

VARIABILITY IN ANTAGONIST MUSCLE ACTIVITY AND PEAK TORQUE DURING ISOMETRIC KNEE STRENGTH TESTING

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ABSTRACT

BACKGROUND & OBJECTIVE: Strength testing is common in the treatment of people with knee pathology and in research related to knee health. Variability in the magnitude of antagonist muscle activity and peak torque measurements during isometric knee strength testing is not well defined and has potential implications of strength test validity and reliability. The aim of this study was to determine the magnitude and variability (side-to-side, session-to-session) of antagonist muscle activity and peak torque during isometric knee strength testing and to compare and contrast the results of males and females.

METHODS: Electromyograms and torque data were collected from 30 active young people (15 males, 15 females) during isometric strength testing of the knee extensors and flexors at two sessions that took place approximately one week apart. The magnitude of antagonist muscle activity and peak torque during isometric knee strength testing was calculated and the variability in these parameters assessed.

RESULTS: Significant side-to-side differences were observed in the magnitude of antagonist muscle activity when the leg with higher antagonist activity was contrasted with the leg with lower antagonist activity ($P < 0.001$). Significant side-to-side differences were also observed when peak torque measurements were contrasted in a similar manner ($P < 0.001$). No significant differences were observed in peak torque and antagonist activity measurements between sessions. Significantly higher vastus medialis antagonist activity was observed in females ($P < 0.001$).

CONCLUSIONS: Our findings suggest that significant variability in antagonist muscle activity and peak torque is present during maximal isometric knee strength testing. This variability may reduce the accuracy of knee strength tests, especially when side-to-side comparisons are made as is typical in clinical settings. The results of this study may be helpful when interpreting strength test results and setting criteria for patient progression.

INTRODUCTION

Knee strength tests are commonly used by clinicians who treat patients with knee pathology and scientists who study the etiology and effects of knee disorders, treatment methods for these conditions, and treatment outcomes in this population. Isometric knee strength tests allow the knee to be fixed in a safe position during testing and inherently provide control that assists with test reproducibility. Isometric tests are also preferable when performing knee strength tests involving superimposition of electric stimuli (i.e., interpolated twitch or burst superimposition tests), which allow quantification of quadriceps muscle activation levels in addition to voluntary torque generation capacity.¹

It is widely accepted that the peak torque generated at a joint is the sum of the moments generated by the agonist and antagonist muscles acting at the joint.² Antagonist muscle activity, commonly referred as coactivation or co-contraction, is defined as simultaneous activation of both agonist and antagonist muscle groups during static or dynamic contractions.³ Antagonist muscle activity during maximal contractions theoretically produces a moment that may counter the moment of interest, thereby reducing test accuracy. For example, hamstring muscle activity during knee extensor strength testing produces a flexion moment that may result in an underestimation of true knee extensor strength. It is generally assumed that antagonist muscles are essentially silent during strength tests; however, evidence from studies evaluating isokinetic strength tests suggests otherwise.^{4,6} It is unclear whether findings from dynamic isokinetic tests are translatable to isometric strength tests. Moreover, data on the side-to-side and session-to-session variability in antagonist muscle activity during knee strength testing is lacking. An understanding of the variability in antagonist activity is meaningful as this information could have

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important implications for strength testing validity and reliability. Finally, it is unknown if there are sex differences in the magnitude of antagonist activity present in maximal isometric contractions about the knee. Recent evidence of sex differences in muscle activation during sub-maximal contractions about the knee suggests that this is a possibility.⁷ Knowledge of such differences would be meaningful as it would further understanding of sex differences in human physiology and may have implications for strength tests and rehabilitation.

The aim of this study was to determine the magnitude and variability (side-to-side, session-to-session) in antagonist muscle activity and torque measurements during maximal isometric strength testing of the knee extensors and flexors. Based on pilot work, we hypothesized that significant (approximately 10% maximum) antagonist activity would be observed in the lateral hamstrings and the quadriceps muscles during maximal voluntary isometric contractions (MVICs). In addition, we hypothesized that significant side-to-side and session-to-session variability in antagonist muscle activity and peak torque measurements would be observed. A secondary aim of the study was to contrast the results of males and females of similar age and activity-level to determine if antagonist activity during maximal isometric contractions differs by sex. We hypothesized that no significant differences in antagonist muscle activity would be observed between males and females.

