Title Page

Joint angle affects volitional and magnetically-evoked neuromuscular performance differentially

Claire Minshull, PhD. Senior Lecturer, Exercise Physiology and Health[1]

David Rees MChOrth. FRCS. Consultant Orthopaedic Surgeon[2]

Nigel Gleeson PhD. Reader Rehabilitation Sciences[3]

[1]School of Science and Technology, Nottingham Trent University, Nottingham, UK, NG11 8NS.

[2]National Centre for Sports Injury Surgery, RJAH Orthopaedic Hospital, Shropshire, UK, SY10 7AG.

[3]School of Health Sciences, Queen Margaret University Edinburgh, UK, EH21 6UU.

The study design and assessment protocols were approved by Nottingham Trent University Ethics Committee for Human Testing.

Correspondence address: Dr. Claire Minshull, Neuromechanical Research Group, School of Science and Technology, Nottingham Trent University, Clifton Lane, Nottingham, U.K., NG11 8NS. E-mail: claire.minshull@ntu.ac.uk

Abstract

This study examined the volitional and magnetically-evoked neuromuscular performance of the quadriceps femoris at functional knee joint angles adjacent to full extension. Indices of volitional and magnetically-evoked neuromuscular performance (N= 15 healthy males; 23.5 ± 2.9 years; 71.5 ± 5.4 kg; 176.5 ± 5.5 cm) were obtained at 25°; 35° and 45° of knee flexion. Results showed that volitional and magnetically-evoked peak force (PF_V; P_TF_E, respectively) and electromechanical delay (EMD_V; EMD_E, respectively) were enhanced by increased knee flexion. However, greater relative improvements in volitional compared to evoked indices of neuromuscular performance were observed with increasing flexion from 25° to 45° (e.g. EMD_V; EMD_E: 36% vs. 11% improvement, respectively; $F_{[2,14]} = 6.8$; $p < 0.05$). There were no significant correlations between EMD_V and EMD_E or PF_V and P_TF_E, respectively at analogous joint positions. These findings suggest that the extent of the relative differential between volitional and evoked neuromuscular performance capabilities is joint angle-specific and not correlated with performance capabilities at adjacent angles, but tends to be smaller with increased flexion. As such, effective prediction of volitional from evoked performance capabilities at both analogous and adjacent knee joint positions would lack robustness.

1. Introduction

Optimal functioning of skeletal muscle is considered fundamental to the capability for proper stabilisation of synovial joints and prevention of musculoskeletal injury; its achievement also forms the goal of many physical therapy interventions [Johansson et al, 1991; Bailey et al, 2003]. Maximal volitional activation (MVA) of skeletal muscle underpins the assessment of strength capacity, however, in patient populations, or in individuals suffering from injury, MVA may be impaired by waning motivation, pain and, or, the associated inhibitory processes [Hopkins and Ingersoll, 2000]. Magnetic stimulation is becoming increasingly used as a painless alternative to electrical stimulation and recent research has confirmed similar twitch responses between the two methods following peripheral nerve stimulation [Newman et al, 2003; Verges et al, 2008]. There is a growing body of evidence that supports the use of magnetic stimulation in both clinical and healthy populations for the measurement of skeletal muscle performance capacity [e.g. Polkey et al, 1996; Mador et al, 2003; Hamnegard et al, 2004; Man et al, 2004; Sathyapala et al, 2007; Swallow et al, 2007]. For example, magnetically-evoked peak twitch force of the quadriceps subsequent to femoral nerve stimulation has been described as useful indicator of quadriceps strength and fatigue in healthy individuals and in patients suffering from chronic obstructive pulmonary disease [Polkey et al, 1996; Hamnegard et al, 2004; Vivodetzev et al, 2005]. Data derived from these assessments may also be important where performing a true MVA is not possible, for example, in the presence of pain following surgery [Man et al, 2004].

