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ABSTRACT

Context: It is very important to empirically determine the optimal ankle position for the quadriceps femoris (QF) strengthening during isometric exercises. **Objective:** To examine the effect of different ankle positions on torque and electromyography (EMG) activity of QF during maximal isometric contraction. **Study Design:** Within-subject, repeated measures. **Setting:** University laboratory. **Participants:** Thirty-six healthy volunteers (15 males and 21 females). **Main Outcome Measures:** The isometric strength of the QF was measured at three different ankle positions: active dorsiflexion (AD), active plantarflexion (AP), and neutral position (NP). Simultaneously, three different ankle positions were assessed for EMG activity of the vastus medialis (VM), vastus lateralis (VL), and rectus femoris (RF) muscles during maximal voluntary isometric contraction (MVIC). **Results:** The peak torque per body weight and average peak torque were significantly higher in AD than in AP and NP ($P < .01$). The VM and RF MVIC EMG activity were significantly higher in AD than in AP and NP ($P < .01$). The VL MVIC EMG activity was significantly higher in AD than in AP and NP ($P < .01$), and was significantly higher in AP than in NP ($P < .05$). **Conclusions:** These results indicate that the three different ankle positions affect the QF torque and EMG activity. In particular, AD position may be more efficient for improving QF strength than AP and NP position. Future studies should prove whether long-term duration QF isometric exercise effects on muscle strength and functional performance in different ankle position.

Key words: Ankle position, Quadriceps femoris, Torque, Electromyography, Maximal voluntary isometric contraction

INTRODUCTION

The quadriceps femoris (QF) is the strongest muscle in the human body and is an important factor in activities of daily living and sports activity.[1,2] QF weakening is known as a potential component of musculoskeletal disorders, such as knee degenerative arthritis, ligament injury, and patellofemoral pain syndrome.[3-7] In addition, healthy elderly people, who are known to have higher fall risk, may also have QF weakness.[8,9] Therefore, QF strengthening is essential in post-injury rehabilitation and in preventing injury.

Various QF strengthening exercises, such as squat, lunge, leg extension, and leg press are used in rehabilitation and sports field.[5] However, performing these exercises is difficult for elderly people who do not have enough capacity to perform them and for acute immobilized patients who experience pain after injury. In this case, isometric contraction exercise can be an alternative method. Isometric contraction involves muscular actions in which the length of the muscle does not change and no movement of the joint is visible.[10] Isometric exercise can be used for general strength conditioning and for rehabilitation, when strengthening the muscles without placing undue stress on the joint is warranted.[10]

In previous studies, the hip and knee joint angles were found to affect the QF isometric exercise, and maximal isometric force was generated in the hip flexion of 110–130° and the knee flexion of 60°.[11,12] These findings were supported by the muscle length-tension relationship.[13] The length-tension relationship is a biomechanical principle of variation in muscle tension due to muscle length changes. Skeletal muscles need more actin-myosin cross bridges in order to produce higher magnitudes of force. However, if the sarcomere is not within the optimal range of length, the number of actin-myosin linkages will decrease and the produced muscle force will eventually decrease.[14-16] Therefore, it is an important key to determine the optimal muscle length-tension relationship in the muscle strengthening exercise of a specific muscle.

Some previous studies have suggested the ankle position as a factor that may affect the QF strengthening exercise.[17,18] In these studies, the active dorsiflexion (AD) or plantarflexion (AP) position was found to have superior QF electromyography (EMG) activity than the neutral position (NP), and the authors recommended either AD or AP position to facilitate QF strengthening. However, the majority of studies regarding QF strengthening were published long time ago, and their subjects were studied in a supine position with the hip and knee fully extended without considering the optimal angle of the knee and hip joint. In addition, the QF-generated torque value was not analyzed, and only the EMG activity measured in different ankle positions was analyzed. Therefore, it would be necessary to investigate the optimal ankle position for isometric contraction of the QF in consideration of the above factors. And it is very meaningful to find the optimal conditions for isometric contraction exercise of the knee joint for early rehabilitation after injury or sport field. The purpose of this study was to investigate the effect of the different ankle positions on the torque value and EMG activity of the QF during maximal isometric contraction. We hypothesized that AD and AP during QF maximal isometric contraction may determine greater torque value and EMG activity of QF than NP position.