METHODS

Subjects

Thirty active young people (age 22.6 ± 1.7 years, BMI 22.7 ± 2.7 , Tegner Activity Score⁸ 6.3 ± 1.1) with no history of significant lower extremity injuries volunteered to participate in this study. The sample included 15 males and 15 females who were similar in age (male 22.9 ± 1.4 years, female 22.3 ± 2.0 years) and activity level (Tegner Activity Scores: male 6.4 ± 1.4 , female 6.1 ± 0.7). Exclusion criteria included a history of significant lower extremity muscle or tendon injury, knee ligament injury, abnormal KT-2000™ evaluation (≥ 3 mm side-to-side difference in laxity), history of lower extremity surgery, an ankle sprain or fracture within the prior six months, lower extremity nerve injuries, abnormal gait pattern, and the inability to complete two testing session within a 2 week period. A brief physical examination of the lower extremity was performed bilaterally to confirm that subjects could be considered to be injury-free with good lower extremity function. No potential subjects were excluded from the study based on their physical exam or medical history. All subjects were right leg dominant as determined by asking the subjects which leg they would use to kick a ball as far as possible. This

study was approved by the University of Iowa Human Subjects Research Institutional Review Board and each subject provided written informed consent to participation using a form approved by this review board.

Testing Procedures

Subjects performed a five minute “warm-up” on a cycle ergometer just prior to participation. Double differential surface electromyography (EMG) preamplifiers (model MA-311, Motion Lab Systems, Inc., Baton Rouge, LA, USA; 20x gain, > 100,000 M Ω , noise < 1.2 μ V RMS) were then applied over the muscle bellies of the semitendinosus (MH), biceps femoris longus (LH), vastus lateralis (VL), rectus femoris (RF), and vastus medialis (VM) muscles after cleaning the skin with alcohol swabs. Electrode placement sites were selected according to the recommendations of Perotto.⁹ Manual muscle testing was performed to confirm appropriate electrode placement and to check for signs of crosstalk from adjacent muscles. Subjects were then positioned on and secured to a HUMAC NORM Testing and Rehabilitation System (Computer Sports Medicine, Inc., Stoughton, MA, USA) according to the manufacturer’s testing guidelines. Subjects sat on a small platform placed on the testing system’s chair to unload the thigh and thereby minimize the likelihood of noise associated with pressure on the EMG preamplifiers fixed over the hamstrings muscles. Knee and hip position were standardized at 60° and 90° of flexion, respectively. The test system’s torque arm pad was fixed to the shank approximately 7 cm proximal to the medial malleolus. The length of the torque arm and all test system position settings were recorded for use in repeat testing. The order in which subjects’ legs were tested was randomized *a priori* using a computer-based random number generator.

Three baseline EMG traces were collected just prior to strength testing while subjects sat quietly on the test system. Five sub-maximal isometric knee extension and flexion trials were then performed to familiarize the subjects with isometric contractions and prepare the subjects’ muscles for testing. Strength testing was initiated following a one minute rest period. Subjects performed five maximal isometric knee extension contractions (Figure 1) and five maximal isometric knee flexion contractions in alternate order (i.e., extension, flexion, extension, flexion, etc). All trials were five seconds in duration. Fatigue was minimized by standardizing 90 seconds of rest between extension and flexion trials so that 180 seconds transpired between like trials. Maximal effort was facilitated through the use of loud verbal encouragement and by allowing subjects to view their real time torque curves on the test system’s display



Figure 1. A subject performing an isometric knee strength test on the test system.

during testing. When testing was completed on the first side, subjects were positioned for testing of the opposite side. The testing procedures for the opposite leg were identical to those used when testing the first leg. When subjects had completed testing with both legs they were scheduled to return to the laboratory one week later when repeat testing was performed using identical methods.

Signal Sampling, Conditioning, and Processing

Electromyograms and torque signals were sampled at 1000 Hz using software written in LabVIEW 7.0 (National Instruments Corporation, Austin, TX, USA). The signals from the HUMAC NORM Testing and Rehabilitation System were passed through an eighth order analog Butterworth low pass filter with a cut-off frequency of 10 Hz and then converted to torque values (N·m) using calibrated conversion factors that were validated onsite prior to testing. Electromyographic signals were conditioned by passing them through an eighth order analog Butterworth low pass filter with a cut-off frequency of 500 Hz. A second LabVIEW program was used to

determine the peak torque value in each trial and to post-process the EMG data. All EMG data were full-wave rectified. The baseline EMG trials were averaged and then subtracted from the EMG data recorded during each trial. The integrated EMG (IEMG) magnitude during the 100 ms window preceding peak torque was used for the analysis of antagonist muscle activity. This window provides EMG data that are particularly meaningful because these are the data that are most closely related to the peak torque measurement. The five 100 ms IEMG samples recorded for each muscle in each direction were averaged for use in analysis (i.e., the five 100 ms IEMG samples for the VL muscle recorded during the extension trials were averaged and the five 100 ms IEMG activity for the VL muscle in the flexion trials were averaged). The magnitude of antagonist muscle activity present during testing (hamstrings muscle activity in extension trials and quadriceps muscle activity in flexion trials) was determined by representing the values recorded when the muscles were antagonists as a percentage of the respective values recorded when the muscles were agonists. For example, the magnitude of lateral hamstrings activity present during knee extensor strength testing was determined by: (mean LH IEMG activity in extension / mean LH IEMG activity in flexion) x 100. Each subject's mean peak torque for knee extension and flexion was determined by averaging the peak torque values from the five maximal trials in the respective movement directions. The torque produced by each subject was corrected for gravity to account for the weight of the subject's limb. A limb symmetry index was calculated for each subject using the following equation: (mean peak torque produced by the weaker leg / mean peak torque produced by the stronger leg) x 100.

