Journal of Kerman University of Medical Sciences

JKMU

Journal of Kerman University of Medical Sciences, 2017; 24(5): 368-378

Comparison of generalized and directed co-contraction of knee joint muscles during four different movements for strengthening the quadriceps

Amir Ali Jafarnezhadgero, Ph.D. [1], Mohammad Mahdi Bahramisharif, M.Sc. [2], Mahdi Majlesi, Ph.D. [3]

1- Assistant Professor, Department of Physical Education and Sport Sciences, Faculty of Educational Science and Psychology, University of Mohaghegh Ardabili, Ardabil, Iran (Corresponding author; amiralijafarnezhad@gmail.com)

2- Master Student, Department of Sport Biomechanics, Faculty of Humanities, Islamic Azad University, Hamedan Branch, Hamedan, Iran

3. Assistant Professor, Department of Sport Biomechanics, Faculty of Humanities, Islamic Azad University, Hamedan Branch, Hamedan, Iran

Received: 5 June, 2017 Accepted: 11 November, 2017

ARTICLE INFO

Article type:
Original article

Keywords:
Electromyography
Weight lifting
Knee joint

Abstract

Background: Different movements have a role in strengthening the quadriceps muscles based on knee joint co-contraction, hamstring to quadriceps and vastus medialis to vastus lateralis muscles activity ratios. This provides useful information about each movement's role in rehabilitating patients with anterior cruciate ligament injury, osteoarthritis and patellofemoral pain syndrome. This study compared the rate of generalized and directed co-contraction of knee joint muscles during free weight, Smith's one-legged and two-legged machine squats and deadlift movement.

Methods: Fourteen healthy power lifters (mean age of 26 ± 7 years old) participated in this study. A portable electromyography system with six pairs of bipolar surface electrodes was used to record the activity of the gastrocnemious medialis, long head of biceps femoris, semitendinosus, vastus lateralis, rectus femoris, and vastus medialis muscles at a sampling frequency of 1200 Hz. The participants had enough experience to perform the four movements. The participants carried out each movement five times at intensity equal to 50% of one-repetition-maximum level. Repeated-measure analysis of variance was used for statistical analysis.

Results: Rate of medial co-contraction was higher in deadlift movement compared to Smith one-legged machine ($P = 0.042$) and free weight squats ($P = 0.044$), respectively. Ratio of hamstring to quadriceps muscles activity was higher during deadlift movement compared to free weight squat ($P= 0.022$). The generalized co-contraction value at the knee joint was the lowest in deadlift movement and highest in Smith one-legged machine squat.

Conclusion: To strengthen quadriceps muscles in people suffering from anterior cruciate injury, deadlift movement is more effective than free weight squat. Smith one-legged machine squat is more effective than the other three movements for athletes who want to strengthen muscular groups.

Citation: Jafarnezhadgero A.A, Bahramisharif M.M, Majlesi M. Comparison of generalized and directed co-contraction of knee joint muscles during four different movements for strengthening the quadriceps. Journal of Kerman University of Medical Sciences, 2017; 24(5): 368-378.

Introduction

The American College of Sports Medicine has recommended doing exercise for at least one set of weight training for two days a week (1). Because of increased muscle's physiological cross-sectional area, muscle capillary and coordination in motor unit's recruitment, doing strengthening exercises such as free weight movements or with devices are used to improve neuromuscular performance (2, 3).

In various occupational and recreational activities, the human knee joint is exposed to high risk injuries (4-6). Different rehabilitation exercises are currently used in non-surgical and post-surgery management of joint disorders (7, 8). Free weight squat, Smith's one-legged and two-legged machine squats, and the deadlift movement are four common movements in bodybuilding. The quadriceps, hamstrings, gastrocnemius, gluteus maximus and erector spinae muscles are involved in these movements. Weight training skills which involve multiple muscles have numerous neuromuscular and biomechanical similarities to many athletic movements such as running and jumping (3).

The open- and closed-kinetic chain exercises generate different patterns of muscular activities and ligament forces (9). Because of their similarities to daily activities and more muscles' interaction in other joints compared to open-kinetic chain exercises, closed-kinetic chain exercises are mostly used in rehabilitation (9, 10). Since the above-mentioned four exercises are closed-kinetic chain exercises, they are often used in a clinical setting for knee rehabilitation after anterior cruciate ligaments surgery (11), knee osteoarthritis (12) and patellofemoral pain (13). For example, several studies have measured muscle activity about the knee joint during squat (10, 14, 15) and some of them have compared rate of muscle activity while performing squat movement with Smith machine and free weight (16-18). Because of different methodologies, different results have been reported about lower limb muscles' activities in this regard (16-18).