METHODS

Participants

A power analysis was performed using G-Power software (Franz Faul, Christian-Albrechts-Universität, Kiel, Germany) to achieve a significant level of 0.05, a power of 0.95, and an effect size of 0.25. The results of the power analysis showed that this study would require 36 subjects. A total of 36 healthy male and female college students with no known knee pathologies volunteered to participate in this study (15 males and 21 females, age = 24.03 ± 3.42 years, body weight = 60.53 ± 10.09 kg, height = 1.68 ± 0.09 m, and body mass index = 21.44 ± 1.84 kg/m^2). All participants had a normal ankle range of motion (dorsiflexion 0–30°, plantarflexion 0–48°) and were informed about the purpose of the study, the experimental procedure, and the potential risks related to the measurements. Individuals with a reported history of cardiovascular, musculoskeletal, or neurological disease were excluded. All participants provided written informed consent prior to participation in the study. The study was approved by the Institutional Review Board of Dae-jeon University (201706HR01403).

Measurement of QF isometric torque

The QF isometric torque was measured by Biodex® System 3 PRO isokinetic dynamometer (Biodex Medical Systems, Shirley, NY, USA) on the participants' dominant leg. In order to determine the dominant leg, the participants were asked to decide which leg they usually use to kick a ball. Prior to the test, all participants performed a five-minute warm-up using a stationary cycle and tested procedures using sub-maximal practice trials to familiarize with the equipment. After a 10-m rest time, each participant was seated in a comfortable and upright position with a 110° hip flexion and 60° knee flexion to generate maximal voluntary isometric contraction (MVIC) of the knee joint.[11,12] Their trunk, pelvis, and thigh were fixed to the dynamometer chair with Velcro straps (Velcro USA Inc., Manchester, NH, USA) in order to minimize body movement and to optimize movement of the knee joint of the dominant leg during testing.[19,20] The lateral femoral epicondyle of the knee joint was aligned with the mechanical axis of the dynamometer, and then the knee attachment was fixed 1 cm above the medial malleolus. Each participant was required to fold the arms across the chest to prevent compensation by upper limbs and to promote maximal isometric contraction in response to visual stimuli from a computer monitor.[21,22] The test was performed two times in three different ankle joint positions: AD (specific instruction: "extent your knee as hard as you can while pulling your toe"), AP ("extent your knee as hard as you can while pushing your toe"), and NP ("extent your knee as hard as you can while keeping the ankle neutral position"). The test sequence was randomized using a sealed envelope system. The maximal isometric contraction was performed for five seconds and twice in each ankle joint position and the peak torque generated over 2 repetitions was recorded and normalized to body weight (PT/BW) and average values (Avg. PT) for statistical analysis. Participants were allowed a two-minute rest time between each set and trail. The test was immediately discontinued if the subject complained of discomfort or pain.

Measurement of QF muscle EMG activation

The QF muscle activity was assessed by the wireless surface EMG for the vastus medialis (VM), vastus lateralis (VL), and rectus femoris (RF) muscles during the isometric strength test, and measured each muscle activity in three different ankle positions. The muscle activity recordings were obtained by bipolar circular surface electrodes (Ag/Cl; 0.8 cm diameter) placed on each muscle at a fixed inter-electrode distance of 2 cm. Prior to electrode placement, to minimized skin resistance we removed skin hair at the site of the attachment, and cleaned the site with alcohol, and attached the electrodes according to the direction of the muscle fibers. VM electrodes were placed 20% of the distance from the medial joint line of the knee to the anterior superior iliac spine (ASIS).[23] The electrodes were placed at an angle of approximately 45° to along the longitudinal axis of the muscle fibers. VL electrodes were placed at the midpoint between the head of the greater trochanter and the lateral femoral epicondyle,[24] while RF electrodes were placed at 50% of the distance from the ASIS to the superior pole of the patella.[23] The muscles were determined as follows: VM at 50° from the long axis of the femur and 5 cm from the superior medial border of the patella; VL at 12–15° from the long axis of the femur and 15 cm from the superior lateral border of the patella; RF at 7–10° medially in the frontal plane at the mid-point of the muscle belly, halfway between the ASIS and the superior pole of the patella.[25]