Data Management and Analysis

All statistical analyses were performed using SPSS for Windows (SPSS Inc., Chicago, IL, USA). Descriptive statistics were calculated for each variable. Repeated measures ANOVA with 2 within-subjects factors (side, session) and sex as a between-subjects factor was used to evaluate differences by side, session, and sex for each dependent variable (MH activity in peak extension, LH activity in peak extension, VL activity in peak flexion, RF activity in peak flexion, VM activity in peak flexion, peak torque in extension, and peak torque in flexion). Our pilot-testing suggested that the limb that had higher magnitude of antagonist activity and peak torque varied considerably between subjects and was not related to subjects' limb dominance. Consequently, the variability between legs mathematically canceled out making it appear that there was no difference by side. Therefore, the magnitude of antagonist muscle activity was contrasted

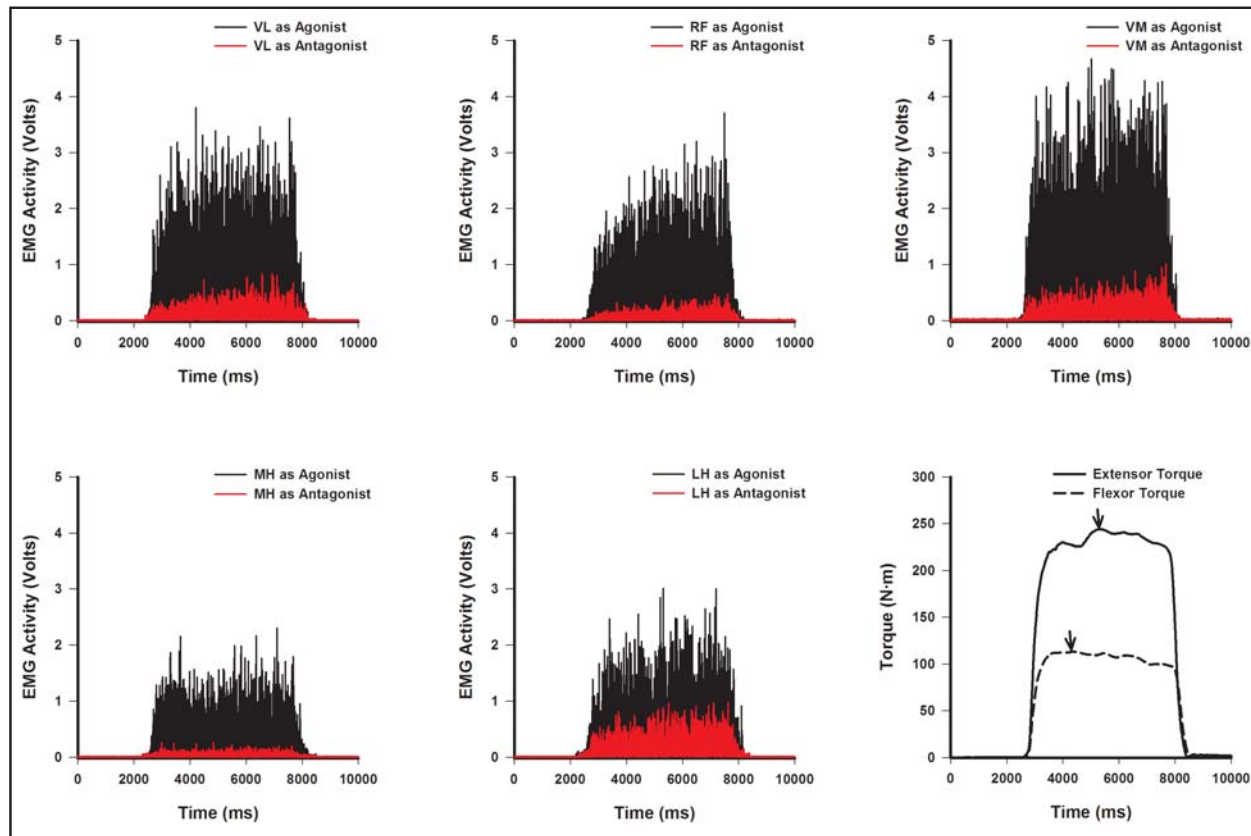


Figure 2. A sample raw electromyographic recording of muscle activity with associated torque traces from a subject's isometric knee extensor and flexor strength tests. The agonist (black) and antagonist (red) activity of the five knee muscles tested demonstrate the noteworthy antagonist activity during isometric knee strength testing. Arrows indicate the epoch at which the subject produced peak torque values. VL: Vastus Lateralis; RF: Rectus Femoris; VM: Vastus Medialis; MH: Semitendinosus; LH: Biceps Femoris Longus.

by side (right vs. left) and also by contrasting the results of the leg that produced higher antagonist muscle activity with the leg that produced lower antagonist muscle activity. Similar contrasts (right vs. left and higher vs. lower) were performed for peak torque measurements.

