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Revisiting the influence of hip and knee angles on quadriceps excitation measured by surface electromyography

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Abstract

Background: The quadriceps muscle group includes one biarticular (crosses the hip and the knee) and three monoarticular (crosses the knee only) muscles. The influence of hip and knee angles on quadriceps muscles excitation remains inconclusive in the literature. **Research question:** To re-examine the excitation of the biarticular and monoarticular quadriceps muscles during maximum voluntary isometric contractions at different hip and knee angles. **Type of study:** Cross-sectional experimental study. **Methods:** Ten recreationally active subjects (5 males, 5 females) performed maximum voluntary isometric contraction of knee extensors at six knee angles (90°, 100°, 110°, 120°, 130° and 140°) on an isokinetic dynamometer. The protocol was repeated at three hip positions: sitting, inclined and supine. During the test, surface electromyography was employed to record muscle activity of the rectus femoris (RF), vastus lateralis (VL) and vastus medialis (VM). Repeated measures ANOVA (hip x knee) was used to determine the effect of hip and knee angles on peak torque and muscle excitation. **Results:** A significant hip by knee interaction was found for RF (P = 0.013). As the knee angle increased, VL and VM excitation decreased (P < 0.001). Higher excitation was observed in the sitting position, followed by inclined and then the supine position for both VL (P = 0.004) and VM (P = 0.046). **Conclusions:** As expected, changes in knee angle influence the excitation of all surface quadriceps muscles. However, changes in hip angle, though only alter the biarticular muscle length, influence both biarticular and monoarticular muscle excitation. The large discrepancy among studies warrants further attention.
Keywords: monoarticular; biarticular; isometric; torque; EMG

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Introduction

The quadriceps muscle group includes one biarticular (two-joint) and three monoarticular (one-joint) muscles. The biarticular muscle, rectus femoris (RF), crosses the hip and knee joints and works as both hip flexor and knee extensor. The three monoarticular muscles, vastus lateralis (VL), vastus medialis (VM) and vastus intermedius, cross only the knee joint and are responsible for producing knee extension movement. With increasing knee extension, the length of all quadriceps muscles decreases. On the other hand, changes in hip angle only influence the length of the RF while the lengths of other monoarticular quadriceps muscles remain unaltered. Thus one may expect that knee angle would influence the excitation of all quadriceps muscles, whereas hip angle would only affect the excitation of RF.

Previous work has examined the influence of hip and/or knee angles on quadriceps excitation using electromyography (EMG). Most studies agree that changes in knee angle influence quadriceps muscle excitation [1-7], with a few exceptions [8-10]. However, no consistent evidence on how quadriceps EMG pattern changes with the knee angle during maximum voluntary isometric contraction (MVIC) has been found. A more extended knee position has been shown to increase, decrease or display a non-linear relationship with the excitation of monoarticular knee extensor muscles during MVIC [3-5]. In contrast to speculation that hip angle would only influence the RF muscle, one study showed that VL and VM, as opposed to RF excitation, were affected by changes in hip angle during MVIC [5]. Others found that hip angle influenced all VL, VM and RF activation [7]. Thus the influence of hip and knee angles on knee extensor muscles excitation remains inconclusive. To better understand the role of muscle length and adjacent joint positions on muscle recruitment pattern, further studies are needed.

The purpose of the present study was to re-examine the excitation of the biarticular and monoarticular knee extensor muscles during MVIC at different hip and knee angles. It was hypothesized that changes in the knee angle will influence the excitation of all knee extensor muscles, while changes in the hip angle will only affect the biarticular muscle excitation.

Methods

Subjects

Ten recreationally active subjects (5 males; 5 females; mean ± SD: age 22.9 ± 2.2yrs, mass 67.8 ± 15.7kg, height 171.5 ± 1.3cm) participated in the study. All subjects were free from current lower-extremity injury or pain at the time of the study. Informed consent was obtained from all subjects prior to experimental procedures which were approved by the university Institutional Review Board.