Co-contraction of the knee joint muscles can alter the joint's stability and articular loading (19). There are generally two types of co-contraction: generalized and directed (20). Knee joint muscles' co-contraction changes the rate of articular stability (directed co-contraction) and loads (generalized co-contraction) in this joint (21). In generalized co-contraction, all agonists and antagonists of the knee co-activate equally. However, in directed co-contraction lateral agonists and antagonists are activated to directly support external movement and reduce the concentration of articular loading in the medial knee compartment (22). Generalized co-contraction is less effective in preventing condylar lift-off because of its non-directionality, and may increase all articular loading (20, 23).

Based on our knowledge, no research has compared muscles co-contraction values during the four movements of free weight squat, Smith one-legged and two-legged squats and deadlift movement. Thus, this study compared the rate of generalized and directed muscles' co-contraction while doing these movements. These movements have an influential role in the rate of knee joint co-contraction, hamstring to quadriceps and vastus medialis to vastus lateralis muscles electromyography activity ratio. This provides useful information for therapists, coaches and athletes about the role of each movement in rehabilitation of patients with anterior cruciate ligament injury, osteoarthritis and patellofemoral pain syndrome.

Materials and Methods

Participants

Fourteen healthy men who were power lifters participated in this study. Their average age was 26 ± 7 years old. Their mean of height was 177 ± 11 cm, and their average weight was 81 ± 5 kg. They were selected from sports clubs of

Hamedan city, Iran. They signed an informed written consent form before participation and filled a questionnaire about their medical history and sports activities. This study was in line with the principles of Declaration of Helsinki for investigations on humans.

Inclusion and exclusion criteria

The inclusion criteria were having: 1) enough experience in doing free weight, Smith one-legged and two-legged machine squats, and deadlift movement (Figure 1) which are common in bodybuilding; 2) having three of these movements in the current exercise plans and doing them on a regular basis; 3) having three to five years of strength training experience.

The exclusion criteria were having: 1) a history of trauma, surgery of lower extremities or a vertebral column; 2) considerable leg length (greater trochanter to floor) discrepancy; 3) congenital or developmental abnormalities of the lower limbs; 4) paralysis of the lower extremities; 5) any of the following diagnoses: symptomatic cerebrovascular disease, atherosclerosis of the lower extremities, spondylarthritis, spinal stenosis, chronic back pain (sciatic syndrome), or a painful knee or hip joint and any other neurologic, rheumatologic, or musculoskeletal disorders; and 6) had done physical exercises 48 hours before the examination;

Procedure

A week before the experiment, the test procedure was fully explained to the participants and a one-maximum repetition was measured for each individual and all movements. Legs' distance in all movements was 108% of shoulders width (24). Ascending phase of movements was defined by kinematics data. The movements' start and end points were from 90° of flexion to full knee extension. Metronome was used to control the movements' speed. The time duration equal to one second was selected for each phase. In this study, Olympic standard barbell bar (20.5 kg), its specific weights and Smith device (Mobarez company, Tehran, Iran), with 120 cm length, 220 cm width and 230 cm height and device bar of 29.9 kg were used. In the training day, the participants warmed up themselves spontaneously for 10 minutes with a stretching and general warm up program (2). The correctness of movements was supervised by an experienced coach.

Kinematics record and muscles activity

A Vicon MX Motion Systems device consisting of four T-series cameras (Oxford Metrics, Oxford, United Kingdom) was used for capturing kinematic data with sampling rate of 100 Hz. Sixteen skin-mounted markers were applied to bony landmarks according to the Plugin-Gait marker set (Oxford Metrics, Oxford, United Kingdom) for the lower extremity analysis. The marker set consisted of: bilateral anterior superior iliac spine, bilateral posterior superior iliac spine, bilateral mid-thigh-cuff, bilateral lateral femoral epicondyles, bilateral mid-shank cuff, bilateral lateral malleoli, bilateral heels, and bilateral toes between second and third metatarsal heads.