RESULTS

Antagonist Muscle Activity

Antagonistic muscle activity (Figure 2) was observed in each muscle during maximal isometric knee strength testing (mean quadriceps activity: 7 to 16% maximum, mean hamstrings activity: 7 to 19% maximum) (Table 1). Each of the five muscles had significant differences ($P < .001$) in mean antagonist IEMG activity between sides when the leg producing higher IEMG activity was contrasted with the leg producing lower IEMG activity (Figure 3); however, when the activity of each muscle was contrasted by side (i.e., right vs. left), no significant differences were observed ($P = 0.192$ to 0.670 , Figure 4A). No muscle displayed significant differences in activity between sessions ($P = 0.078$ to 0.848 , Figure

4B); however, the leg that produced higher antagonist activity changed across test sessions in about 50% of the sample. Females had significantly higher ($P = .001$) mean antagonistic vastus medialis IEMG activity than males; all other muscles displayed no significant difference by sex ($P = 0.130$ to 0.518 , Figure 3).

Peak Torque

Males produced greater mean peak torque ($P < .001$) than females (Table 1). As was the case with antagonist muscle activity, there was no significant difference by side when the peak torque generated by the subjects' right thigh muscles was contrasted with the results from their left side ($P = 0.150$ for extensor peak torque, $P = 0.536$ for flexor peak torque, Figure 5A); however, a significant difference ($P < .001$) was observed for both torque directions when results of the leg that produced higher peak torque were contrasted with those from the leg that produced lower peak torque (Figure 5B). The mean knee extensor side-to-side symmetry index

TABLE 1
Antagonist muscle activity (% maximum) and peak torque (N•m) during isometric knee strength testing

Sex	Limb		Session 1	95% CI	Session 2	95% CI
Female	Right	VL _{Flex}	11.63 ± 1.44	8.81 - 14.45	9.17 ± 1.08	7.05 - 11.29
		RF _{Flex}	12.05 ± 1.85	8.42 - 15.68	10.75 ± 1.95	6.93 - 14.57
		VM _{Flex}	16.32 ± 1.08	14.20 - 18.44	13.57 ± 0.87	11.86 - 15.28
		MH _{Ext}	9.12 ± 1.57	6.04 - 12.20	10.06 ± 1.70	6.73 - 13.39
		LH _{Ext}	14.17 ± 3.53	7.25 - 21.09	12.24 ± 1.60	9.10 - 15.38
		PT _{Ext}	177.87 ± 8.24	161.72 - 194.02	180.95 ± 9.83	161.68 - 200.22
		PT _{Flex}	93.47 ± 4.55	84.55 - 102.39	91.98 ± 4.84	82.49 - 101.47
Female	Left	VL _{Flex}	8.85 ± 0.83	7.22 - 10.48	9.13 ± 0.74	7.68 - 10.58
		RF _{Flex}	10.83 ± 2.17	6.58 - 15.08	10.76 ± 1.62	7.58 - 13.94
		VM _{Flex}	15.77 ± 1.16	13.50 - 18.04	16.49 ± 1.49	13.57 - 19.41
		MH _{Ext}	10.57 ± 1.75	7.14 - 14.00	8.13 ± 1.23	5.72 - 10.54
		LH _{Ext}	15.46 ± 2.65	10.27 - 20.65	15.75 ± 2.72	10.42 - 21.08
		PT _{Ext}	193.79 ± 9.47	175.23 - 212.35	181.98 ± 10.94	160.54 - 203.42
		PT _{Flex}	98.32 ± 4.39	89.72 - 106.92	95.91 ± 5.03	86.05 - 105.77
Male	Right	VL _{Flex}	7.11 ± 0.72	5.70 - 8.52	8.96 ± 0.97	7.06 - 10.86
		RF _{Flex}	7.84 ± 1.09	5.70 - 9.98	7.43 ± 1.48	4.53 - 10.33
		VM _{Flex}	12.28 ± 0.83	10.65 - 13.91	11.37 ± 1.04	9.33 - 13.41
		MH _{Ext}	6.64 ± 0.71	5.25 - 8.03	7.24 ± 1.42	4.46 - 10.02
		LH _{Ext}	14.83 ± 3.05	8.85 - 20.81	15.99 ± 3.76	8.62 - 23.36
		PT _{Ext}	246.59 ± 11.45	224.15 - 269.03	254.10 ± 12.40	229.80 - 278.40
		PT _{Flex}	141.45 ± 7.94	125.89 - 157.01	136.12 ± 8.05	120.34 - 151.90
Male	Left	VL _{Flex}	7.39 ± 0.83	5.76 - 9.02	8.19 ± 2.09	4.09 - 12.29
		RF _{Flex}	9.87 ± 2.67	4.64 - 15.10	9.35 ± 2.60	4.25 - 14.45
		VM _{Flex}	12.15 ± 1.42	9.37 - 14.93	10.44 ± 0.87	8.73 - 12.15
		MH _{Ext}	8.22 ± 1.01	6.24 - 10.20	7.82 ± 1.04	5.78 - 9.86
		LH _{Ext}	19.13 ± 2.70	13.84 - 24.42	16.06 ± 2.50	11.16 - 20.96
		PT _{Ext}	251.81 ± 12.10	228.09 - 275.53	258.70 ± 10.0	239.10 - 278.30
		PT _{Flex}	138.86 ± 7.49	124.18 - 153.54	137.66 ± 8.26	121.47 - 153.85

