore, isometric force production is joint

K.T. Ebersole (✉) · T.J. Housh · G.O. Johnson
T.K. Evetovich · D.B. Smith · S.R. Perry
MABL 137, Center for Youth Fitness and Sports Research,
University of Nebraska-Lincoln, Lincoln, NE 68588-0229, USA

angle specific. This is due, in part, to differences in motor unit activation patterns and the muscle length-related overlap of actin and myosin cross-bridges (Haffajee et al. 1972; Ford et al. 1981; Kuling et al. 1984; Solomonow et al. 1991; Weir et al. 1995b). Like isometric force production, muscle stiffness is also associated with the number of attached cross-bridges (Ford et al. 1981; Barry and Cole 1990; Ettema and Huijing 1994). The previous studies in which linear and non-linear MMG amplitude-isometric torque relationships were reported utilized only one joint angle. Therefore, it is possible that the relationship between MMG amplitude and isometric force production may be influenced by the joint angle at which these parameters are measured. That is, the interrelationships between joint angle, isometric force production, motor unit activation patterns, and muscle stiffness may influence the pattern of MMG amplitude responses to incremental force production during isometric muscle actions. Therefore, the purpose of this investigation was to examine the effect of leg flexion angle on the relationship between MMG amplitude and isometric torque production.

Methods

Subjects

Nine male subjects [mean (SD) age, 24.2 (2.82) years; height, 179.21 (4.77) cm; body mass, 90.21 (18.18) kg] volunteered to participate in the investigation. The study was approved by the University Institutional Review Board for Human Subjects and all subjects completed a health history questionnaire and signed a written informed consent prior to testing.

Torque measurements

Isometric muscle actions of the dominant leg extensors (based on kicking preference) were performed on a calibrated CYBEX 6000 Isokinetic Dynamometer (CYBEX Division of LUMEX, Ronkonkoma, NY, USA) at leg flexion angles of 25, 50, and 75° below full extension. Following two submaximal warm-up trials, maximal voluntary contractions (MVC) were performed at each leg flexion angle. The highest torque output from two, 6-s maximal isometric muscle actions was selected as the MVC for each leg flexion angle. Determination of the MVCs was followed by two, 6-s submaximal muscle actions at 25, 50, and 75%MVC. Two practice trials preceded the two submaximal test trials at each leg flexion angle. During each submaximal practice and test trial, the subjects viewed the torque display on the CYBEX 6000 monitor to help them to maintain the desired torque level. From the two test trials, the submaximal torque measurement that was closest to the desired %MVC was selected as the representative trial. Two minutes rest was given between each torque measurement, and the order of testing for the leg flexion angles and submaximal trials were randomized for each subject.

MMG measurements

The MMG signal was detected by a piezoelectric crystal contact sensor (Hewlett-Packard, 21050A, bandwidth 0.02–2000 Hz) that was placed on the RF midway between the superior border of the patella and the inguinal fold. A stabilizing ring was used to ensure consistent contact pressure of the sensor (Bolton et al. 1989) and double-sided foam tape helped to hold the sensor in place. The raw MMG signal was stored on a personal computer (Macintosh 7100/80 AV Power PC) and expressed as the root mean square amplitude using computer software (MP100, Biopac Systems, Santa Barbara, CA, USA). The sampling frequency was 1000 points per second and the MMG signal was low-pass filtered at 150 Hz. For each torque measurement, the MMG amplitude was calculated for a 2-s time period corresponding to the 3rd and 4th seconds of the 6-s isometric muscle action to assure that the MMG signal corresponded to the desired torque level.

Statistical analysis

Separate two-way repeated measures analyses of variance (ANOVAs, %MVC by leg flexion angle) were used to analyze the torque (Nm) and MMG amplitude (mV) data. Follow-up analyses included one-way repeated measures ANOVAs and Tukey post-hoc comparisons. An alpha of $P < 0.05$ was considered to be statistically significant for all comparisons.