The bilateral heels and toes markers could not be attached directly to the participants' skin as it was covered with shoes. Therefore, instead of anatomic landmarks, markers were attached to appropriate positions on the shoe surface. All electromyography signals were registered and measured with a surface electromyography recorder (BTS FREE EMG 300, BTS Bioengeering, Italy) at a sampling frequency of 1200 Hz, a common mode rejection ratio of more than 110 dB at 50-60 Hz. The device provided completely wireless communication between the preamps and signal collecting unit. The Ag-AgCl electrodes were placed on a thoroughly shaved and cleaned skin with a center-to-center distance of 20 mm, parallel with the muscle fibers. Also, for recording electromyography activity, electrodes were placed on selected dominant lower limb muscles (including medial gastrocnemius, vastus medialis, rectus femoris, vastus lateralis, biceps femoris, and semitendinosus) based on the surface electromyography for non-invasive assessment of muscle (SENIAM) protocol (25). Then maximum voluntary isometric contractions (MVIC) of muscles were recorded and used for normalization. MVIC repetitions of quadriceps muscles group were recorded in the 90° knee and hip flexion situation while doing the knee extension in a sitting position. MVIC repetition of biceps femoris muscle and semitendinosus was recorded in the same knee and hip situation while doing the knee flexion movement (2). MVIC repetition for medial part of the gastrocnemius muscle was recorded in the knee extension position and while the ankle was in neutral position. In this position, the participants did isometric plantar flexion movement against resistance.

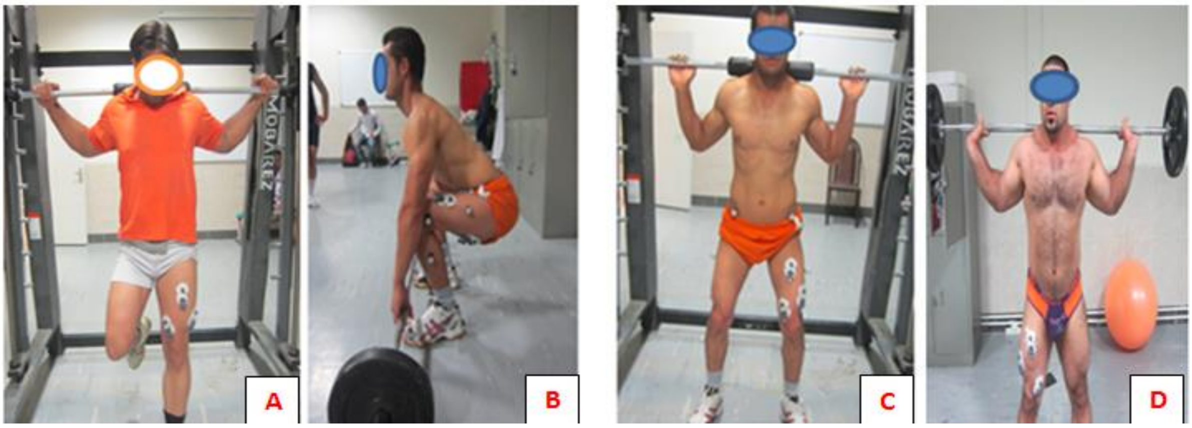

Figure 1. Type of exercise (A: Smith one-legged machine squat, B: dead lift, C: Smith two-legged machine squat, D: Free weight squat.

After MVIC testing, the participants did each movement for three times with intensity equal to 50% of one-repetition-maximum. The sequence was randomly selected with respect to both movements and MVIC repetitions. A rest period of three to five minutes was allowed between two consecutive efforts.

Data processing

The raw EMG signals were differentially amplified (1000 gain), band-pass filtered (10 to 500 Hz), and digitalized (16-bit resolution, 4-kHz sampling frequency) within the wireless electromyography sensors. First, the start and end points of the movement trials were determined as the time window using the synchronized kinematic data. After data rectification, the root mean square (RMS) values were calculated with a 200 ms size of window and then normalized to the peak electromyography amplitude at MVIC, and expressed as a percentage of its value. The rate of muscular activity was calculated during knee extension phase. In this study, the generalized co-contraction was calculated by the sum of electromyography activity of all knee joint muscles (26). The rate of directed co-contraction between medial and lateral knee joint muscles and between extensor and flexor muscles of the knee joint was calculated with the following equation (26):

Directed co-contraction = 1- (Average agonist muscles activity / average muscle antagonist)

In the above equation, when the number is closer to zero, the rate of co-contraction is higher, and when the number is closer to 1 or -1 then co-contraction is less. Hamstring to quadriceps and vastus medialis to vastus lateralis muscles' electromyography activity ratios were also calculated during the movements.

Statistical analysis

The normality of the variable's distributions was verified by Shapiro-Wilkin test. Repeated-measures analysis of variance test was used for statistical analysis. The significance level was set at $p < 0.05$ for all analyses. Statistical analysis was done with statistical package for social sciences (SPSS) version 18 (Chicago, IL, USA). Also, the effect size was calculated with Cohen's d formula: (Mean 1 − Mean 2) / ([standard deviation 1 + standard deviation 2]/2), in which d values become positive, if the difference between the means is in the predicted sense. This parameter classifies the effect size as small if $d \geq 0.20$, medium if $d \geq 0.50$, and large if $d \geq 0.80$ (27).