Despite its popularity, there is a lack of research that details the magnetically-evoked neuromuscular activation characteristics of the knee musculature over a range of functional joint angles, which are close to full extension [Newman et al, 2003]. This is important because of the prevalence of knee injuries and orthopaedic trauma that occur in this functional range. For example, even in healthy populations the majority of key knee ligament injuries are non-contact [Mandelbaum et al, 2005], occur with the knee positioned proximal to full extension [Ireland et al, 1997] and within a very short time-frame of the initial disordered biomechanics [Shultz et al, 2001]. Accordingly, it would seem reasonable to evaluate the corresponding neuromuscular activation capabilities at these joint positions [Huston and Wojtys, 1996; Gleeson et al, 2001; Shultz et al, 2001] albeit with controlled laboratory-based assessments that attempt to isolate the capabilities and contributions of a single muscle group to functional performance. Prior investigations have typically considered the capability for evoked quadriceps performance at knee flexion angles of 90°, where 0° = full extension [Polkey et al, 1996; Hamnegard et al, 2004], which is close to the peak of the length-tension curve for optimal force production, rather than more 'functional' and vulnerable joint positions.

Given the influences of the force-length relationship of muscle whereby muscle fibres produce less force at shorter or longer lengths than the optimum length [McComas, 1996], and the potential for associated altered patterns of neural activation [Babault et al, 2003], it becomes important to understand the implications of altered relationships between tension generated from evoked and voluntary muscle activations when they are extrapolated to more vulnerable and extended joint positions. This is especially true in situations where the decision-making processes concerning rehabilitation and injury avoidance capacity in already vulnerable populations is informed by data derived form these types of assessment.

The aim of this study was to examine the characteristics of volitional and magnetically-evoked neuromuscular performance of the quadriceps femoris at joint angles proximal to full knee extension.

2. Methods

2.1 Participants

Fifteen physically active (at least 3 times per week), asymptomatic males (age 23.5 ± 2.9 years; body mass 71.5(± 5.4 kg; height 176.5 ± 5.5 cm) gave their written informed consent to participate in this wholly repeated-measures design study. Participants were instructed to refrain from strenuous physical activity for the 24-hours prior to the test. Assessment protocols were approved by the University Ethics Committee for Human Testing.

2.2 Experimental procedures

A familiarisation session was performed 48-72h prior to testing, during which time participants became habituated to the testing procedures and accommodated to rapid maximum activation of the quadriceps (variation of <2% peak force and no systematic changes between consecutive efforts [$p > 0.05$]). Indices of quadriceps volitional and magnetically-evoked neuromuscular performance were obtained at three functionally-relevant knee angles: 25° (0.44 rad), 35° (0.61 rad) and 45° (0.79 rad) of knee flexion (0 degrees represents full extension) and each condition was presented in random order and separated from the next by 10 minutes of rest. Participants were seated on the custom-built dynamometer [modified from Gleeson et al, 1995] (hip flexion angle 40° flexion) and the immovable lever-arm of the dynamometer was attached to the dominant leg of the participant by a padded ankle-cuff and adjustable strapping just proximal to the lateral malleolus." Each knee flexion angle was identified for each participant during activation of the involved musculature using a goniometer-system and was maintained throughout testing. This configuration was an approximation of functional hip and knee joint positions during orthopaedic trauma/injuries in healthy [Ireland et al, 1996] and frail individuals [Tideiksaar, 1988; Grabiner et al, 2008]. The dynamometer's and knee joint's axes of rotation were aligned as closely as possible. Adjustable, non-compliant strapping was placed across the pelvis and just proximal to the knee joint to localise the action of the involved musculature (see figure 1). The non-dominant leg was left unsecured in a similar position.

- Insert Figure 1 Here -

2.3 Assessment of neuromuscular performance

Magnetic stimulation was performed first on each test occasion in order to minimise the possible potentiating effects of prior MVA associated with the volitional testing [Minshull et al, 2007; 2008].