Experimental procedures

Subject's body mass and height were measured using standard methods. Subjects were given time to warm up and familiarize themselves with an isokinetic dynamometer (System 3 Pro, Biodex Medical System, NY, USA) before the testing protocol began. For the main protocol, the subject's right knee joint centre was aligned with the axis of the dynamometer crank arm. Straps were used to immobilize the trunk, pelvis and thigh of the tested leg. The weights of the tested leg and the crank arm due to gravity were corrected for by measuring a passive isometric torque with the right leg relaxed in a close to full knee extension position. Each subject performed a 3s maximal voluntary isometric contraction of the knee extensors at six knee angles (90°, 100°, 110°, 120°, 130° and 140°, full knee extension = 180° respectively) on the isokinetic dynamometer. To minimize the influence of fatigue, subjects rested for approximately 60s between trials [11]. The test was repeated at three pre-specified dynamometer chair settings to vary the hip joint angle: sitting, inclined and supine (Figure 1) where hip angles were measured using a goniometer during the isometric contractions. The three hip angles were 110 ± 3°, 139 ± 4° and 164 ± 3° for sitting, inclined and supine, respectively. The protocol was presented to all subjects in a systematic order without randomization as a previous study showed no effect of fatigue or learning for a similar protocol [5]. During the isometric contraction, verbal encouragements were provided by the same researcher for all subjects. No visual feedback was given throughout. Peak isometric torque data were recorded for each trial. All torque data were normalized first to subject's body mass and then to the value recorded during the first trial (sitting, knee angle = 90°).

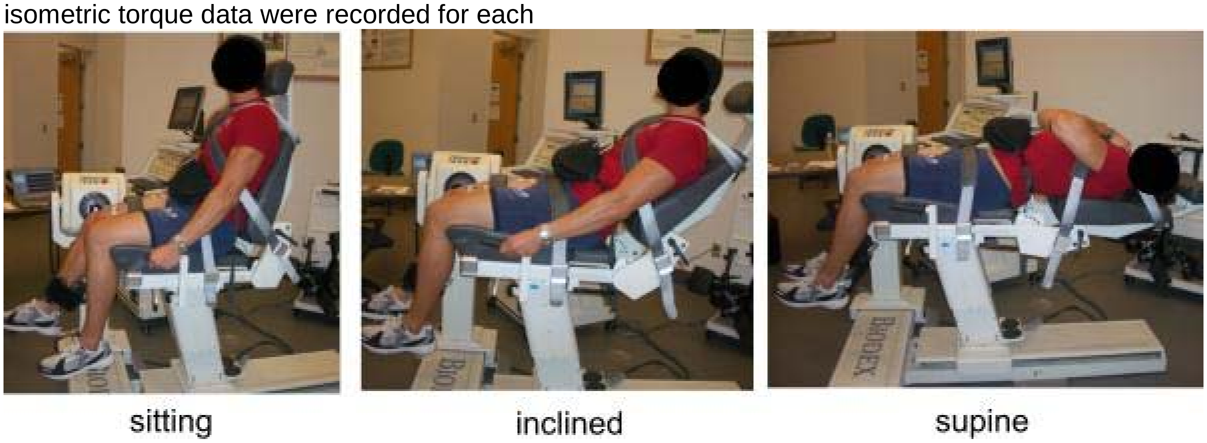

Figure 1: Peak isometric torque at six knee angles were measured at three hip positions: sitting, inclined and supine

Prior to the test protocol, the skin of the subjects was cleaned in preparation for placing the EMG electrodes at the middle of the muscle belly of three superficial quadriceps muscles: RF, VL and VM. The skin preparation procedures included shaving off hairs, abrading lightly with sand paper and then wiping with alcohol pads. Single differential Ag/AgCl bar electrodes (1.0 × 0.1cm) with 1cm interelectrode distance were then placed on these muscles along the direction of the muscle fibres. One common ground electrode was placed on the lateral malleolus of the right ankle. During the MVIC test protocol, a wireless surface EMG system (Myomonitor III, Delsys Inc., Boston, MA) was used to measure muscle excitation of the RF, VL and VM at 1000Hz. Raw EMG data were band-pass filtered (20 – 450Hz), full-wave rectified and then root mean squared (RMS) with a 0.5s window. The highest RMS value averaged over a 1s window was used for analysis. All EMG data were normalized to the RMS value recorded during the first trial (sitting, knee angle = 90°). A sum of muscle excitation was calculated by adding the normalized RMS values of all three muscles.