Data are presented as mean ± standard error of the mean with 95% confidence intervals. VL, Vastus Lateralis; RF, Rectus Femoris; VM, Vastus Medialis; MH, Semitendinosus; LH, Biceps Femoris Longus; Flex, Flexion; Ext, Extension; PT, Peak Torque.

was 89.9% for females and 91.5% for males. The mean knee flexor symmetry index was 92.5% for females and 87.1% for males. Peak torque values were similar across sessions for both muscle groups (Figure 4B). The leg that produced higher peak torque remained the same in majority of the subjects across test sessions (knee extensors: 70% consistent, knee flexors: 80% consistent).

DISCUSSION

The mean antagonist muscle activity observed in the hamstrings and quadriceps muscles of the subject in this study during maximal isometric knee extensor

and flexor strength testing ranged from 7.1% to 19.1% of maximum values (Table 1), which supports our first hypothesis. These data are consistent with the findings from studies evaluating antagonistic muscle activity in isokinetic tests.^{5,6} The magnitude of antagonistic activity observed in the lateral hamstrings and vastus medialis muscles was similar and substantially higher than the magnitude of activity observed in the vastus lateralis, rectus femoris, and medial hamstrings muscles. This finding is also consistent with results in the isokinetic testing literature.⁴ The magnitude of lateral hamstrings activity during knee extension trials was generally about

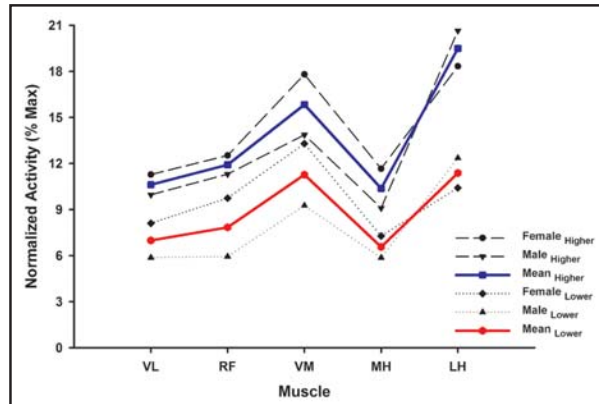


Figure 3. Plots demonstrating the difference between the mean normalized antagonist activity by side for the 5 muscles of the male and female subjects when the values of the leg that produced higher antagonist activity was contrasted with those from the leg that produced lower antagonist activity. Bold colored lines represent the mean for all subjects irrespective of the sex of the subject. All muscles exhibited significant differences between sides ($P < 0.001$). Females had significantly higher VM antagonist activity when compared to males ($P = 0.001$). Note the limb that produced lower VM antagonist activity in females is similar in magnitude to the limb that produced higher VM in males. VL: Vastus Lateralis; RF: Rectus Femoris, VM: Vastus Medialis; MH: Semitendinosus; LH: Biceps Femoris Longus.

twice that recorded from the medial hamstrings irrespective of the side tested or test session. This agrees with the results of Aagaard et al.⁶ who reported values of approximately 30% maximum for the lateral hamstrings and 10% maximum for the medial hamstrings during maximal isokinetic knee extension. Aagaard et al.⁶ attributed the

observed hamstrings activity during knee extensor testing to a protective mechanism associated with loading of the ACL during intense quadriceps muscle contraction in terminal knee extension. In the current study, however, subjects were tested in an isometric fashion at 60° of knee flexion, which is a point in the knee range of motion at which the ACL experiences little strain.¹⁰ Despite this fact, we observed significant hamstrings activity during maximal knee extension trials. This finding argues against ACL strain being a primary source of the observed antagonistic hamstrings activity.