2.3.1. Magnetically-evoked muscle activation

Supra-maximal magnetic stimulation of the femoral nerve and associated activation of the knee extensors was achieved by means of double wound coil (70 mm) that was powered by a Magstim 200^2 stimulator (Magstim Co. Ltd., Whitland, Dyfed, Wales). The optimum site for stimulation of the nerve was defined as the site that elicited the largest twitch force and M-wave amplitude. The magnetic coil was placed in the femoral triangle just lateral to the femoral artery, then small manual iterative positional changes (approx. 10 in number and 5-mm deviations on average) of the coil were made that were commensurate with increasing size of responses during a series of discrete stimulations. This optimised coil position was maintained manually throughout the remainder of the test and participants were instructed to remain relaxed throughout. The protocol deployed to elicit and verify supra-maximal stimulation was in accordance with the methodology described previously by Minshull et al, [2007; 2008] whereby supra-maximal stimulation was defined as the intensity of stimulation at which there was subsequently no more than a 5% increase in M-wave peak amplitude and peak twitch force despite a 10% or greater increase in the intensity of stimulation, and verified using a procedure that would mimic the approach to the physiological verification of the attainment of maximal oxygen uptake. Thus supra-maximal stimulation was verified by simultaneous visual inspection of the data during a sequence of seven discrete stimulations of increasing intensity that commenced at 40% of the Magstim 200's maximal capacity output with increments of 10% up to 100% of capacity and by retrospective analyses of M-wave and peak twitch force data. Sequential stimulations were separated by at least 10 seconds [Moore and Kukulka, 1996]. Magnetically-evoked indices of performance were derived from three supra-maximal stimulations.

2.3.2 Maximal volitional activation (MVA)

On receipt of an auditory signal the participants attempted to activate their musculature as rapidly and forcefully as possible by extending their knee joint against the immovable restraint offered by the apparatus. Another auditory signal was given to the participant after 2 - 3 seconds of MVA to cue neuromuscular relaxation. The three intra-trial MVA replicates were each separated by at least 10-seconds to enable neuromuscular recovery [Moore and Kukulka, 1991].

2.3.3. Indices of neuromuscular performance

Volitional static peak force (PF_V) and magnetically-evoked peak twitch force (P_TF_E) were corrected for the effects of gravity and recorded as the mean response of three intra-trial replicates in which the highest force was recorded in each trial.

Electromyographic activity (EMG) was recorded from the m. vastus lateralis during the estimation of PF_V and P_TF_E. The EMG was recorded using bipolar surface electrodes (self-adhesive, Ag/AgCl; 10 mm diameter; Unilect, UK) hat were applied over the belly of the m. vastus lateralis (at 2/3 of the distance between the palpable anatomical landmarks of the anterior spina iliaca and the superior lateral border of the patella) and parallel to the orientation of the muscle fibres. The inter-electrode distance was 30-mm and a reference electrode was placed 30-mm lateral and equidistant from the recording electrodes. Standardised skin preparation techniques yielded inter-electrode impedance of less than 5 kΩ. The raw unfiltered EMG signals were passed through a differential amplifier (1902 Mk IV; Cambridge Electronic Design,UK), with input impedance 10,000 MOhms, CMMR 100 dB, gain 1000 and filtered using a 2nd order Butterworth low-pass filter with 1kHz cut-off frequency. The signals, which incorporated minimal interference from induced currents associated with external electrical and electromagnetic sources and noise inherent in the remainder of the recording instrumentation, were analogue-to-digitally converted at 2.5 kHz sample rate, ensuring a significant margin of reserve between the highest frequency expected in the EMG signal and the Nyquist frequency and minimal intrusion from aliasing errors [Gleeson, 2001]. The EMG signals remained unfiltered during subsequent analyses. Volitional and magnetically-evoked electromechanical delay (EMD_V and EMD_E, respectively) were computed as the mean response of three intra-trial muscle activations in which the time delay between the onset of electrical activity and the onset of force was recorded. The onsets of electrical activity and muscle force were defined as the first point in time at which each signal exceeded consistently the 95% confidence limits associated with the background electrical noise amplitude in quiescent muscle [Minshull et al, 2007].

2.4. Statistical analysis

The selected performance indicators were described using ordinary statistical procedures (mean ± SD). The effect of joint angle was assessed for each index of performance using separate three (angle: 25; 35; 45 degrees) by two (mode of muscle activation: volitional; magnetically-evoked) analysis of variance (ANOVAs) with repeated measures on both factors. Orthogonal polynomial *a priori* contrasts were used to confirm the extent of expected curvilinear responses of performance indicators associated with altered knee flexion position. Relationships amongst PF_V and P_TF_E and amongst associated indices of EMD_V EMD_E at three knee joint positions were computed using Pearson product-moment correlations. Statistical significance was accepted at $p < 0.05$.