Muscle activation data were obtained by using analysis software EMG Analyzer Version 2.9.37.0 (BTS Bioengineering, Milano, Italy). The sampling rate of the EMG activity was set to 1,000 Hz and the collected EMG activity raw data were band-pass filtered between 20–500 Hz to remove artifact and high-frequency noise. The raw EMG signals were processed using a root mean square (RMS) method with a 0.5-s window. Muscle activation data were measured two times for 5-s according to the ankle position. The first and last seconds of each MVIC EMG activity were eliminated, and the remaining 3-s of EMG data was analyzed.[22]

Statistical analysis

Data were statistically analyzed using PASW Statistics for Windows, Version 18.0 (SPSS Inc., Chicago, IL, USA), and continuous variables, such as age, body weight, height, body mass index, isometric torque values, and EMG data were presented as mean ± standard deviation. The repeated-measures ANOVA was conducted to compare the isometric torque values (i.e., PT/BW and Avg. PT) and EMG activity of the QF in each ankle position during the isometric strength test. Adjustments were made if a violation of sphericity was found (Huynh-Feldt adjustment if the sphericity estimate > 0.75, Greenhouse-Geisser otherwise). Post-hoc multiple comparison with Bonferroni correction was conducted if repeated-measures ANOVA showed statistically significant differences among the three ankle positions. Statistical significance for α was set at 0.05.

RESULTS

All subjects successfully completed the required tests. The torque values in different ankle positions during the QF maximal isometric contraction are presented in Table 1. The PT/BW of the QF differed significantly according to the ankle positions (AD: 256.39 ± 50.11 %, AP: 252.30 ± 54.90 %, NP: 246.01 ± 54.59 %; respectively, $p < 0.01$), and post-hoc Bonferroni comparison results showed that the AD was associated with a significantly higher torque than the AP and NP (respectively, $p < 0.01$, $p < 0.05$) (Table 1; Figure 1). The Avg. PT was significantly different in different ankle positions (AD: 159.44 ± 43.24 Nm, AP: 152.25 ± 46.42 Nm, NP: 147.51 ± 44.19 Nm; $p < 0.01$), and post-hoc Bonferroni comparison revealed that the AD was associated with a significantly higher torque than AP and NP ($p < 0.01$) (Table 1; Figure 1).

The MVIC EMG activity of QF in different ankle positions are shown in Table 2. Significant differences were detected in the MVIC EMG activity of the RF measured according to the ankle position (AD: 288.44 ± 73.20 ㎶, AP: 264.04 ± 86.00 ㎶, NP: 250.86 ± 78.31 ㎶; $p < 0.01$), post-hoc Bonferroni comparisons confirmed that the MVIC EMG activity was significantly increased in the AD compared to AP and NP ($p < 0.01$) (Table 2; Figure 2). In VM, a significant difference was found in MVIC EMG activity according to the ankle position (AD: 174.54 ± 70.01 ㎶, AP: 160.13 ± 72.43 ㎶, NP: 149.33 ± 67.11 ㎶; $p < 0.01$), post-hoc Bonferroni comparison showed that the MVIC EMG activity was significantly higher in the AD than in the AP and NP ($p < 0.01$) (Table 2; Figure 2). Similarly, the VL MVIC EMG activity varied significantly according to the ankle position (AD: 211.24 ± 76.92 ㎶, AP: 185.03 ± 72.16 ㎶, NP: 172.40 ± 68.89 ㎶; $p < 0.01$), and Bonferroni comparison revealed that the MVIC EMG activity in AD was significantly increased compared to that in the other two ankle positions ($p < 0.01$), and that the MVIC EMG activity in AP was significantly increased compared to that in the NP ($p < 0.05$) (Table 2; Figure 2).