Statistical analysis

The Shapiro-Wilk test was first used to test for normality of all data sets. When data were not normally distributed, log transformation was applied. Dependent variables included the peak isometric torque, muscle excitation of the RF, VL (log transformed) and VM, as well as the sum of muscle excitation (log transformed). Independent variables were the hip and knee angles. Repeated measures ANOVA (hip x knee) was used to determine the effect of hip and knee angles on each of the dependent variables. Mauchly's test was used to examine whether the assumption of sphericity was violated and if so, the Greenhouse-Geisser estimate was used to correct the degree of freedom. Post hoc analyses with Bonferroni adjustments were performed where appropriate. Statistical significance was set at $P<0.05$. Data are expressed as mean ± SD.

Results

A significant main effect of knee angle was found for all variables (Table 1). At a fixed hip angle, a quadratic torque-angle relationship was observed as knee angle changed for all three hip positions (Figure 2). There was a significant main effect of hip angle on peak isometric torque (Table 1). Post hoc analysis revealed that the torque values were significantly higher in the inclined than the supine positions (Figure 2).

Table 1: P-value of repeated measures ANOVA (hip × knee)

Variable	Hip	Knee	Hip × Knee
Isometric torque	0.037*	< 0.001*	0.472
Rectus femoris	0.315	< 0.001*	0.013*
Vastus lateralis	0.004*	< 0.001*	0.472
Vastus medialis	0.046*	< 0.001*	0.821
Sum of excitation	0.006*	< 0.001*	0.296

*Statistical significant main effect (*P*<0.05)

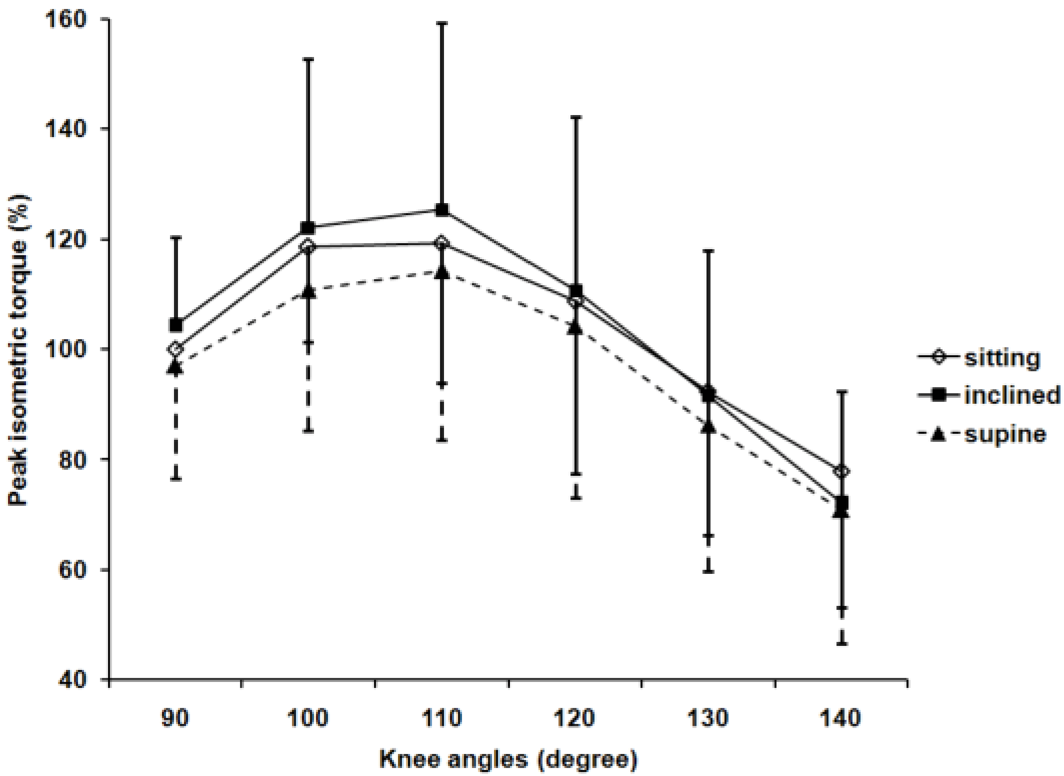

Figure 2: Comparison of normalized peak isometric torque at three hip angles and six knee angles. Significant main effect of hip: P=0.037 (post hoc: inclined vs. supine); main effect of knee: P<0.001 (post hoc: 90° vs. 100°, 90° vs. 140°, 100° vs. 130°, 100° vs. 140°, 110° vs. 120°, 110° vs. 130°, 110° vs. 140°, 120° vs. 130°, 120° vs. 140°, 130° vs. 140°). Data are presented as mean (SD).