Results

There were no significant differences in vastus medialis to vastus lateralis ratios during the four movements ($p > 0.05$; Figure 2).

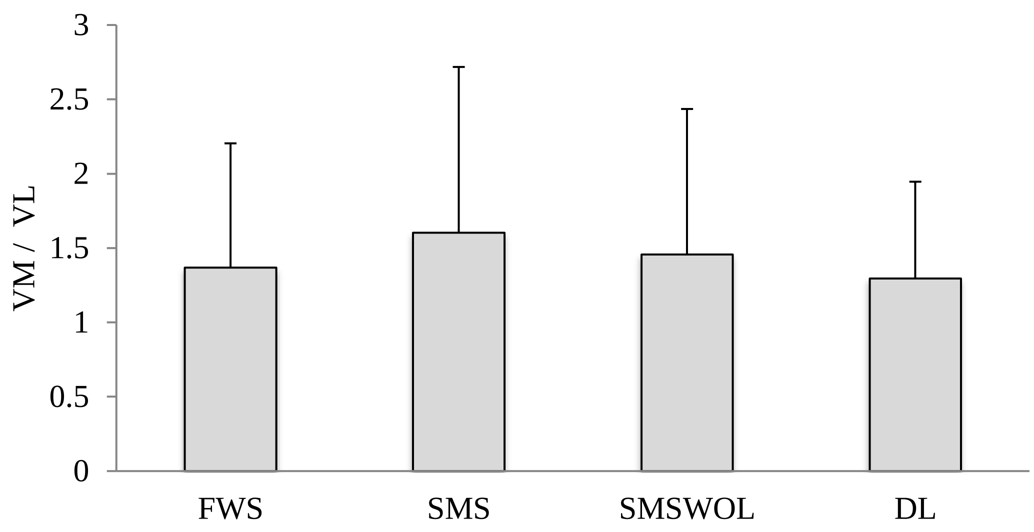

Fig 2. Ratio of activity in vastus medialis to vastus lateralis (VM / VL) during performing of four movements

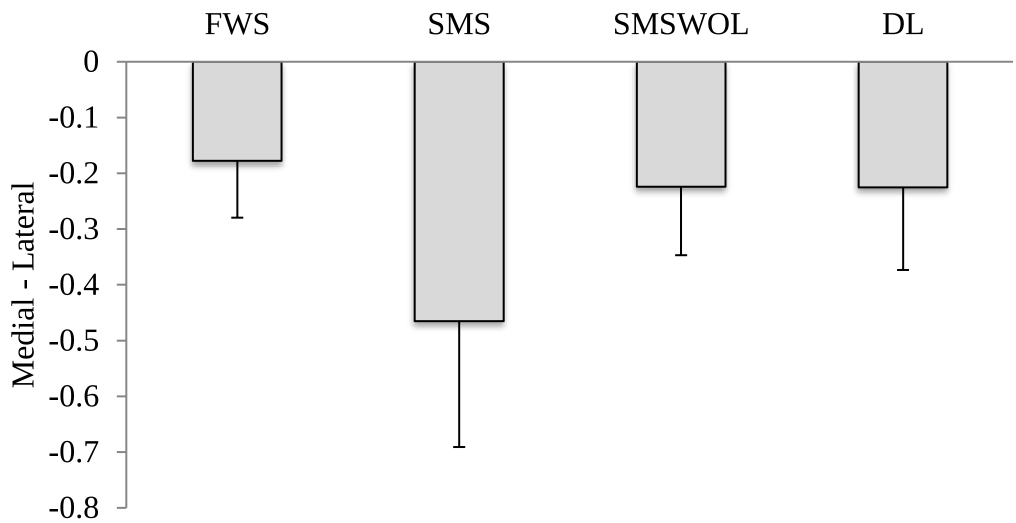

Fig 3. The value of directed co-contraction between medio- lateral muscles of the knee joint muscles during performing of four movements

There was no significant difference in directed co-contraction of medio-lateral muscles between different movements (p > 0.05; Figure 3). The rate of medial co-contraction in deadlift movement was lower than Smith one-legged machine squat (p = 0.042; d = 0.53) and free weight squat (p = 0.044; d = 0.55) movements (Figure 4).