3. Results

Significant interactions associated with the repeated-measures ANOVAs showed that indices of volitional and magnetically-evoked muscle force production (PF_V ; P_TF_E) and electromechanical delay (EMD_V; EMD_E) both improved as a function of a greater knee flexion angle; group mean absolute scores of PF_V and P_TF_E increased and group mean absolute scores of EMD_V; EMD_E decreased. However, changes associated with the volitional mode of muscle activation were significantly more pronounced ($F_{[2,28]} = 23.5$; $p < 0.001$; $F_{[2,28]} = 7.3$; $p < 0.01$, respectively), (see figures 2 and 3). *A priori* polynomial contrasts confirmed expected curvilinear improvements from 25° - 45° knee flexion for both magnetically-evoked and voluntary indices of performance (PF_V; P_TF_E $F_{[1,14]} = 31.3$; $p < 0.001$, EMD_V; EMD_E $F_{[1,14]} =$ 13.0; $p < 0.01$). Performance comparisons of PF_V vs. P_TF_E from 25° - 35° and from 35°- 45° represent increases of 13.4% vs. 15.0% and 21.6% vs. 13.7%, respectively. Equivalent comparisons for EMD_V vs. EMD_E from 25° - 35° and 35°- 45° represent decreases of 1.5% vs. 1.6% and 24.4% vs. 8.3%, respectively.

- Insert Figure 2 Here -

- Insert Figure 3 Here –

There were no significant correlations amongst variables PF_V and P_TF_E (table 1) and, EMD_V and EMD_E (table 2) at analogous joint angles (range: $r = -0.21$ to 0.35), apart from a significant negative correlation ($r = -0.558$, $p<0.05$) at 45° between EMD_V and EMD_E.

- Insert Table 2 Here -

- Insert Table 3 Here –

4. Discussion

The purpose of this study was to investigate selected characteristics of the volitional and magnetically-evoked neuromuscular performance capacity of the quadriceps femoris musculature at different functional knee joint angles. The current results reflecting performance capabilities at 25°, 35° and 45 ° of knee flexion demonstrated that greater flexion was associated with superior quadriceps contractile force. Although subtle alterations in the extensor moment arm will have contributed to angle-specific performance [Maganaris et al, 2004], this finding is congruent with the predictions of the length-tension relationship [McComas, 1996] in which there is likely to be a more favourable degree of myofilament and contractile protein overlap at 45° than at 25° of knee flexion. Greater angles of knee flexion also elicited superior (i.e. shorter) electromechanical delays and this observation is consistent with previous findings [e.g. Chan et al, 2001]. The observed variations in electromechanical delay performance are likely to reflect the influence of joint angle on the degree of myofillament overlap [McComas, 1996], the discharge properties of the motoneurons and the capability for neural activation [Komi et al, 2000] and the compliance characteristics of the musculo-tendinous complex [Muraoka et al, 2004]. While it's not possible to quantify the relative effects of each of these processes in the current study, under most circumstances the majority of the EMD is determined by the time required to stretch the series elastic component (SEC) [Zhou et al., 1998; Granata et al, 2000; Kubo et al, 2000; Muraoka et al, 2004]. The SEC, which is comprised primarily of the tendon and the connective tissue layers [McComas, 1996], contributes during muscle activation by acting like a spring resisting external attempts to change muscle length. The observation in this current study of shorter quadriceps EMD latencies at greater knee flexion angles (i.e. 45° vs. 25°) would thus be expected under conditions where the SEC is stretched [Muraoka et al, 2004] and there is favourable myofillament overlap.

It is interesting to note that the results show considerably greater relative improvements in PF_V and EMD_V versus P_TF_E and EMD_E as the knee flexion angle altered from 25° to 45° (figures 2 and 3). Altered neural activation of the quadriceps at extreme and mid-range joint positions has been reported with corresponding changes to volitional performance [Komi et al, 2000; Babault et al, 2003; Desbrosses et al, 2006]. Although it is not possible from the current data to estimate the relative contributions of the various influential processes, it may be plausible that the relative differences in evoked and volitional performances at altered joint positions might be determined by inherent differences in patterns of activation of the motor units (Maffiuletti, 2010), and which might be further mediated by joint position-specific and inhibitory processes that modulate access to the full quota of large high threshold motor units under voluntary conditions [Tsuji and Nakamura, 1998; Zhou et al, 1998]. The potential for such inhibitory-driven regulation of performance and differential between evoked and volitional indices of electromechanical delay has been recognised previously in experiments involving single positions of joints [Zhou et al, 1995; Minshull et al, 2007; 2008]. However, the results of the present study offer novel insight into the progressive nature of regulation with reducing joint flexion towards full anatomical joint extension. It is plausible that increased stress placed on the anterior cruciate ligament towards end range knee extension [Johnson et al, 1991] might have provoked greater inhibition of the quadriceps during volitional testing at 25° compared to 45° knee flexion.

