Reliability of Low-Density Multi-Channel Electromyography in Assessing Quadriceps Femoris Muscle Excitation

Düşük Yoğunluklu Çok Kanallı Elektromiyografi ile Kuadriseps Femoris Kas Aktivasyonunun Güvenilirliğinin İncelenmesi

Beyza TAYFUR[1], Dylan MORRISSEY[2], Stuart Charles MILLER[3]

ABSTRACT

Bipolar electromyography (EMG) has limited ability to describe within-muscle activation patterns. Low-density multi-channel EMG (LDmEMG) is a promising method to assess muscle excitation. This study aimed to determine the intra- and inter-session reliability of LDmEMG in the quadriceps femoris muscle. Seven asymptomatic participants (aged 28 (27–33), BMI 26.9 (20.6–36.4), 5 males) performed maximum voluntary isometric contractions on an isokinetic dynamometer across two sessions one week apart. Rectus femoris (RF), vastus medialis (VM), and vastus lateralis (VL) borders were identified by ultrasound, and a 64-channel LDmEMG grid was applied. Single-channel data and average signals across each muscle and the whole quadriceps were extracted. Good to excellent intra- and inter-session reliability (ICC3,1abs = 0.84–0.93) was observed for overall quadriceps, RF, and VM. Single-channel reliability ranged from good to excellent intra-session (ICC3,1abs = 0.75–0.96) and moderate to excellent inter-session (ICC3,1abs = 0.52–0.96), except for the distal RF, which showed poor reliability (ICC3,1abs <0.5). VL reliability was consistently lower than RF and VM. In conclusion, LDmEMG provides a reliable assessment of quadriceps muscle excitation, though less reliable in VL. Further studies are warranted to enhance VL reliability and develop 2D excitation maps for clinical and research use.

Keywords: Electromyography, Quadriceps Femoris, Muscle Activation, Muscle Excitation

ÖZ

Bipolar elektromiyografi (EMG), kas içi aktivasyon paternlerini açıklamada yetersiz kalmaktadır. Düşük yoğunluklu, çok kanallı EMG (LDmEMG) kas aktivasyonunun değerlendirilmesinde umut verici bir yöntemdir. Bu çalışmanın amacı, kuadriseps femoris kasında LDmEMG'nin oturum içi ve oturumlar arası güvenilirliğini belirlemektir. Çalışmaya 7 sağlıklı gönüllü (yaş 28 (27–33), BKİ 26,9 (20,6–36,4), 5 erkek) katılmıştır. Katılımcılar, iki ayrı günde izokinetik dinamometre üzerinde maksimum izometrik kasılmalar gerçekleştirmiştir. Rektus femoris (RF), vastus medialis (VM) ve vastus lateralis (VL) sınırları ultrason ile belirlenmiş ve 64 kanallı LDmEMG uygulanmıştır. Tek kanal ve kas ortalaması (RF, VM, VL ve kuadriseps toplamı) verileri incelenmiştir. Kuadriseps genelinde, RF ve VM için oturum içi ve oturumlar arası güvenilirlik iyi ile mükemmel düzeyde (ICC3,1abs = 0,84–0,93) bulunmuştur. Tek kanal güvenilirliği oturum içinde iyi ile mükemmel (ICC3,1abs = 0,75–0,96), oturumlar arasında ise orta ile mükemmel (ICC3,1abs = 0,52–0,96) arasında değişmiştir. RF'nin distal uçları düşük güvenilirlik göstermiştir (ICC3,1abs <0,5). VL güvenilirliği diğer kaslara kıyasla daha düşüktür. Sonuç olarak, LDmEMG kuadriseps kas aktivasyonunu değerlendirmede güvenilir bir yöntemdir. Ancak VL kası için güvenilirlik düşüktür. Bu yöntemin klinik ve araştırma ortamlarında kullanımını desteklemek için ileri çalışmalar gereklidir.

Anahtar Kelimeler: Elektromiyografi, Kuadriseps Femoris, Kas Aktivasyonu, Kas Uyarılması

Ethical approval for this study was acquired from the Queen Mary University of London Ethics of Research Committee (QMREC2014/24/173).