There are several possible explanations for the observed antagonist activity. At least some of the antagonist activity could be directed at stabilizing the femur so that the agonist musculature has a stable platform from which to transfer force to the tibia. This simple and reasonable explanation is, however, rather difficult to test. Another plausible explanation relates to a broad increase in excitability in the nervous system during maximal effort. Although standard testing procedures includes the use of seatbelts and positioning aimed at minimizing compensation strategies and loss of energy (e.g., crossing the arms over the chest), it is obvious that muscle contraction is occurring broadly when one observes the facial expressions and muscle tone of the arms, shoulders, and opposite legs of the person being tested. This broad activity suggests that the excitability in the nervous system is increased in a relatively global manner as it is unlikely that there is a direct benefit from most of this extraneous muscle contraction. Mini-

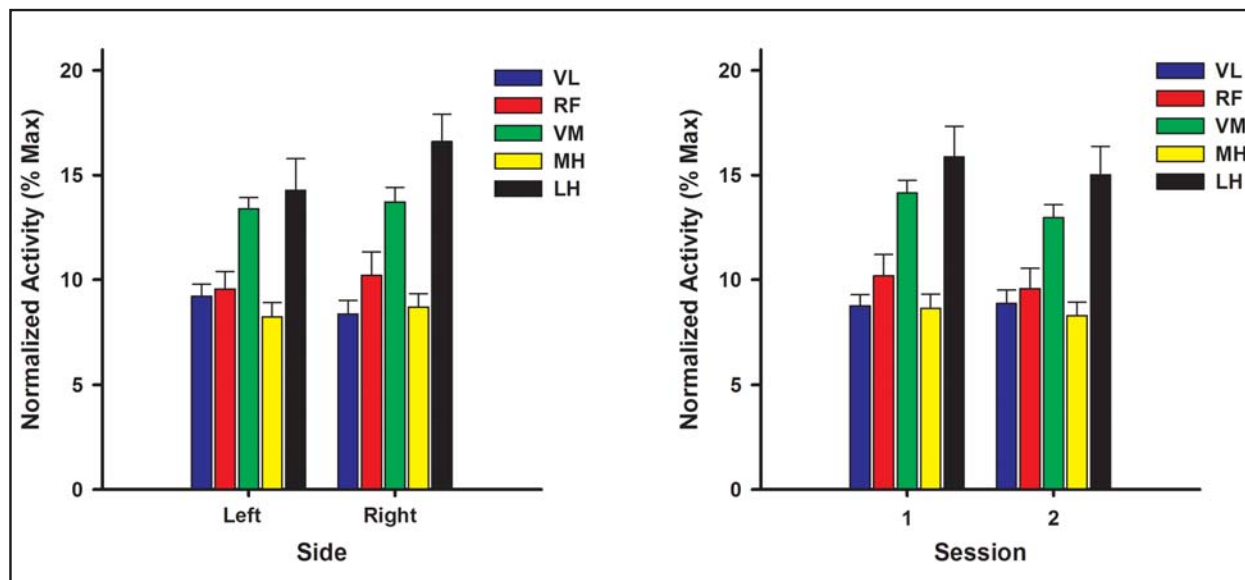


Figure 4. The mean normalized antagonist activity for the 5 knee muscles contrasted between left and right side (A) and across test sessions (B). Note that there are no differences in the magnitude of antagonist activity between left and right side and across test sessions. Error bars represent standard error of the mean. VL: Vastus Lateralis; RF: Rectus Femoris, VM: Vastus Medialis; MH: Semitendinosus; LH: Biceps Femoris Longus.