A further aim of this study was to investigate the robustness of correlations between indices of volitional and evoked performance capabilities over the three knee positions. With the exception of a statistically significant but biologically weak (coefficient of determination < 0.32) negative relationship between magnetically-evoked and volitional indices of electromechanical delay at 45° of knee flexion ($r = -0.558$; $p < 0.05$, table 2), the results showed there were no relationships between indices of volitional and magnetically-evoked neuromuscular performance of the quadriceps femoris at analogous joint positions. Further analyses also revealed no relationships between indices of volitional performance capabilities at knee positions that are proximal to full extension (25°) and evoked twitch parameters at more force-optimised joint positions (45°) ($r = -0.05$ and 0.25, $p > 0.05$ for $P_TF_E45°$: $PF_V25°$ and $EMD_E45°$; $EMD_V25°$, respectively). Optimal functioning of skeletal muscle, and in particular the capability for rapid activation of muscle is paramount for proper stabilisation of synovial joints [Schultz et al, 2001]. Whilst the present methods of assessment may provide a valuable means to obtaining information regarding skeletal muscle performance capability, the current data suggests that it would not be possible or appropriate to attempt to predict angle-specific volitional performance capabilities from either magnetically-evoked estimates of performance at corresponding knee joint positions, or indeed to predict angle-specific volitional performance capabilities from those evoked at neighbouring joint positions. For example, indices of magnetically-evoked performance capacity at knee angles that offer favourable myofilament overlap would not correctly predict the quality of either evoked or volitional performance capability at joint positions proximal to full extension, where key ligamentous structures are under greatest mechanical strain and might be threatened by inferior muscular strain-shielding [Beynnon and Johnson, 1996]. It is likely, therefore, that despite the obvious appeal and simple logistics of a single evoked assessment [Polkey et al, 1996; Vivodtzev et al, 2005], such an approach may underestimate the extent of vulnerability to musculoskeletal injury at extended knee positions, even when superior neuromuscular performance has been observed at force-optimised positions.

4.2. Implications for research and clinical practice

In conclusion, this study has shown greater relative improvements in volitional compared to evoked indices of neuromuscular performance of the quadriceps femoris with increasing knee flexion. No consequential relationships were observed between indices of volitional and magnetically-evoked neuromuscular performance at either analogous or adjacent joint positions. Therefore, in order to avoid potential errors in prediction and of interpretation, it should be imperative that volitional and evoked neuromuscular performance capabilities are assessed directly and specifically at the relevant knee joint angle of interest. Future research might seek to identify the specific inhibitory-driven mechanisms influencing performance and the capability for voluntary neural activation across joint angles.

References

Babault N, Pousson M, Michaut A, Van Hoecke J. Effect of quadriceps femoris muscle length on neural activation during isometric and concentric contractions. Journal of Applied Physiology 2003;94(3):983-90.

Bailey A, Goodstone N, Roberts S, Hughes J, Roberts S, van Niekerk L, Richardson J, Rees D. Rehabilitation After Oswestry Autologous-Chondrocyte Implantation: The OsCell Protocol. Journal of Sports Rehabilitation 2003;12(2):104-118.

Beynnon BD, Johnson RJ. Anterior cruciate ligament injury rehabilitation in athletes. Sports Medicine 1996;22 (1):54-64.

Chan AYF, Lee FLL, Wong PK, Wong CYM, Yeung SS. Effects of knee joint angles and fatigue on the neuromuscular control of vastus medialis oblique and vastus lateralis muscle in humans. European Journal of Applied Physiology 2001;84(1-2):36-41.

Desbrosses K, Babault N, Scaglioni G, Meyer JP, Pousson M. Neural activation after maximal isometric contractions at different muscle lengths. Medicine and Science in Sports and Exercise 2006;38(5):937-44.

Gleeson NP. Assessment of neuromuscular performance using electromyography. In: Eston RG, Reilly T, editors. Kinanthropometry and Exercise Physiology Laboratory Manual: Tests Procedures and Data (2nd ed). London: Routledge: 2001. p. 37-63.