[1]PhD, Beyza TAYFUR, Sports Physiotherapy, School of Physiotherapy and Rehabilitation, Kırşehir Ahi Evran University, beyza.tayfur@ahievran.edu.tr, ORCID: 0000-0003-4632-9541
[2]Prof, Dylan MORRISSEY, Physiotherapy, Sports and Exercise Medicine, Queen Mary University of London, d.morrissey@qmul.ac.uk, ORCID: 0000-0001-7045-3644
[3]PhD, Stuart Charles MILLER, Biomechanics, Sports and Exercise Medicine, Queen Mary University of London, stuart.miller@qmul.ac.uk, ORCID: 0000-0002-8140-2612

İletişim / Corresponding Author: Beyza TAYFUR
e-posta/e-mail: Beyza.tayfur@ahievran.edu.tr

Geliş Tarihi / Received: 01.10.2025
Kabul Tarihi/Accepted: 14.11.2025

INTRODUCTION

Surface electromyography (sEMG) is a non-invasive method to assess muscle electrical properties in real-time. Traditional sEMG approaches use a pair of electrodes positioned on a single point of the muscle to assess myoelectrical excitation, providing a single waveform. However, this approach cannot measure complex within-muscle excitation patterns, also known as coordination (1).

Multi-channel sEMG uses multiple electrodes positioned on the target muscle, providing localized waveforms (2, 3). This allows detection of individual motor-unit action potentials and conduction velocity along muscle fibers (4), enabling regional comparisons within muscle (5, 6).

However, multi-channel approaches have limitations. Manual electrode placement with non-standard inter-electrode distances is time-consuming (3). Ready-to-use arrays standardize distance but are often high-density and cover small areas, limiting full muscle coverage (7, 8). Therefore, muscle-specific low-density set-ups are required for full coverage.

Quadriceps femoris excitation is frequently studied due to its role in ambulation and function. Bipolar sEMG prevents capturing structural heterogeneity and regional differences within quadriceps (9). To address this, we designed a low-density, high surface area, multi-channel sEMG (LDmEMG) configuration covering the vastus medialis (VM), rectus femoris (RF) and vastus lateralis (VL), reflecting underlying muscle geometry. This setup was designed to provide broader muscle coverage while maintaining ease of application and cost efficiency.

Therefore, the rationale for this study was to evaluate whether this practical and muscle-specific LDmEMG configuration could yield reliable within- and between-session measurements across the quadriceps. Establishing its reliability is a critical step before its potential use in clinical and research contexts to investigate muscle activation patterns and neuromuscular coordination.

The aim of this study was to measure intra- and inter-session reliability of this new configuration for total quadriceps, individual muscles, and individual channels, to assess suitability for clinical and research purposes.

MATERIAL AND METHOD

Participants

Seven adults with no musculoskeletal injury history or symptoms (median age 28 [27–33], BMI 26.9 [20.6–36.4], 5 males) were recruited following ethical approval (QMREC2014/24/173). All participants were physically active but not competitive athletes, engaging in regular recreational activities such as running, cycling, or fitness training at least three times per week. The mean Tegner activity score was 4 ± 2, indicating moderate activity levels consistent with participation in recreational sports and active daily living.

Study Procedure

LDmEMG Design

A 64-channel unipolar sEMG system (REFA8-64e4b4a, 2048 Hz, TMSI, Netherlands) was used. Electrodes (input impedance >100 MΩ; CMRR >90 dB) were actively shielded, with 1-mm silver/silver chloride sensing areas, referenced to the mean of all electrodes (average reference) (Figure 1).

Three grids were designed: VM: 3 linear arrays of 6 electrodes, 50° angle between parallel channels RF: 2 linear arrays of 13 electrodes, no angle VL: 2 linear arrays of 10 electrodes, 30° angle(10, 11).

Inter-electrode distance: 20 mm[16]. Grids were flexible to adapt to skin movement during contraction (Figure 2).

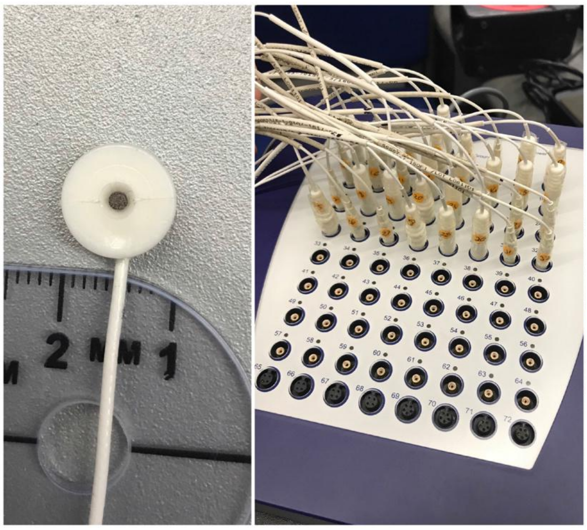

Figure 1. Unipolar Electrode and TMSI 64-Channel EMG System.