There was a significant main effect of hip angle on VL, VM and the sum of muscle excitation but not RF excitation (Table 1). Overall, higher excitation was generally observed in the seated position, followed by inclined and then the supine positions. Post hoc analyses showed that the excitation during sitting was higher than that during supine for VL and sum of excitation but not VM. As the knee angle increased, all muscle excitation decreased (Figures 3-6). A significant hip by knee interaction was detected in RF excitation (Table 1). At 90° knee angle, RF excitation while sitting was significantly higher than that in the supine position (Figure 3). As the knee extended, RF excitation during sitting decreased sharply while excitation in the inclined and supine positions remained relatively unchanged. This results in the RF excitation during sitting being the lowest at 140° knee angle.

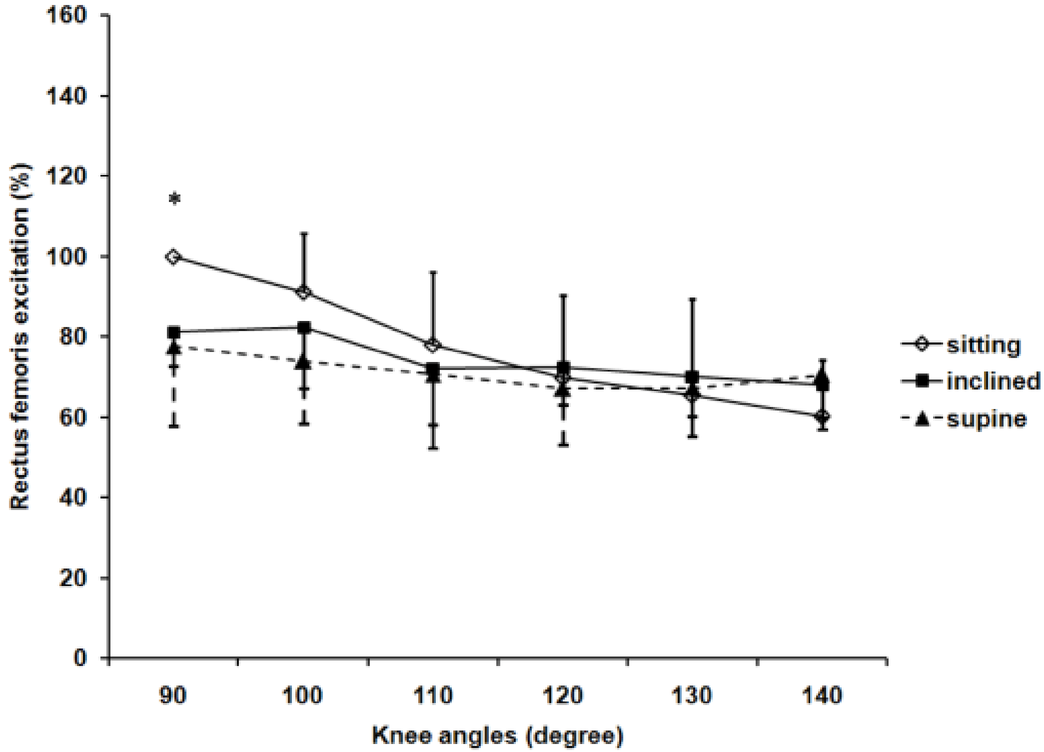

*Figure 3: Comparison of normalized rectus femoris EMG at three hip angles and six knee angles. Significant main effect of knee: P<0.001 (post hoc: 90° vs. 120°, 90° vs. 130°, 90° vs. 140°, 100° vs. 110°, 100° vs. 110°, 100° vs. 120°, 100° vs. 130°, 100° vs. 140°), hip × knee interaction: P=0.013 (*post hoc: sitting vs. inclined) . Data are presented as mean (SD).*