Results

Torque

Figure 1 shows the relationships between torque (Nm) and %MVC (25, 50, 75, and 100%MVC) for the three leg flexion angles (25, 50, and 75°). For each leg flexion angle, the subjects produced the submaximal (25, 50, and 75%MVC) torque within ±1%. Torque increased significantly ($P < 0.05$) for each %MVC (100 > 75 > 50 > 25%MVC) for all three leg flexion angles. Furthermore, for each %MVC, the torque at 75° of leg flexion > 50° > 25°.

Mechanomyography

Figure 2 presents the relationships between MMG amplitude (mV) and %MVC (25, 50, 75, and 100%MVC) for the three leg flexion angles (25, 50, and 75°). At 25° of leg flexion, there were significant ($P < 0.05$) differences in MMG amplitude between %MVC levels (100 > 75 > 50 and 25%MVC). At 50° and 75° of leg flexion, the significant ($P < 0.05$) differences in MMG amplitude at the different %MVC levels were 100 and 75 > 50 > 25%MVC.

Discussion

Isometric torque production

The results of the present study were consistent with those of previous investigations (Pocock 1963; Haffajee et al. 1972; Kulig et al. 1984; Weir et al. 1994, 1995a,b) in which it was reported that isometric torque production for the leg extensors is joint angle specific. Kulig et al. (1984) reported that maximal isometric torque for leg extension is produced at a joint angle that corresponds closely to the 75° of leg flexion used in the present study. Like the present study, Kulig et al. (1984) also found