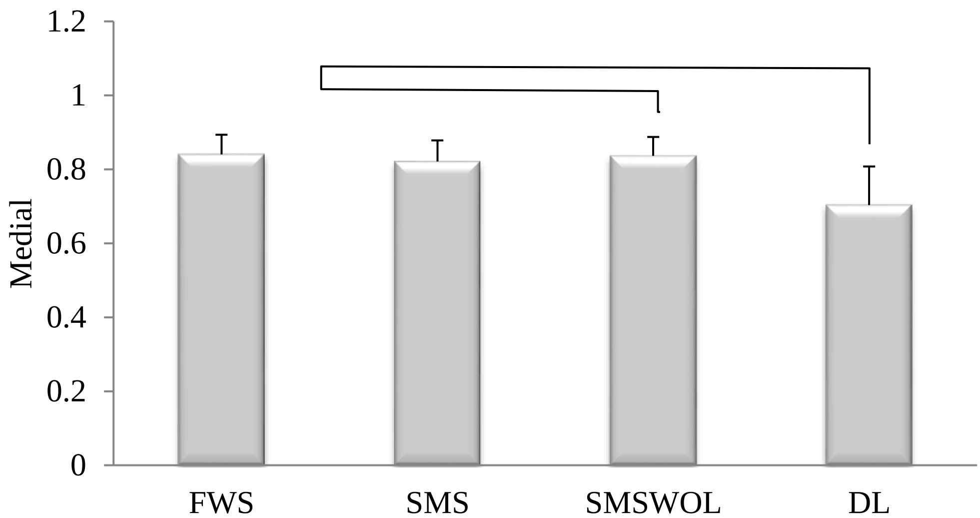

Fig. 4. The value of directed co-contraction between medial knee joint muscles

Ratio of hamstring to quadriceps muscles activity was more than free weight squat during deadlift movement (P = 0.022; d = 0.12); however, this ratio was not significantly different among other movements (p > 0.05; Figure 5).

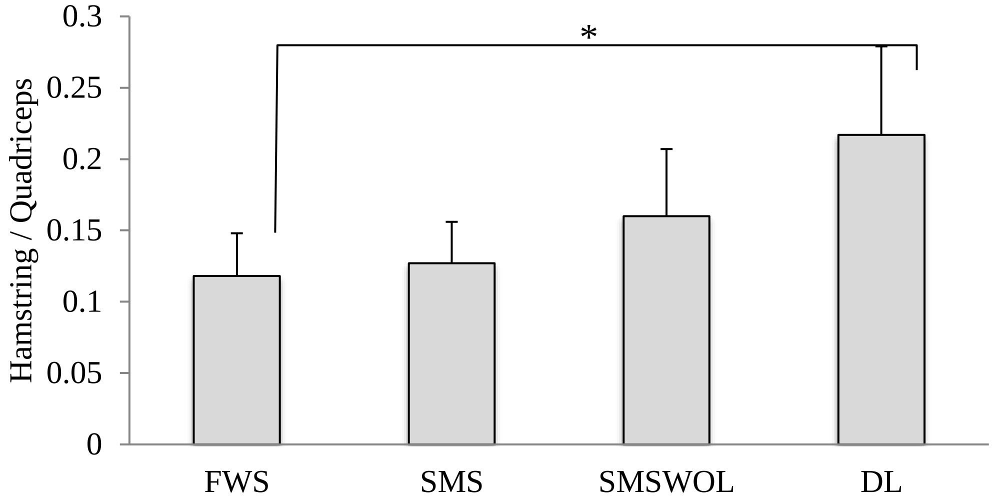

Fig. 5. The ratio of hamstring activity to quadriceps during performing of four movements

*P<0.05

The generalized co-contraction value in the deadlift movement had the lowest rate while Smith one-legged machine squat movement had the highest rate ($p \leq 0.05$; F(3) = 59.22). Values of generalized co-contraction between Smith two-legged machine and free weight squats were not significantly different ($p > 0.05$) (Figure 6).