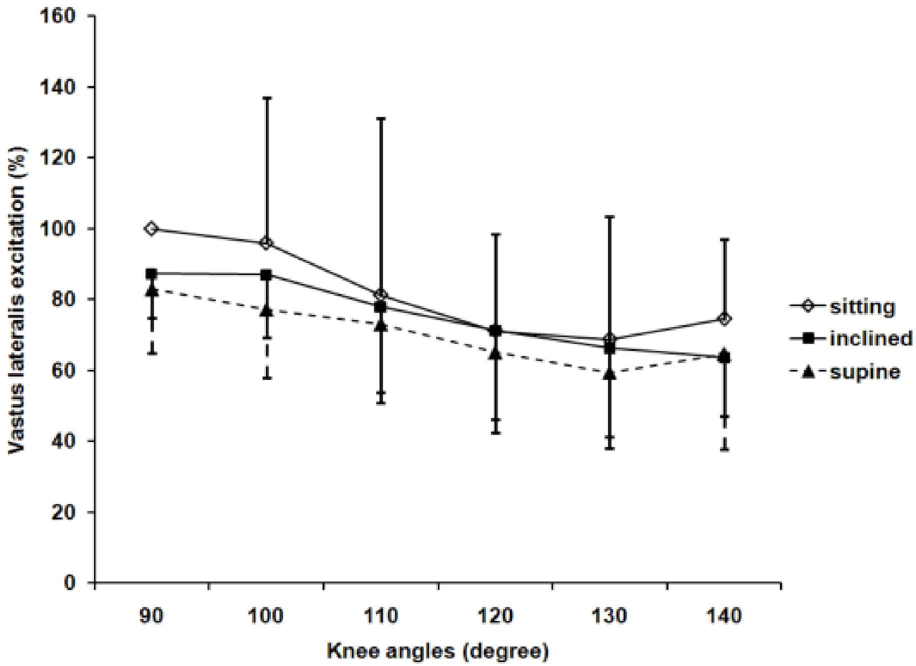

Figure 4: Comparison of normalized vastus lateralis EMG at three hip angles and six knee angles. Significant main effect of hip: P=0.004 (post hoc: sitting vs. supine), main effect of knee: P<0.001 (post hoc: 90° vs. 130°, 90° vs. 140°, 100° vs. 120°, 100° vs. 130°, 100° vs. 140°). Data are presented as mean (SD).