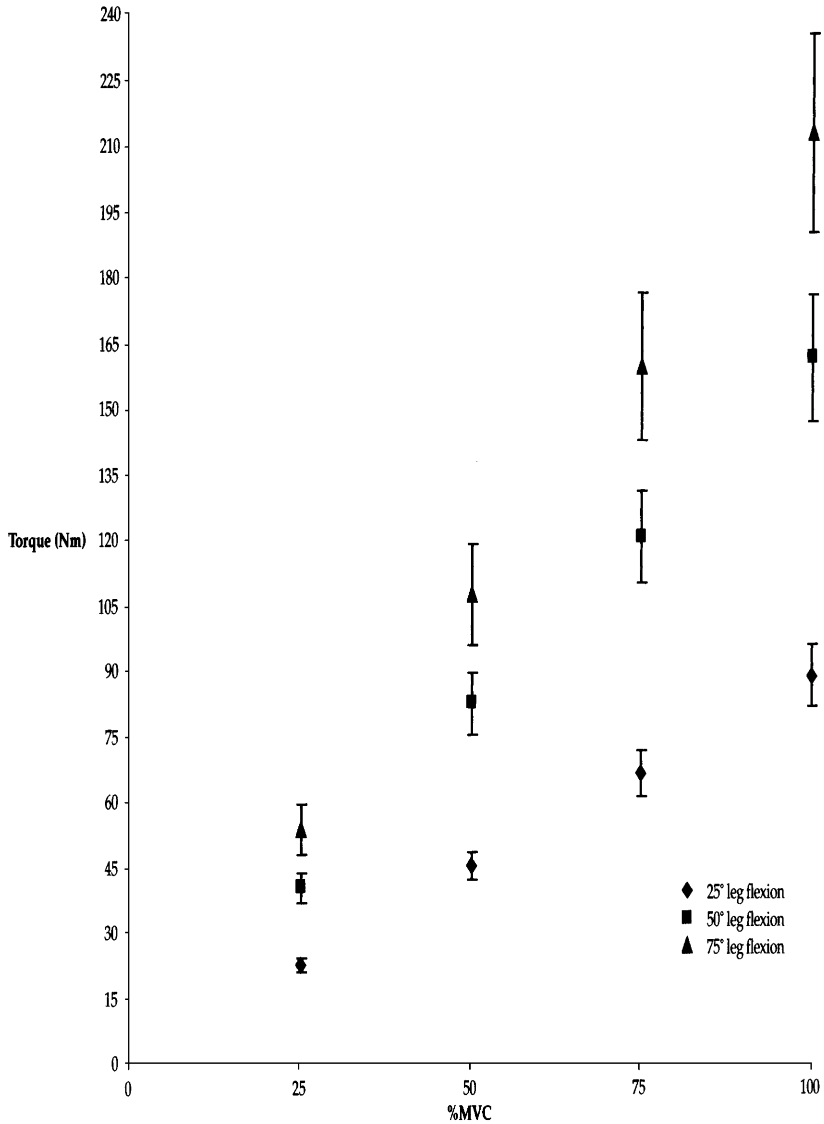

Fig. 1 The relationship ($\bar{X} \pm$ SEM) between isometric torque and percent maximum voluntary contraction (*%MVC*) for each leg flexion angle (25, 50, and 75°)

that knee joint angles closer to full extension resulted in less isometric torque production. The mechanism underlying the joint angle specificity for isometric torque production is unknown, but may be due to the selective regional activation of motor units within a particular muscle, differential activation of the four leg extensor muscles, biomechanical considerations not associated with muscle activation, and/or differences in the overlap of actin and myosin filaments (Pocock 1963; Lieb and Perry 1968, 1971; Haffajee et al. 1972; Lindh 1979; Kulig et al. 1984; Van Zuylen et al. 1988; Weir et al. 1995b).

Joint angle differences in MMG amplitude

The results of the present investigation indicate that for each %MVC, the MMG amplitude was greatest at 75° of leg flexion, followed by 50° and 25°. Orizio et al. (1993, 1996) have suggested that the amplitude of the MMG signal is determined by the number and firing rate of active motor units, and for the RF, Zhang et al. (1996) reported a linear relationship between MMG and EMG amplitude values during isometric muscle actions of increasing force at knee-joint angles of 30° ($r = 0.82$), 60° ($r = 0.92$), and 90° ($r = 0.81$). Furthermore, previous studies (Haffajee et al. 1972; Weir et al. 1994, 1995b) have revealed that between 25° and 75° of leg flexion, the EMG amplitude and torque production of the quadriceps increases as the degree of leg flexion increases. It has been suggested that certain knee joint angles have a mechanical advantage over other angles within the range of motion (Lieb and Perry 1971; Weir et al. 1995b), and this could result in joint-angle-specific muscle fiber activation patterns and isometric torque production (Van Zuylen et al. 1988). Therefore, we hypothesize that the patterns (75 > 50 > 25° of leg flexion) of MMG amplitude and isometric torque production for each %MVC may have been due to joint-angle-specific differences in mechanical advantage and motor unit activation patterns. That is, a greater degree

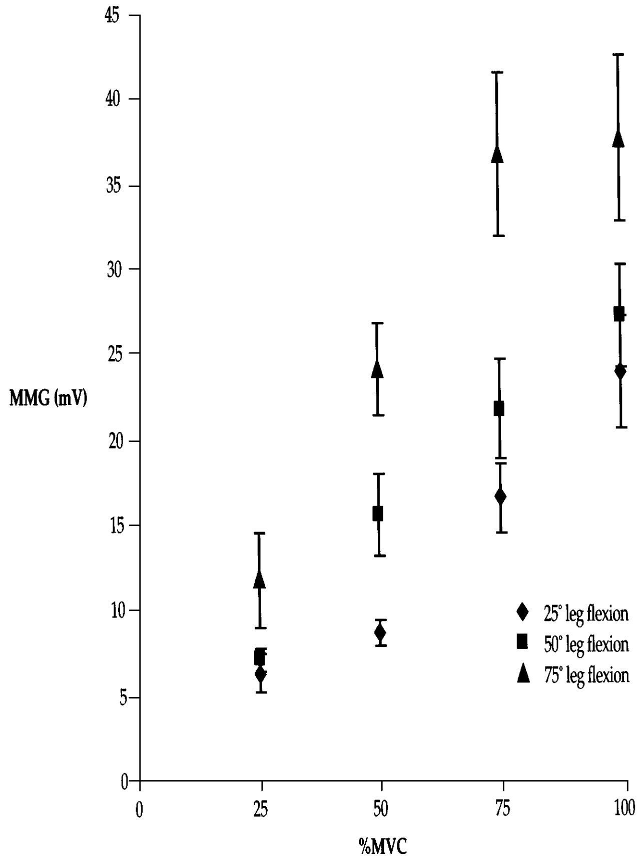

Fig. 2 The relationship (X̄ ± SEM) between Mechanomyogram (*MMG*) amplitude and %MVC for each leg flexion angle (25, 50, and 75°)