DISCUSSION

The QF is a very important muscle that provides stability during standing or walking. In addition, this muscle must be strengthened in case of the knee disorders, such as degenerative arthritis or patellofemoral pain syndrome. The aim of the current study was to determine the optimal ankle position for QF strengthening in early knee rehabilitation. We analyzed the isometric torque and EMG activity of the QF measured in different ankle positions during the isometric strength test. The results showed that torque values and EMG activity of the QF in AD were significantly increased compared to those in the AP and NP position.

Several previous studies aimed to determine the optimal ankle position for QF strengthening.[17,18,26,-29] However, they showed conflicting results and this question still has to be answered. In agreement with the results of the present study, Gough and Ladley reported that AD position during isometric contraction of the quadriceps was associated with higher EMG activity of the VM, VL, and RF than AP and resting NP.[17] Katyal et al. showed that a three weeks quadriceps exercise program was more effective with AD than with AP and NP in improving the quadriceps strength in patients with knee osteoarthritis.[28] Although they analyzed a different type muscle contraction, Kim et al. noted that the AD during isokinetic knee strength training was more effective for improving QF strength than the AP.[29] These three studies have reported that AD of the ankle joint is more effective for strengthening muscles than AP or NP position in isometric or isokinetic QF strength training.

Conversely, other studies that assessed the peak torque and EMG activity according to the ankle position in isokinetic strength test of the QF have found no significant differences in QF peak torque and EMG activity in different ankle positions.[26,27] However, when the ankle was dorsiflexed, the knee flexor peak torque increased. The authors concluded that by dorsiflexion, the gastrocnemius was stretched at the ankle joint, creating a more favorable length-tension relationship for producing the knee flexor force. It is well known that two joint muscles, such as gastrocnemius, influence the knee flexor torque.[20,31] With the ankle fixed in plantarflexion, the length of the gastrocnemius is actively shortened and it becomes difficult to generate sufficient torque of the knee flexor. On the contrary, by dorsiflexion, the gastrocnemius is stretched, thus generating a more favorable length-tension relationship for producing a higher knee flexor torque.[27]

In the present study, maximal isometric contraction of the QF was performed with the hip and knee joint fixed. In addition, the actual muscle length of the quadriceps did not change even if the position of the ankle joint was changed. Therefore, it is difficult to explain the results of the present study by the length-tension relationship. One possible explanation of the results is the motor irradiation of central origin. Motor irradiation is a sudden spread of synergistic muscular co-activation resulting from a forceful single joint movement. Dimitrijevic et al. reported that maximal voluntary contraction of ankle dorsiflexors was regularly accompanied by activation of other muscles (i.e., quadriceps and hamstring),[32] usually first in the ipsilateral leg and later in the contralateral leg. The present study results showed that when a maximal isometric contraction of the QF is accompanied by a strong ankle contraction, a greater QF force is generated. Therefore, this result is consistent with those of a previous study that showed that ankle dorsiflexion leads to greater irradiation of the knee extensors, whereas ankle plantarflexion leads to knee flexors greater irradiation.[33]