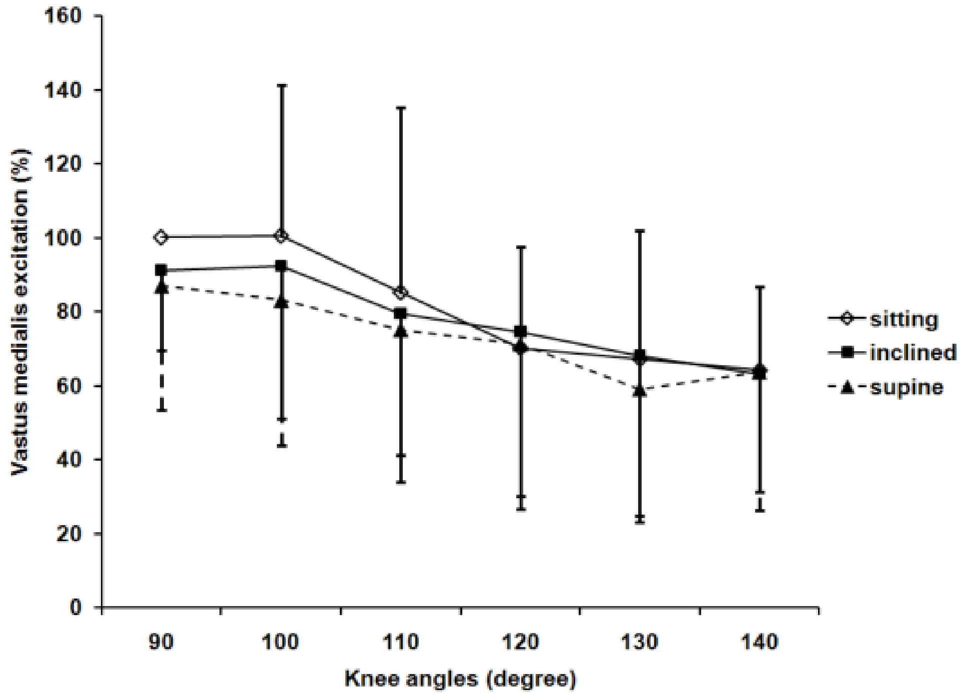

Figure 5: Comparison of normalized vastus medialis EMG at three hip angles and six knee angles Significant main effect of hip: P=0.046 (no significant post hoc findings), main effect of knee: P<0.001 (post hoc: 90° vs. 130°, 90° vs. 140°, 100° vs. 110°, 100° vs. 120°, 100° vs. 130°, 100° vs. 140°, 110° vs. 130°). Data are presented as mean (SD).

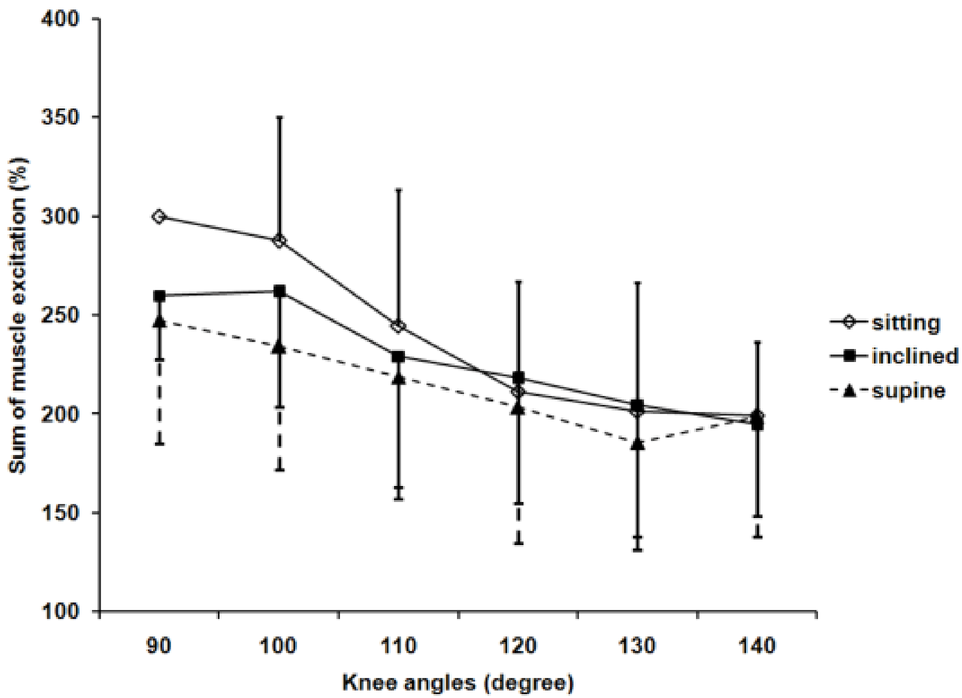

Figure 6: Comparison of sum of muscle excitation at three hip angles and six knee angles. Significant main effect of hip: P=0.006 (post hoc: sitting vs. supine), main effect of knee: P<0.001 (post hoc: 90° vs. 120°, 90° vs. 130°, 90° vs. 140°, 100° vs. 110°, 100° vs. 120°, 100° vs. 130°, 100° vs. 140°, 110° vs. 130°). Data are presented as mean (SD).

Discussion

This study compared monoarticular and biarticular knee extensor muscles excitation during MVIC at various muscle lengths resulting from manipulating the hip and knee angles. This study's first hypothesis that changes in knee angle would influence the excitation for all knee extensor muscles was supported. However, with regard to the study's second hypothesis, changes in hip angle influenced the excitation of not only the biarticular but also the two monoarticular muscles.

Muscle excitation and torque production

At any fixed hip angle, increasing the knee angle resulted in a decrease in the sum of muscle excitation (Figure 6), while the maximum torque produced by the knee extensor muscles displayed a quadratic relationship with the knee angle (Figure 2). When the knee angle was fixed, the overall pattern of change in torque production (inclined > sitting > supine, Figure 2) also differed from that in muscle excitation (sitting > inclined > supine, Figure 6) in response to changes in hip angle. These observations reinforce previous findings that the EMG-angle relationship does not correspond well with the torque-angle relationship [12,13].