Gleeson NP, Rakowski S, Reilly T.. Reproducibility of indices of anterior tibio-femoral displacement in active and inactive men. In: Atkinson G, Reilly T, eds. Sport Leisure and Ergonomics.London: E and FN Spon. 1995 p198-203.

Grabiner MD, Donovan S, Bareither ML, Marone JR, Hamstra-Wright K, Gatts S, Troy KL. Trunk kinematics and fall risk of older adults: translating biomechanical results to the clinic. Journal of Electromyography and Kinesiology 2008;18(2):197-204.

Granata KP, Ikeda AJ, Abel MF. Electromechanical delay and reflex response in spastic cerebral palsy. Archives of Physical Medicine and Rehabilitation 2000;81(7):888-894.

Hamnegård CH, Sedler M, Polkey MI, Bake B. Quadriceps strength assessed by magnetic stimulation of the femoral nerve in normal subjects. Clinical Physiology and Functional Imaging 2004;24(5):276–280.

Hopkins JT, Ingersoll CD. Arthrogenic muscle inhibition: a limiting factor in joint rehabilitation. Journal of Sports Rehabilitation 2000;9(2):135-159.

Huston LJ, Wojtys EM. Neuromuscular performance characteristics in elite female athletes. American Journal of Sports Medicine 1996;24(4):427-436.

Ireland MJ, Gaudette M, Crook S. ACL injuries in the female athlete. Journal of Sports Rehabilitation 1997;6(2):97-110.

Johansson H, Sjolander P, Sojka P. A sensory role for the cruciate ligaments. Clinical Orthopaedics and Related Research 1991;268:161-178.

Komi PV, Linnamo V, Silventoinen P, Sillanpaa M. Force and EMG power spectrum during eccentric and concentric actions. Medicine and Science in Sports and Exercise 2000;32(10):1757–1762.

Kubo K, Akima H, Kouzaki M, Ito M, Kawakami Y, Kanehisa H, Fukunaga T. Changes in the elastic properties of tendon structures following 20 days of bed-rest in humans. European Journal of Applied Physiology 2000;83(6):463-468.

Mador MJ, Bozkanat E, Kufel TJ. Quadriceps fatigue after cycle exercise in patients with COPD compared with healthy control subjects. Chest. 2003;123(4);1104-1111.

Maffiuletti NA. Physiological and methodological considerations for the use of neuromuscular electrical stimulation. European Journal of Applied Physiology. 2010; 110(2):223–234.

Maganaris CN. Imaging-based estimates of moment arm length in intact human muscle-tendons. European Journal of Applied Physiology 2004 91;(2-3):130-9.

Man WD, Moxham J, Polkey MI. Magnetic stimulation for the measurement of respiratory and skeletal muscle function. The European Respiratory Journal 2004;24(5):846-60.

Mandelbaum BR, Silvers HJ, Watanabe DS, Knarr JF, Thomas SD, Griffin LY, Kirkendall DT, Garrett W. Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes. American Journal of Sports Medicine 2005;33(7):1003-1010.

McComas AJ. Skeletal Muscle: Form and Function. Human Kinetics, Champaign, Illinois, USA; 1996.

Minshull C, Gleeson N, Eston RG, Bailey A, Rees D. Single measurement reliability and reproducibility of volitional and magnetically-evoked indices of neuromuscular performance in adults. Journal of Electromyography and Kinesiology 2009;19(5):1013-23.

Minshull C, Gleeson NP, Walters-Edwards M, Eston R, Rees D. Effects of acute fatigue on the volitional and magnetically-evoked electromechanical delay of the knee flexors in males and females. European Journal of Applied Physiology 2007;100(4):469-478.

Moore MA, Kukulka CG. Depression of Hoffmann reflexes following voluntary contraction and implications for proprioceptive neuromuscular facilitation therapy. Physical Therapy 1991;71(4):321-329.

Muraoka T, Muramatsu T, Fukunaga T, Kanehisa H. Influence of tendon slack on electromechanical delay in the human gastrocnemius in vivo. Journal of Applied Physiology 2004;96(2):540-544.

Newman SA, Jones G, Newham DJ. Quadriceps voluntary activation at different joint angles measured by two stimulation techniques. European Journal of Applied Physiology 2003;89(5):496-499.