Another possible explanation for our results is the specific motor task provided in this study (i.e., NP: “extent your knee as hard as you can while keeping the ankle neutral position,” AD: “extent your knee as hard as you can while pulling your toe,” AP: “extent your knee as hard as you can while pushing your toe”), which made possible bi-articular movement and possibly resulted in a lager ankle-knee synergy (i.e., functional coupling motion between the pretibial muscles and quadriceps). Angst et al. aimed to quantify the change of the QF EMG activation and functional performance by single leg hop with and without ankle dorsiflexion during isometric load on the leg press.[2] Their results showed an increased EMG activity of the QF and single leg hop distance under dorsiflexion condition. Authors concluded that these findings could be used to improve the effects of training and rehabilitation, to increase functional muscle performance and knee stability. Simultaneous different muscular activity may be linked in the corresponding motor-neural centers of the brain and the spinal cord.[2] Knee extension is linked with simultaneous dorsiflexion in human locomotion. In particular, in the initial contact, the heel strike motion through ankle dorsiflexion simultaneously facilitates strong contraction of the QF, and the strong contraction of the QF at this time is of importance for stabilization of the knee in order to support the body weight.[2,32,34] The results of this study also understood that the simultaneously knee extension and ankle dorsiflexion are more synergistic than other ankle positions by functional coupling motion.

The present study has several limitations that require consideration when interpreting the results. First, although the number of subjects was statistically calculated, it is difficult to generalize the results because of the small sample size. Second, in general, QF strengthening exercises are performed for knee joint disorder and elderly people; however, this study was conducted on young and healthy subjects. Third, we cannot confirm the effects of long-term duration training on muscle strength and functional benefit. Therefore, future studies should prove whether long-term duration QF isometric exercise effects on muscle strength and functional performance in different ankle position. In addition, it is necessary to investigate the effect of intervention on patients with knee disease or quadriceps muscle weakness.

CONCLUSION

In sport and clinical field, it is often limited movement or weight bearing of the knee joint during early knee rehabilitation after injury. At this time, isometric contraction exercise without pain is recommended, however, the ankle position in isometric QF strengthening exercise is still applied without sufficient consideration. Our results showed that torque values and EMG activity of the QF in AD were significantly increased compared to those in the AP and NP position. These results of this study are clinically meaningful by suggesting optimal ankle joint position and our findings suggest that isometric QF strengthening exercise can improve muscle strength most effectively with the AD position than with AP and NP. We propose to perform AD position during isometric exercise to restore QF strength at the early knee rehabilitation.

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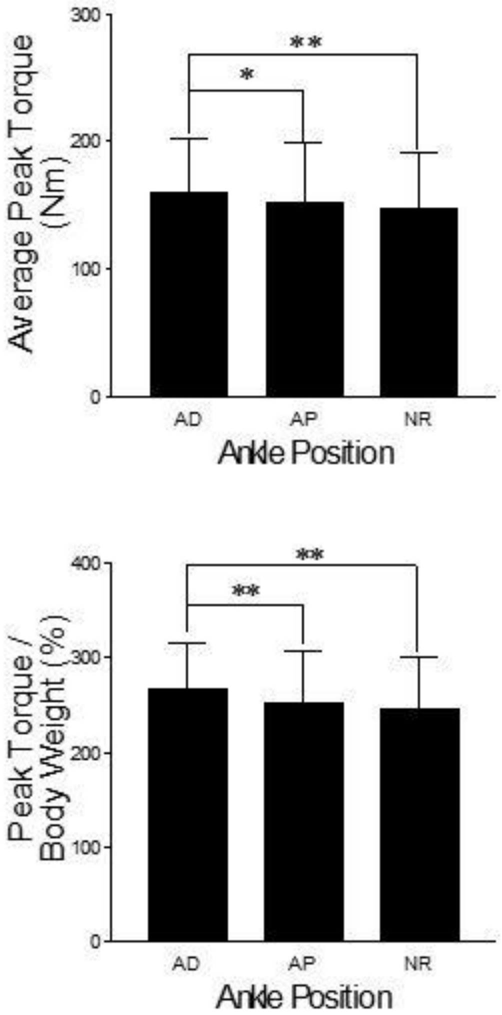

Figure 1. Comparison of torque values of quadriceps femoris according to different ankle position. Respectively, AD, AP, NR ankle position. AD: active dorsiflexion; AP: active plantarflexion; NR: neutral resting. * Significance at $p < 0.05$, ** Significance at $p < 0.01$.