In the literature, a neuro-physiological compensation mechanism has been proposed that muscle excitation increases due to reduced force production capability at shorter muscle length [5]. This mechanism was reinforced in a study showing that as the length of the biarticular muscle gluteus maximus decreased, EMG increased, whereas torque generation decreases [12]. However, this neuro-physiological compensation mechanism does not explain the results of the present study. First, all monoarticular muscles excitation decreased, as opposed to increased, with shorter muscle length at which the torque production was low. Moreover, at a fixed knee angle, RF excitation did not change linearly with muscle length at the three hip positions. In another study on the effect of hip angle on quadriceps muscles activation, higher EMG and voluntary isometric torque were both seen at a short (sitting) compared to long (supine) muscle lengths [7]. Thus the previously proposed neuro-physiological compensation mechanism cannot be universally applied to all muscles and/or subjects.

The quadratic torque-angle relationship during maximum isometric contraction of the knee extensors observed in this present study was comparable to that reported in the literature [3,14]. This torque pattern was also in agreement with the finding of Hasler and colleagues [5] for the knee: intermediate angle has higher torque than more extended knee angles. This is, however, not the case for the hip angle. In their study, systematic increase in knee extension torque was found with increasing hip extension with the highest torque observed in the supine position. The results in this present study showed that knee extension torque, although it increased from the sitting to inclined positions, declined at the supine position. Maffiuletti and Lepers [7] also demonstrated that MVIC for knee extension torque was 10.6 ± 11.2% higher in a sitting position compared to a supine position, a finding similar to this present study's finding.

Combined muscles excitation

In this present study, the sum of excitation was significantly influenced by both hip and knee angles. One study found the total EMG of all quadriceps muscles was 17% higher in mid-hip position than in the supine position [10]. This parallels this present study's findings that the sum of muscle excitation was higher in the inclined than the supine positions. In contrast, another study showed that the combined average EMG of the three superficial quadriceps muscles was not influenced by hip angle [4]. The lack of difference in Eloranta's [4] study may be related to their small sample size (n=5) with the partial data set lost, and that the sitting position data was discarded for all subjects.

Monoarticular muscles

For the two monoarticular muscles VL and VM, this present study observed that as knee angle increased, muscle excitation decreased for all hip positions. The decrease in muscle excitation with knee extension may be explained by the physiological relationship of Type Ia afferent input and the quadriceps motoneuron input [3]. Becker and Awiszus [3] proposed that having a more flexed knee joint yields longer muscle spindle lengths, which in turn leads to a higher steady-state Type Ia discharge rate. This larger Type Ia input to the motoneuron pool will yield a greater total excitatory drive, thus reducing the total deficit in voluntary activation.

Quadriceps muscles activation was shown to decrease with knee extension in both this present study and in the Becker and Awiszus's [3] studies. The same pattern was also seen in the study by Eloranta [4] in the inclined position, but not in the supine position, at which muscle activation increased with the knee angle. Hasler and colleagues [5] found that VM and VL excitation was higher at 170° than 130° knee angle, while excitation at 90° typically fell between 170° and 130°. This present study's results are only in partial agreement with theirs - that muscle excitation at 90° was higher than that at 130°. Interestingly, one study showed no influence of knee angle on EMG of any quadriceps muscles measured by wire electrodes [10]. The reason for the lack of difference remains unclear since many of the other studies agree that the knee angle affected quadriceps excitation [1-7].

Regarding the influence of hip angle on monoarticular muscles, this present study's results reject the hypothesis that hip angle would not influence VL and VM excitation. The authors' observation parallels previous findings that hip angle affected both VL and VM [5,7,10]. In the study by Hasler and colleagues [5], VL showed higher excitation at 90° and 180° whereas VM displayed higher excitation at 90° than intermediate hip angles (112°, 135°, 157°). In contrast to the study by Hasler et al. [5], Salzman and colleagues [10] showed higher quadriceps excitation at an inclined position than in the sitting or supine positions. A more recent study indicated that VL and VM excitation were higher in a sitting than a supine position [7]. In the present study, both VL and VM excitation were higher in the sitting position, followed by the inclined and then supine position. While the present study's results are in agreement with the study by Maffiuletti and Lepers [7], a non-linear relationship between monoarticular muscles excitation and hip angle was not observed as shown in two previous studies [5,10].