Polkey MI, Kyroussis D, Hamnegard CH, Mills GH, Green M, Moxham J. Quadriceps strength and fatigue assessed by magnetic stimulation of the femoral nerve in man. Muscle Nerve. 1996;19(5):549-555.

Sathyapala SA, Marsh GS, Hopkinson NS, Moxham J, Polkey MI. Systemic aspects of COPD. Thorax 2007;62;A54-A55.

Shultz SJ, Perrin DH, Adams MJ, Arnold BL, Gansneder BM, Granata KP. Neuromuscular response characteristics in men and women after knee perturbation in a single-leg, weight-bearing stance. Journal of Athletic Training 2001;36(1):37-43.

Snyder-Mackler L, Delitto A, Stralka SW, Bailey SL. Use of electrical stimulation to enhance recovery of quadriceps femoris muscle force production in patients following anterior cruciate ligament reconstruction. Physical Therapy 1994;74(10):901-7.

Swallow EB, Gosker HR, Ward KA, Moore AJ, Dayer MJ, Hopkinson NS, Schols AM, Moxham J, Polkey MI. A novel technique for nonvolitional assessment of quadriceps muscle endurance in humans. Journal of Applied Physiology 2007;103(3):739–746.

Tideiksaar R. Falls in the elderly. Bulletin of the New York Academy of Medicine 1988;64(2):145-163.

Tsuji I, Nakamura R. Time course of tension development on knee extensor muscle on twitch, tetanic and fast voluntary contraction in normal subjects. Tohoku Journal of Experimental Medicine 1988;155(3):225-232.

Vivodtzev I, Wuyam B, Flore P, Lévy P. Changes in quadriceps twitch tension in response to resistance training in healthy sedentary subjects. Muscle Nerve. 2005;32(3):326-334.

Zhou S, Carey MF, Snow RJ, Lawson DL, Morrison WE. Effects of muscle fatigue and temperature on electromechanical delay. Electromyography and Clinical Neurophysiology 1998;38(2):67-73.

Zhou S, Lawson DL, Morrison WE, Fairweather I. Electromechanical delay in isometric muscle contractions evoked by voluntary, reflex and electrical stimulation. European Journal of Applied Physiology and Occupational Physiology 1995;70(2):138-145.

FIGURE 1. Participant and dynamometer orientation.

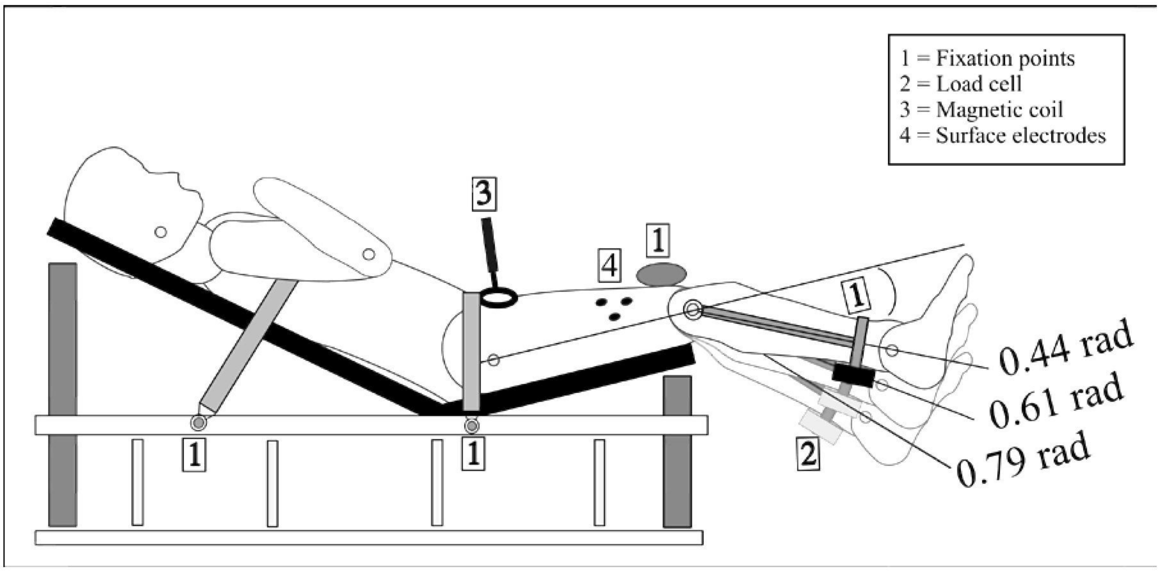

FIGURE 2. Quadriceps PF_V and P_TF_E values at three knee joint positions (0° = full extension; group mean ± SD).