of leg flexion resulted in a mechanical advantage which caused increased activation and, therefore, a greater isometric torque production and MMG amplitude.

MMG amplitude versus isometric torque relationships

The results of the present study indicate that the pattern of the MMG amplitude-isometric torque relationship was joint angle specific. The MMG amplitude increased up to 75%MVC for each of the leg flexion angles (25, 50, and 75° of leg flexion; Fig. 2). At 25° of leg flexion, the MMG amplitude continued to increase significantly ($P < 0.05$) from 75 to 100%MVC. At 50° of leg flexion, the MMG amplitude increased up to 100%MVC, but the increase from 75 to 100%MVC was not statistically significant ($P > 0.05$). At 75° of leg flexion, however, the MMG amplitude plateaued between 75 and 100%MVC. Stokes and Dalton (1991a) stated that the discrepancy between their findings of linear MMG-isometric torque for the quadriceps and the non-linear relationship reported for the biceps brachii by Orizio et al. (1989) may be due to the fact that the "Quadriceps and biceps were only tested at one joint angle and may show different relationships at different angles." The present findings support this hypothesis by Stokes and Dalton (1991a) and suggest that the conflicting results reported in previous studies regarding the force-related increase or plateau in MMG amplitude above 80%MVC are due to the joint angle at which the measurements were taken.

Previous studies have reported linear (Stokes and Dalton 1991a,b; Zwarts and Keidel 1991; Stokes and Cooper 1992; Smith and Stokes 1993) or non-linear (Orizio et al. 1989; Maton et al. 1990; Stokes and Cooper 1992; Smith and Stokes 1993; Esposito et al. 1996; Matheson et al. 1997) relationships between MMG amplitude and force (or torque) production. A number of studies (Maton et al. 1990; Stokes and Dalton 1991a,b; Zwarts and Keidel 1991; Stokes and Cooper 1992; Smith and Stokes 1993) have reported linear or exponential increases in MMG amplitude up to 100%MVC, while others (Orizio et al. 1989; Smith and Stokes 1993; Esposito et al. 1996; Matheson et al. 1997) have found increases up to approximately 80%MVC and then a plateau or decrease in MMG amplitude at 100%MVC. Zwarts and Keidel (1991) indicate that an increase in motor unit recruitment and firing rate accounted for the linear MMG amplitude-force relationship found in their study. Maton et al. (1990), however, found an exponential increase in MMG amplitude and suggested that it may have been due to the superficial location of fast-twitch motor units that are closer to the skin surface and, when activated as force production increases, result in a greater slope in MMG amplitude. Therefore, it is possible that the linear or exponential relationships between MMG amplitude and isometric force found in previous studies (Maton et al. 1990; Stokes and Dalton 1991a,b; Zwarts and Keidel 1991; Stokes and Cooper 1992; Smith and Stokes 1993) were due to differences in the fiber type distribution patterns of the muscle involved. It is interesting, however, that both linear and non-linear relationships have been reported for the biceps brachii (Orizio et al. 1989; Maton et al. 1990; Zwarts and Keidel 1991; Esposito et al. 1996), RF (Stokes and Dalton 1991a,b; Smith and Stokes 1993; Matheson et al. 1997), and adductor pollicis (Stokes and Cooper 1992) muscles.