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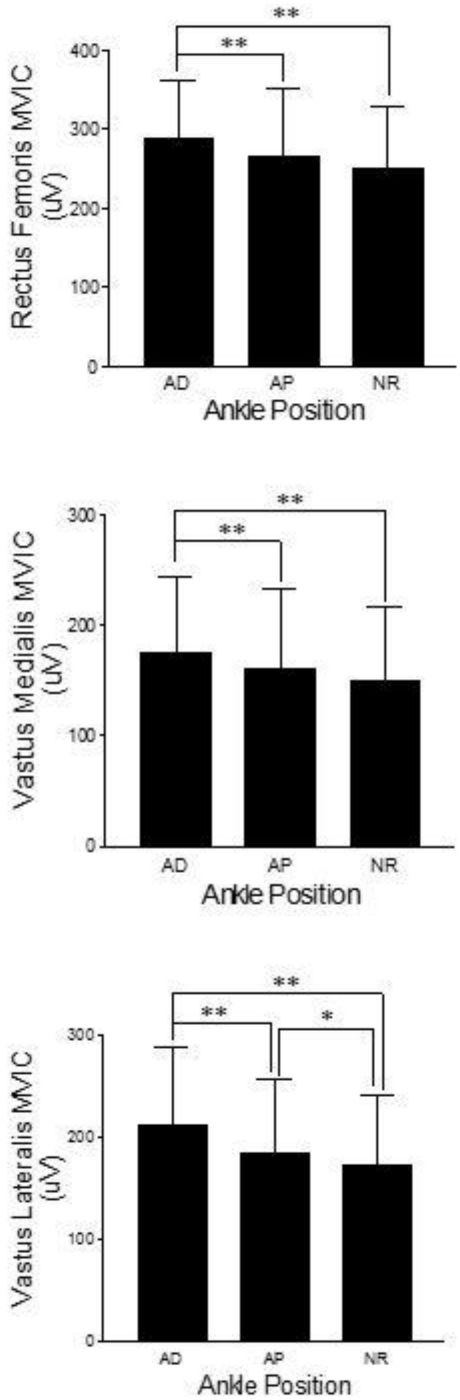

Figure 2. Comparison of EMG activities of quadriceps femoris according to different ankle position. Respectively, AD, AP, NR ankle position. AD: active dorsiflexion; AP: active plantarflexion; NR: neutral resting.* Significance at $p < 0.05$, ** Significance at $p < 0.01$.

Table 1. Comparison of isometric strength of quadriceps femoris according to ankle position (*n* = 36).

Parameters	**Ankle position**			***F***
	AD	**AP**	**NR**	
PT/BW (%)	265.39±50.11	252.30±54.90	246.01±54.59	11.606**
Avg. PT (Nm)	159.44±43.24	152.25±46.42	147.51±44.19	11.596**

Values are expressed as frequencies and means (standard deviation).). ** Significance at $p < 0.01$.
PT/BW: peak torque per body weight; Avg: average; AD: active dorsiflexion;
AP: active plantarflexion; NR: neutral resting.

Table 2. Comparison of muscle activation (MVIC) of quadriceps femoris according to ankle position (*n* = 36).

Parameters	**Ankle position**			***F***
	AD	AP	NR	
RF (MVIC, μV)	288.44±73.20	264.07±86.00	250.86±78.31	23.103**
VM (MVIC, μV)	174.54±70.01	160.13±72.43	149.33±67.11	13.968**
VL (MVIC, μV)	211.24±76.92	185.03±72.16	172.40±68.89	22.439**

Values are expressed as frequencies and means (standard deviation). ** Significance at $p < 0.01$.

RF: rectus femoris; VM: vastus medialis; VL: vastus lateralis; AD: active dorsiflexion; AP: active plantarflexion; NR: neutral resting.