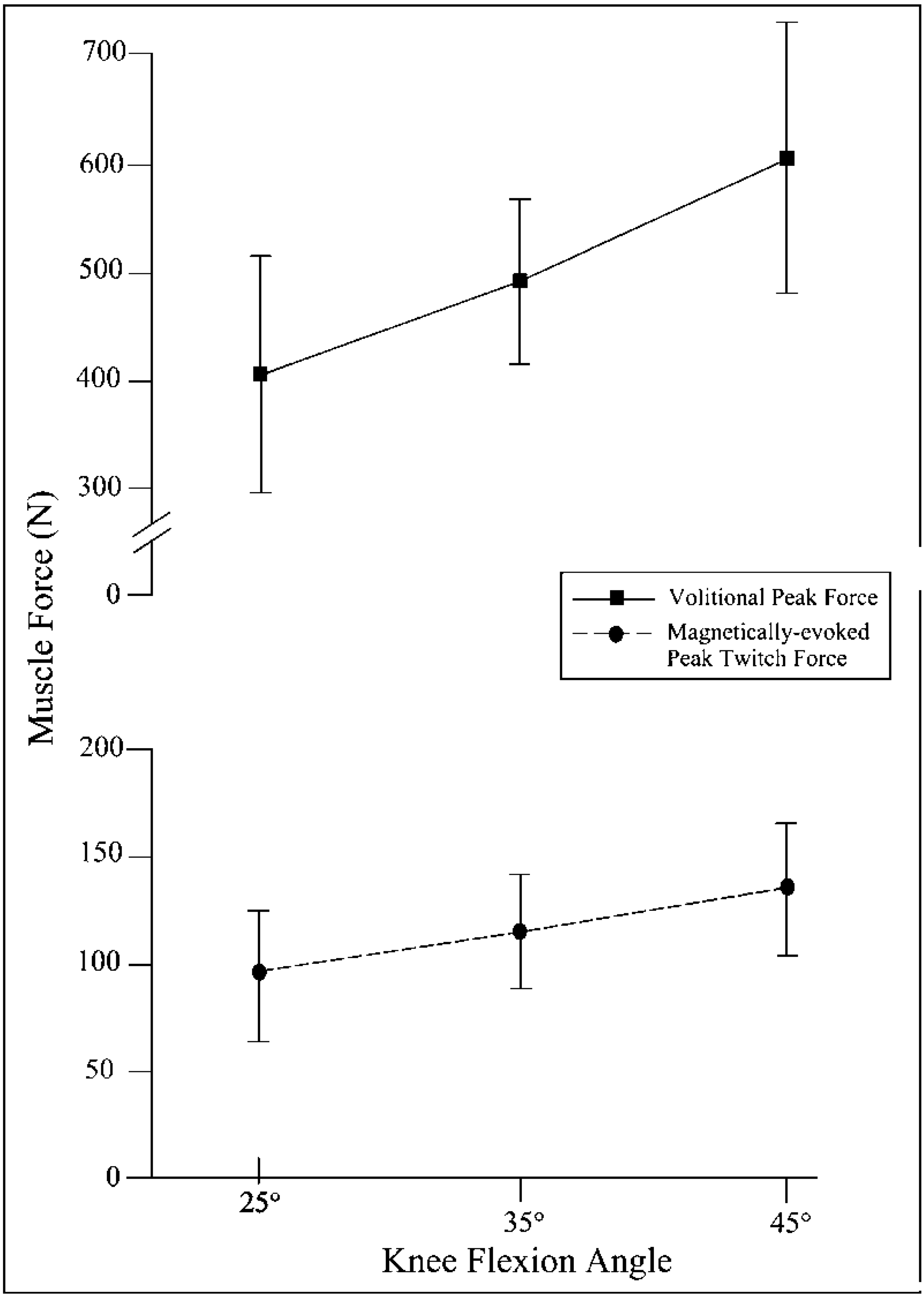

FIGURE 3. Quadriceps PF_V and P_TF_E values at three knee joint positions (0° = full extension; group mean ± SD).