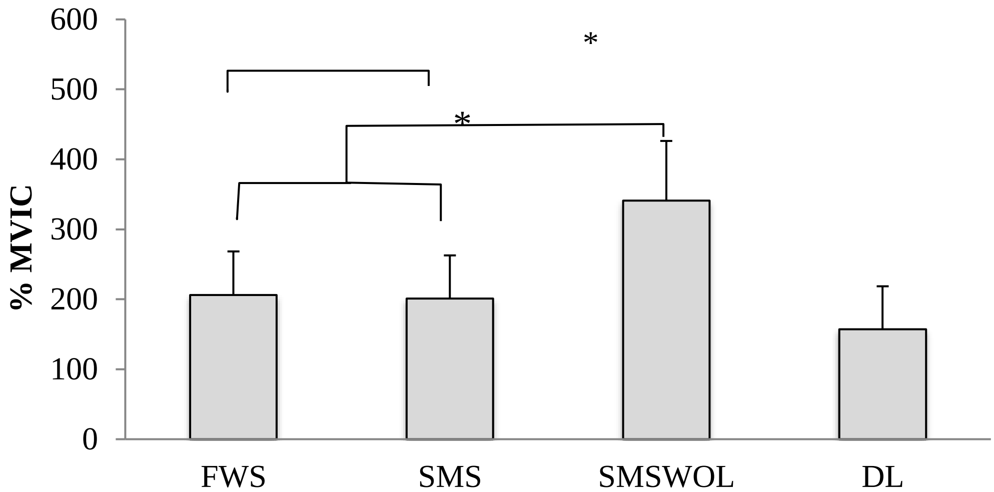

Fig. 6. Generalised co-contraction in knee joint muscles during performing of four movements

*P<0.05

Electromyography activities of the selected lower limb muscles for all movements are presented in Table 1. The activity of vastus medialis, vastus lateralis, biceps femoris, and medial gastrocnemius muscle in Smith one-legged machine squat movement was higher than that the other three movements (P<0.05). The activities of all muscles were not significantly different between free weight and Smith machine squat movements ($p > 0.05$; Table 1).

Table 1. Amplitude (% MVIC) of electromyography activity (mean ± standard deviation) of selected lower limb muscles for all movements are presented

Muscles	Movements			
	FWS	SMS	SMSWOL	DL
Vastus medialis	66.19±24.15$^{*¥}$	70.50±25.13$^{\alpha\$}$	120.14±38.87$^{*\alpha\eta}$	43.09±23.79$^{¥\$\eta}$
Rectus femoris	50.32±29.75	43.75±17.40$^{\$}$	59.27±24.43$^{\eta}$	30.42±16.69$^{\$\eta}$
Vastus lateralis	60.26±31.85$^{*¥}$	57.62±34.62$^{\alpha}$	101.03±49.94$^{*\alpha\eta}$	44.53±23.92$^{¥\eta}$
Biceps femoris	9.88±7.66*	8.91±6.55$^{\alpha}$	21.30±14.97$^{*\alpha\eta}$	10.65±7.95$^{\eta}$
Semitendinosus	8.91±8.90	11.39±13.40	17.98±19.20	11.27±15.78
Medial gastrocnemius	9.99±6.39*	8.64±7.44$^{\alpha}$	21.47±12.35$^{*\alpha\eta}$	11.15±6.91$^{\eta}$

* Significant difference between FWS and SMSWOL

¥ Significant difference between FWS and DL

α Significant difference between SMS and SMSWOL

$ Significant difference between SMS and DL

η Significant difference between SMSWOL and DL

Discussion

This study compared the rate of generalized and directed muscles' co-contraction, hamstring to quadriceps, and vastus medialis to vastus lateralis electromyography activity ratios in the course of four bodybuilding movements. The findings showed that there were no significant differences between vastus medialis to vastus lateralis ratio and rate of co-contraction between the knee's medio-lateral muscles.

Previous researches have shown that in normal people compared to those with patellofemoral pains, two muscular mechanisms prevent the additional patella displacement to the outside. The first is related to early starting work in vastus medialis muscle compared to the vastus lateralis (28) and the second is related to higher activity in vastus medialis in normal people compared to people with patellofemoral pain syndrome (29). However, there was no significant difference between the four movements in vastus medialis to vastus lateralis ratio.

Using medial/lateral directed co-contraction comparison did not reveal any significant differences between the four studied movements. Directed co-contraction of agonist and antagonist muscles of the knee joint are more active in neutralizing the abduction movement on the knee joint and can increase adduction movement in the knee joint (26). It has been shown that an increase in medial co-contraction of the knee is associated with osteoarthritis of the medial knee joint compartment (26, 30). Knee osteoarthritis is an important cause of disability in the elderly (31, 32). Detection of causes of osteoarthritis and prevention of its occurrence, reduce medical costs. According to our results, there was no significant difference in medial co-contraction of the knee between the four movements.

Hamstring muscle's activation provides an additional restraint to anterior tibial translation (19,33,34). An important risk factor involved in anterior cruciate ligament injury is reduction in hamstring to quadriceps electromyography activity ratio (19, 35-38). We did not find any significant difference in hamstring to quadriceps ratio between the four movements.