Much of the existing gym equipment is designed for single joint movements, for example, the knee extension machine. These machines are commonly used for sports training, fitness conditioning and rehabilitation. Results from the present study suggest that monoarticular muscle excitation during single joint movements is affected by adjacent joint positions even though there is no change in muscle length. Future equipment design and development of training protocol for single joint movements may consider the potential influence of adjacent joint positions.

Biarticular muscle

A previous study showed that hip angle did not affect biarticular muscle RF excitation during maximum isometric contraction of the knee extensors [5]. However, this present study found a significant hip by knee interaction on RF excitation (Figure 3). The sitting position allowed higher RF excitation at small knee angles compared to the inclined or supine positions. As the knee was more extended, lower RF excitation was observed in the sitting position than the inclined or supine positions. This supports part of this study's second hypothesis that changes in hip angle would influence biarticular muscle excitation, although such an influence also depends on the knee angle. In the recruitment of muscles for knee extension, consideration may need to be given to all quadriceps muscles working as one group rather than individual muscles. The changes in RF length and excitation due to changes in hip angle may lead to modification in the VM and VL recruitment pattern.

When measured at a fixed knee angle of 90°, one study also found that RF excitation was higher in a sitting than a supine position during MVIC for knee extension [7]. This present study demonstrated the same results at a 90° knee angle. Surprisingly, another study found no RF activity measured by fine wire electrode during knee extension and concluded that the signal detected using surface EMG may be due to cross-talk from adjacent muscles [15]. Although these authors agree that cross-talk may be present in surface EMG, it is difficult to believe that the RF is inactive during knee extension because this is a biarticular muscle that crosses both the hip and the knee. While Bryne and colleagues [15] did not explain why no RF activity was detected, many other studies employing similar fine wire EMG techniques have consistently shown RF activity during knee extension [2,6,8].

Discrepancies in EMG pattern

Large discrepancies exist in the literature (including in this present study) regarding quadriceps muscle excitation at different hip and knee angles. Despite EMG being used widely over the past few decades in research and clinical assessments, it is surprising that no consistent pattern can be observed even in well-controlled conditions. The underlying reason for the differences among studies is not obvious. Such discrepancies do not only lie between studies using surface [4,5,7] and fine wire electrodes [2,6,8,10,15]. There is also evidence that fatigue does not play a role in this type of testing protocol and therefore randomization of the orders of postures or the lack of cannot explain the difference [5,10]. Over years, the advancement in instrumentation may have improved the quality of EMG data. Development of data processing techniques, such as RMS, integrated EMG and wavelet analysis also allow more objective quantification of EMG signals compared to qualitative interpretation in the early studies.

Limitations

The present study presents the testing order of knee and hip angles in a systematic manner. The lack of randomization in the testing order may raise the concern for fatigue effect. Nevertheless, the testing protocol (18 × 3s = 54s of muscle contraction) should not be too demanding considering all subjects were physically active. This present study also provided sufficient resting periods between trials to minimize fatigue. Together with a previous study using similar a protocol, which showed no effect of fatigue or learning [5], these authors believe fatigue would not have a major influence to their data. In fact, presenting testing conditions in a systematic manner may sometimes be preferred to randomization, in order to encourage maximal muscular effort on an isokinetic dynamometer [16].

Conclusions

In the present study, it has been demonstrated that changes in knee angle affect all superficial quadriceps muscles excitation during maximum voluntary isometric contraction of the knee extensors. In contradiction to these authors hypothesis, they also found that changes in hip angle influence the excitation of not only the biarticular but also the monoarticular muscles. These results suggest that in the recruitment of muscles for knee extension, all quadriceps muscles may work as one group, such that changes in RF length and excitation may lead to modification in the recruitment pattern of other monoarticular muscles. The large discrepancy among studies in the EMG pattern in response to changes in adjacent joint configuration warrants further attention.

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