A number of studies (Orizio et al. 1989, 1993, 1996; Esposito et al. 1996; Matheson et al. 1997) have suggested that the plateau or decrease in the MMG amplitude that occurred at high levels of isometric force production were due to the fusion of motor unit twitches and the subsequent tetanus-like state which limited the oscillations of the activated muscle fibers. It has been suggested that force production up to approximately 80%MVC is modulated by increases in motor unit recruitment (Milner-Brown et al. 1973a,b; DeLuca 1979; Freund 1983; Zwarts and Keidel 1991; Bernardi et al. 1995). Above this level, however, additional force is produced by increasing the motor unit firing rates (Milner-Brown et al. 1973a,b; DeLuca 1979; Freund 1983; Bernardi et al. 1995). Esposito et al. (1996) suggested that the decrease in MMG amplitude above 80%MVC indicated the cessation of additional motor unit recruitment. Furthermore, Orizio et al. (1993, 1996) and Matheson et al. (1997) reported that MMG amplitude increased linearly for low firing rates, but was reduced due to the fusion of motor unit twitches at high rates of stimulation.

We believe that the leg flexion angle-specific patterns for the MMG amplitude-isometric torque relationship found in the present study has two potential explanations. These hypotheses involve leg flexion angle differences in: (1) muscle stiffness, or (2) motor unit activation strategies.

Muscle stiffness is primarily a function of the number of attached cross-bridges, and increases as isometric torque increases (Ford et al. 1981; Barry and Cole 1990; Ettema and Huijing 1994). It has been reported (Barry 1987; Stokes and Cooper 1992; Orizio et al. 1989, 1993, 1996) that high levels of muscle stiffness may restrict the muscle fibers' ability to oscillate, thereby decreasing MMG amplitude. With regard to the results of the present study, it is possible that at 25° of leg flexion (where maximal isometric torque production was the lowest; Fig. 1), torque-related increases in muscle stiffness were not sufficient to restrict the activated muscle fibers from oscillating and, therefore, the MMG amplitude increased up to 100%MVC. Although the MMG amplitude increased up to 100%MVC at 50° of leg flexion, the nonsignificant ($P > 0.05$) increase that occurred between 75 and 100%MVC reflected the onset of stiffness-related restrictions of muscle fiber oscillations. At 75° of leg flexion, which resulted in the greatest maximal isometric torque production, however, the plateau in MMG amplitude between 75 and 100%MVC was due to stiffness-related restrictions of the muscle fiber oscillations. This hypothesis suggests that until isometric torque reaches the level associated with 75%MVC at 50° of leg flexion, the muscle stiffness is not sufficient to markedly interfere with muscle fiber oscillations or to significantly affect the pattern of the MMG amplitude-isometric torque relationship.

An alternative hypothesis is that there are leg flexion angle differences in motor unit activation strategies which may influence the contributions of motor unit recruitment and firing frequency to isometric torque production (Eloranta 1989; Suter and Herzog 1997). These leg flexion angle differences may, in turn, affect the pattern of the MMG amplitude-isometric torque relationship. Previous studies (Orizio et al. 1989, 1993, 1996; Esposito et al. 1996; Matheson et al. 1997) have suggested that fusion of the motor unit twitches was responsible for the plateau in MMG amplitude above 80%MVC. Orizio et al. (1989) have suggested that the high motor unit firing rate in the biceps brachii resulted in a "...reduction of the fibre geometrical variations between successive motor impulses..." which caused a decrease in MMG amplitude at high levels of force production (80–100%MVC). Similarly, Matheson et al. (1997) stated that the decrease in MMG amplitude near 80%MVC in the RF was due to wave summation (resulting from the fusion of motor unit twitches) which "...might produce a sound of lower intensity." With regard to the present findings, it is possible that between 75 and 100%MVC at 25° of leg flexion, the motor unit firing frequency was not sufficient to cause fusion of twitches of the activated motor units. At 75° of leg flexion, however, the plateau in the MMG amplitude may reflect the restriction of muscle fiber oscillations due to the high motor unit firing frequency and subsequent fusion of the activated motor unit twitches.

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