Our study demonstrated that the net muscle activation of the knee joint has the lowest value in deadlift movement and has the highest value in Smith one-legged machine squat movement. It is demonstrated that higher generalized co-contraction may unduly increase all articular loading (20, 23, 26). For athletes who aim to strengthen quadriceps muscles groups more, Smith one-legged machine squat movement has a higher muscular involvement than the other movements.

A limitation of the study was that the participants were not motivated enough in doing the exercises. Another limitation was the noises of electromyography recording which prevented the participants from concentrating.

Practical applications

For athletes who aim to strengthen quadriceps muscles groups more, Smith one-legged machine squat movement has a higher muscular involvement than the other three studied movements.

Acknowledgement

We would like to thank all the participants for their participation. Also, we would like to thank Seyed Muhammed Hussein Mousavinasab for editing this text.

References

1. Pollock ML, Gaesser GA, Butcher JD, Després JP, Dishman RK, Franklin BA, et al. American college of sports medicine position stand. the recommended quantity and quality of exercise for developing and maintaining cardiorespiratory and muscular fitness, and flexibility in healthy adults. Med Sci Sports Exerc 1998; 30(6):975-91.
2. Walker S, Peltonen H, Avela J, Häkkinen K. Kinetic and electromyographic analysis of single repetition constant and variable resistance leg press actions. J Electromyogr Kinesiol 2011;21(2):262-9.
3. Escamilla RF, Fleisig GS, Zheng N, Lander JE, Barrentine SW, Andrews JR, et al. Effects of technique variations on knee biomechanics during the squat and leg press. Med Sci Sports Exerc 2001;33(9):1552-66.
4. Sweif RE, Abdallah AA. Comparative study of mechanical and physiological gait efficiency following anterior cruciate ligament reconstruction and rehabilitation. Medicina dello Sport 2015;68(2):279-89.
5. Villosio N, Piccazzo R, Paparo F, Muda A, Garlaschi G. Knee instability signs: preliminary comparison between conventional and weight-bearing MRI in patients with complete anterior cruciate ligament tear. Medicina dello Sport 2013;66(2):253-64.
6. Buda R, Verni E, Ferruzzi A, Di Caprio F, Giannini S. Anterior cruciate ligament replacement with distally inserted doubled hamstring graft: prospective clinical and instrumental evaluation. Medicina dello Sport 2005;58(4):303-11.

7. Fisher NM, Pendergast DR, Gresham GE, Calkins E. Muscle rehabilitation: its effect on muscular and functional performance of patients with knee osteoarthritis. Archives of physical medicine and rehabilitation 1991;72(6):367-74.

8. Ma H, Zhang S, Zhang X. Common acupoints and treatment parameters of acupuncture treatments for knee osteoarthritis. Medicina dello Sport 2014;67(4):653-68.

9. Rao G, Amarantini D, Berton E. Influence of additional load on the moments of the agonist and antagonist muscle groups at the knee joint during closed chain exercise. J Electromyogr Kinesiol 2009;19(3):459-66.

10. Escamilla RF, Fleisig GS, Zheng N, Barrentine SW, Wilk KE, Andrews JR. Biomechanics of the knee during closed kinetic chain and open kinetic chain exercises. Med Sci Sports Exerc 1998;30(4):556-69.

11. Lutz GE, Palmitier RA, An KN, Chao EY. Comparison of tibiofemoral joint forces during open-kinetic-chain and closed-kinetic-chain exercises. J Bone Joint Surg Am 1993;75(5):732-9.

12. Ferreira GE, Robinson CC, Wiebusch M, Viero CC, da Rosa LH, Silva MF. The effect of exercise therapy on knee adduction moment in individuals with knee osteoarthritis: a systematic review. Clin Biomech (Bristol, Avon) 2015;30(6):521-7.

13. Graci V, Salsich GB. Trunk and lower extremity segment kinematics and their relationship to pain following movement instruction during a single-leg squat in females with dynamic knee valgus and patellofemoral pain. J Sci Med Sport 2015;18(3):343-7.

14. McCaw ST, Melrose DR. Stance width and bar load effects on leg muscle activity during the parallel squat. Med Sci Sports Exerc 1999;31(3):428-36.

15. Isear JA Jr, Erickson JC, Worrell TW. EMG analysis of lower extremity muscle recruitment patterns during an unloaded squat. Med Sci Sports Exerc 1997;29(4):532-9.

16. Schwanbeck S, Chilibeck PD, Binsted G. A comparison of free weight squat to Smith machine squat using electromyography. J Strength Cond Res 2009;23(9):2588-91.

17. Anderson K, Behm DG. Trunk muscle activity increases with unstable squat movements. Can J Appl Physiol 2005;30(1):33-45.