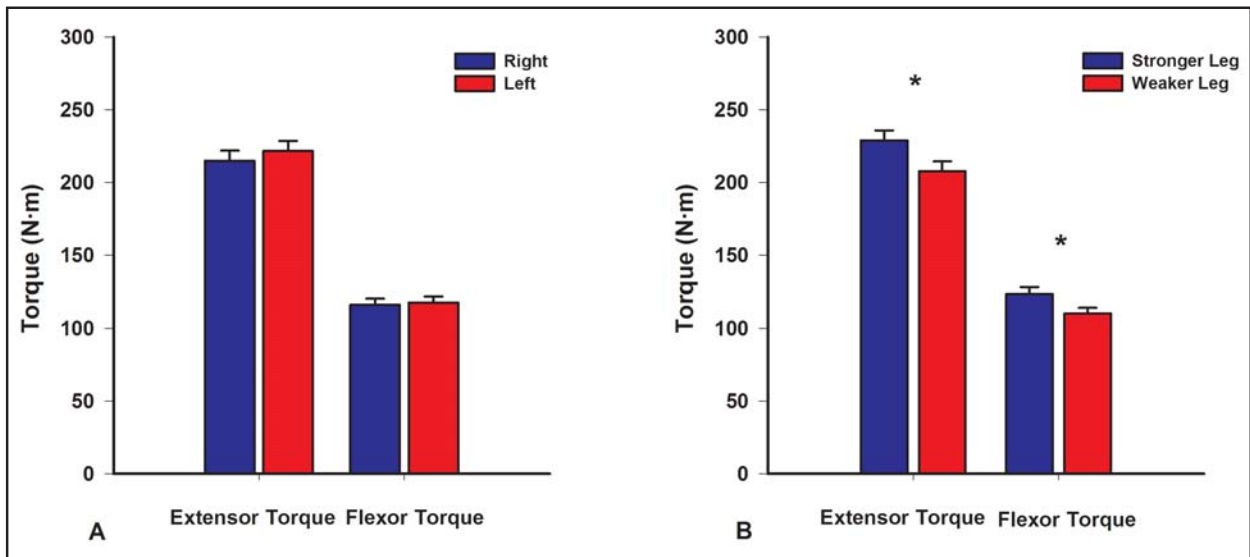


Figure 5. The mean peak torque for the knee extensors and flexors when contrasted as left versus right side was not significantly different. Conversely, significant differences ($P < 0.001$) were observed when the leg that produced higher peak torque was contrasted with the leg that produced lower peak torque (B). This was consistent across test sessions. Error bars represent standard error of the mean and asterisks identify significant differences ($P < 0.05$).

mizing (inhibiting) this widespread increase in neural drive without reducing torque generation is difficult without considerable practice with real-time feedback on performance. Hence, it is reasonable that at least some of the observed antagonist activity is a result of a spillover of neural drive that is difficult to control. A related issue that may also be a factor in the observed antagonist activity is the fact that MVICs are a novel task for many people. Evidence indicating that training can reduce the magnitude of antagonist activity of observed in isometric contractions supports the idea that some of the antagonist activity may be associated with task novelty.^{11,12} Although practice trials are routinely performed before strength testing, the number of practice trials that can be given is limited as fatigue can set in and compromise the test results. Providing a series of training sessions before administering strength tests is generally impractical. Consequently, task novelty is a difficult issue to address.

It is generally assumed that antagonist activity is negligible during knee strength testing based on the widely held concept of reciprocal inhibition (i.e., antagonist muscles are inhibited during tasks in which agonist muscles are highly active).¹³ This assumption is the result of an oversimplification of the phenomenon of reciprocal innervation. Sir Charles Sherrington,¹⁴ who is credited with introducing the concept of reciprocal innervation, in fact suggested that under certain circumstances the nervous system may concurrently activate both the extensor and flexor “half center,” a process that he referred

to as double reciprocal innervation. Antagonist muscle activation is most frequently observed in tasks that require high precision, those that involve high magnitudes of force production, or those that include high velocities of limb movement.¹³ Our findings suggest that although antagonist muscles are largely inhibited, this inhibition is incomplete and-or double reciprocal inhibition is present.

Scientists postulate that antagonist muscle activity is primarily controlled by central mechanisms.^{3,15,16} De Luca and Mambrito¹⁵ suggested that in flexion-extension tasks, agonist-antagonist pairs operate under “common drive” as if they belong to the same motoneuron pool. Researchers have since suggested that while antagonist activity does appear to be controlled primarily through supraspinal mechanisms, the excitation of antagonist motoneuron pools may occur via a pre-synaptic mechanism in which the nervous system actively inhibits the disynaptic Ia inhibitory pathway through descending commands rather than through a common drive mechanism.^{3,16} Understanding the source of this antagonist activity is meaningful with respect to the neurophysiology and sensorimotor control of knee function. Although the exact source of this activity is currently unknown, our results and the literature cited suggest that such activity should be expected and is strongly supported.

We hypothesized that there would be significant variability in the magnitude of antagonist activity observed by side and across days. A significant difference in the magnitude of antagonist activity was observed in like muscles across legs, but there was no difference across

sessions. Close inspection of the data revealed that the leg displaying higher antagonist muscle activity changed across test sessions in about half of the sample. Hence, some variability is in fact present across test sessions.

The observed side-to-side difference in antagonist activity is an important finding because it indicates that this activity (and the moment associated with it) does not mathematically cancel across sides. Although the mean differences in antagonist activity observed in each muscle across sides were relatively small (4 to 6% maximum values), some people had large differences between legs. This suggests that side-to-side differences in antagonist activity are likely to have a larger effect on side-to-side strength comparisons on a patient-by-patient basis than they are when the results of a sample of people are being considered. Moreover, it is the combined effect of the antagonist activity in the muscles of each functional group that must be considered rather than the values of the individual muscles alone. It is not possible to determine whether the observed antagonist activity leads to clinically meaningful measurement error based on the results of the current study alone because the quantification of the moment associated with the antagonist activity would require knowledge of muscle morphology and the EMG-force relationships of each muscle. Determining the moments and measurement error associated with antagonist muscle activity in knee strength testing is the focus of a follow-on research project.

Females consistently demonstrated higher vastus medialis antagonist activity than males, which agrees with data from other studies.^{7,17} Hence, there is a growing body of evidence suggesting that females and males differ in the way they use their vastus medialis muscle. This is interesting considering the evidence related to female predisposition to certain types of knee injury.¹⁸⁻²⁰ We note, however, that it remains unclear whether the observed sex difference in vastus medialis activity is clinically relevant.