18. Cotterman ML, Darby LA, Skelly WA. Comparison of muscle force production using the Smith machine and free weights for bench press and squat exercises. J Strength Cond Res 2005;19(1):169-76.

19. Hedayatpour N, Fathi M. Co-activation of the knee joint flexor and extensor muscles during multidirectional perturbations after fatiguing exercise. Medicina dello Sport 2013;66(2):189-98.

20. Lloyd DG, Buchanan TS. Strategies of muscular support of varus and valgus isometric loads at the human knee. J Biomech 2001;34(10):1257-67.

21. Hubley-Kozey C, Deluzio K, Dunbar M. Muscle co-activation patterns during walking in those with severe knee osteoarthritis. Clin Biomech (Bristol, Avon) 2008;23(1):71-80.

22. Schipplein OD, Andriacchi TP. Interaction between active and passive knee stabilizers during level walking. J Orthop Res 1991;9(1):113-9.

23. Zhang LQ, Xu D, Wang G, Hendrix RW. Muscle strength in knee varus and valgus. Med Sci Sports Exerc 2001;33(7):1194-9.

24. Hesari P, Rabiei M, , JafarnezhadT, Hoseininezhad SE ,Anbarian M. The comparison

of myoelectric activity of selected lower limb muscles during three common quadriceps strength exercises performed with different loads. Sport Medicine 2012; 31(2):31-48. Persian

25. Hermens HJ, Freriks B, Merletti R, Stegeman D, Blok J, Rau G, et al. European recommendations for surface electromyography. Roessingh Research and Development 1999; 8(2):13-54.

26. Heiden TL, Lloyd DG, Ackland TR. Knee joint kinematics, kinetics and muscle co-contraction in knee osteoarthritis patient gait. Clin Biomech (Bristol, Avon) 2009;24(10):833-41.

27. Cohen J. Statistical Power Analysis for the Behavioral Sciences. Academic press; Hilsdale. NJ: Lawrence Earlbaum Associates, Third edition, 2013.

28. Cowan SM, Bennell KL, Hodges PW, Crossley KM, McConnell J. Simultaneous feedforward recruitment of the vasti in untrained postural tasks can be restored by physical therapy. J Orthop Res 2003;21(3):553-8.

29. Makhsous M, Lin F, Koh JL, Nuber GW, Zhang LQ. In vivo and noninvasive load sharing among the vasti in patellar malalignment. Med Sci Sports Exerc 2004;36(10):1768-75.

30. Hodges PW, van den Hoorn W, Wrigley TV, Hinman RS, Bowles KA, Cicuttini F, et al. Increased duration of co-contraction of medial knee muscles is associated with greater progression of knee osteoarthritis. Man Ther 2016;21:151-8.

31. Rudolph KS, Schmitt LC, Lewek MD. Age-related changes in strength, joint laxity, and walking patterns: are they related to knee osteoarthritis? Phys Ther 2007;87(11):1422-32.

32. Lawrence RC, Helmick CG, Arnett FC, Deyo RA, Felson DT, Giannini EH, et al. Estimates of the prevalence of arthritis and selected musculoskeletal disorders in the United States. Arthritis Rheum 1998;41(5):778-99.

33. Elias AR, Hammill CD, Mizner RL. Changes in quadriceps and hamstring cocontraction following landing instruction in patients with anterior cruciate ligament reconstruction. J Orthop Sports Phys Ther 2015;45(4):273-80.

34. Kim HJ, Lee JH, Ahn SE, Park MJ, Lee DH. Influence of anterior cruciate ligament tear on thigh muscle strength and hamstring-to-quadriceps ratio: a meta-analysis. PLoS One 2016;11(1):e0146234.

35. Letafatkar A, Rajabi R, Tekamejani EE, Minoonejad H. Effects of perturbation training on knee flexion angle and quadriceps to hamstring cocontraction of female athletes with quadriceps dominance deficit: Pre-post intervention study. Knee 2015;22(3):230-6.

36. Frank RM, Lundberg H, Wimmer MA, Forsythe B, Bach BR, Verma NN, et al. Hamstring activity in the anterior cruciate ligament injured patient: injury implications and comparison with quadriceps activity. Arthroscopy 2016;32(8):1651-9.

37. Sekir U, Arabaci R, Akova B. Acute effects of static stretching on peak and end-range hamstring-to-quadriceps functional ratios. World J Orthop 2015;6(9):719-26.

38. Yoo WG. Comparison of hamstring-to-quadriceps ratio between accelerating and decelerating sections during squat exercise. J Phys Ther Sci 2016;28(9):2468-69.