A significant difference in peak torque was observed between sides when comparing the leg that produced higher peak torque to the leg that produced lower peak torque, but no significant difference was observed in peak torque measurements across sessions. The significant difference in peak torque between sides was a consistent finding in our sample. About 40% of the subjects displayed a difference of at least 10% between sides at both test sessions. The approach of contrasting the subjects' stronger legs with their weaker legs instead of simply performing a right-to-left comparison has been used by others who have reported similar variance in side-to-side peak torque in isokinetic testing designs.^{21, 22} The opposite leg is commonly used as a comparison for strength tests with the assumption that knee exten-

sor or flexor strength is similar across sides. Although a side-to-side comparison is often the only practical method because pre-injury data are unavailable, our results suggest that the opposite side is in fact a less than ideal comparison for knee strength measurements. The observed side-to-side differences in peak torque may be related to inter-limb variations in muscle morphology, voluntary activation, and-or antagonist activity. Tate et al.²³ have demonstrated that young athletic people usually have side-to-side differences in thigh muscle morphology. Although we are unaware of any published studies in which side-to-side differences in voluntary muscle activation have been assessed by contrasting side-to-side results in the manner used in the current study, preliminary data from our laboratory indicate that side-to-side differences in voluntary activation are common.

The prevalent misconception that knee extensor and flexor strength is similar between sides is understandable because most researchers have evaluated strength by contrasting a sample's right and left legs or their "dominant" and "non-dominant" legs. The variability between legs mathematically cancels out with this approach because about half a sample is usually stronger on the right each side and the other half on the left. Our data provide an example of this cancellation. The side-to-side differences in peak torque observed in this study and by others in isokinetic designs have important implications for clinicians who use strength test results as criteria for patient progression and return-to-sport and for research who use side-to-side strength comparisons in defining the effects of pathology or outcomes of treatment. The fact that it is typical for healthy people to have about 10% differences in knee strength across sides suggests that in the absence of pre-injury data, it is equally likely that a 90% limb symmetry index indicates that there is a 20% strength deficit or no strength deficit at all as it is to indicate that there is a 10% strength deficit. Hence, clinical decision making criteria based on strength should be moderate (e.g., 80% contralateral strength) rather than stringent.

Although our results indicate that knee strength tests are imperfect, it would be inappropriate to conclude that these data argue against using strength tests in clinical practice or research. There is strong evidence that quadriceps strength is critical to knee function and health (references²⁴⁻²⁷ are a small sample from the large body of evidence supporting this statement), which argues for the use of some form of strength testing. In our opinion, isometric strength testing or a derivative of this method²⁸ (i.e., a technique involving superimposition of electrical stimuli during isometric testing to quantify quadriceps activation levels) is the gold-standard for measuring knee strength. Judgment on the amount of error associated

with antagonist activity in strength testing should be withheld until it is quantified. It is likely that the effect of the antagonist activity on knee extensor strength results will be much smaller than the effect on knee flexor test results because the quadriceps are much stronger than the hamstrings and similar amounts of antagonist activity are observed.

This study has some potential limitations that warrant discussion. Our goal was to describe the magnitude of variability of antagonist activity during isometric knee strength testing in “healthy” people so that normative data are present. Consequently, we excluded people with a history of serious lower extremity injuries. This introduced some selection bias into the study. The findings from previous research²⁹ suggest that patients with knee pathology may exhibit greater absolute magnitudes and side-to-side differences in antagonist activity than were observed in this study. Assumptions are made whenever surface electromyography is used. One assumption is that the recording from an electrode is representative of the entire muscle of interest; however, the validity of this assumption is unknown. It is also assumed that the recordings from each muscle are untainted by volume conduction (crosstalk). In order to minimize the likelihood of recording crosstalk, we carefully placed our electrodes using established guidelines, minimized pressure over the electrodes by seating subjects on an elevated platform, performed due diligence in verifying electrode placement and signal quality, and used high quality EMG preamplifiers with a double differential design that is known to minimize the recording of volume conducted signals.³⁰ The fact that antagonist muscle activity was observed in each of the quadriceps and hamstrings muscles tested strongly argues against the observed antagonist activity being a product of crosstalk. Moreover, we have observed similar magnitudes of antagonist activity when recording with intramuscular “fine wire” electrodes during knee strength testing, which has also been reported by other researchers.³¹ For these reasons, we believe that volume conduction was negligible, but acknowledge that it is impossible to rule out the presence of crosstalk.

CONCLUSIONS

The results of this study suggest that antagonist muscle activity is a relatively global finding in the knee extensors and flexors during maximal voluntary isometric contractions. Antagonist muscle activity varied significantly across sides in each of the muscles studied. Peak torque results also varied significantly by side, but not across sessions. Our results highlight the importance of assessing absolute differences between sides rather than simply contrasting the means of right and left or domi-

nant and non-dominant sides. The side-to-side variability in antagonist muscle activity and peak torque indicates that the opposite side is a less than ideal comparison for knee strength. The results of this study may help clinicians and scientists in interpreting the results of strength tests and in setting appropriate strength related criteria for patient progression and return-to-sport.

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