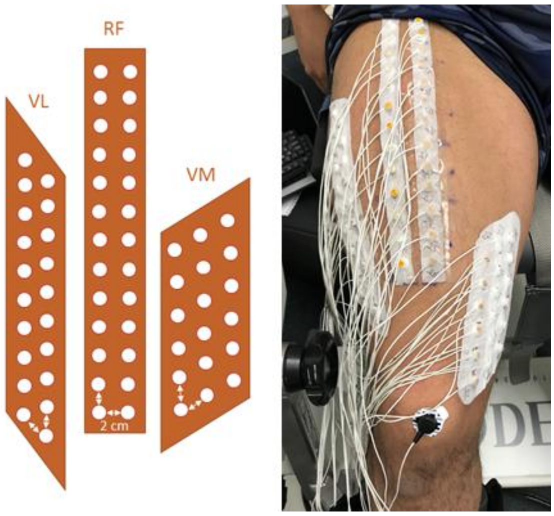

Figure 2. LDmEMG Grid Covering VM, RF, And VL Muscles.

Experimental Protocol

Participants sat with 85° hip flexion and 60° knee flexion on an isokinetic dynamometer (Biodex System 4). Trunk and hips were secured, arms crossed (Figure 3). LDmEMG grids were placed after identifying muscle borders via ultrasound. The reference electrode was placed over the patella of the same leg. Prior to electrode placement, the skin was prepared by shaving hair, skin abrasion with fine sandpaper and cleaning with an alcohol swab.

Participants performed 3–5 submaximal trials and one MVIC for familiarization. Then, 5 repetitions of 5-second MVICs with 60-second rests were completed. Visual feedback and verbal encouragement were provided (12). Participants performed the same procedure 2-7 days after the first session for inter-session reliability. Five repeated contractions were used for intra-session reliability, and the mean of both sessions for inter-session reliability.

Figure 3. Participant Positioning on Isokinetic Dynamometer.

Data Acquisition

The LDmEMG signals were sampled at 2048 Hz. Impedance was assessed prior to collection, and any channels being re-applied if impedance was above 30 kOhm. All data were processed with custom-built MATLAB scripts (MATLAB version R2019a, MathWorks, USA). Data obtained from each electrode were filtered (band-pass 10–1000 Hz; 4th-order Butterworth filter, with zero-lag), rectified and integrated for the mid-3 seconds of each 5-second contraction (iEMG).

Total muscle excitation is defined as the mean of all 64 channels (overall quadriceps).

The excitation of individual quadriceps heads are defined as the mean of all the channels on the respective muscle (VM=18, RF=26, VL=20). Mean MVIC torque was calculated for the mid-3 seconds of each 5-

second contraction and used for MVIC reliability.

Statistical Analysis

Reliability assessed for overall quadriceps, VM, RF, VL and individual channels using SPSS statistical package version 23 (SPSS Inc, Chicago, IL) with intra-class correlation coefficients (ICC, single-rater, two-way mixed-effects model, absolute-agreement). ICC values represented poor (<0.5), moderate (0.5-0.75), good (0.75-0.90), or excellent (>0.90) reliability (13).

Acknowledgements

Post-graduate studies of Ms. Beyza Tayfur are sponsored by the Turkish Ministry of National Education. The sponsors had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

RESULTS AND DISCUSSION

Peak MVIC torque was 195.7±50.7 Nm and 198.4±60.9 Nm in test and retest sessions, respectively.

Reliability

Intra- and inter-session reliability of MVIC, and overall quadriceps, VM, RF, and VL were good to excellent and moderate to excellent, respectively

Table 1. Intra- and Inter-Session Reliability of MVIC, Overall Quadriceps, VM, RF, and VL Integrated EMG. Values Shown are ICC (95% Confidence Interval)

Measure	Intra-session ICC (95% CI)	Inter-session ICC (95% CI)
MVIC	0.93 (0.80–0.98)	0.81 (0.31–0.96)
Overall quadriceps	0.91 (0.78–0.98)	0.91 (0.56–0.98)
Vastus medialis	0.92 (0.78–0.98)	0.90 (0.55–0.98)
Rectus femoris	0.93 (0.81–0.99)	0.93 (0.66–0.99)
Vastus lateralis	0.87 (0.69–0.97)	0.84 (0.12–0.97)

Intra- and inter-session reliability of individual channels was good to excellent intra-session, moderate to excellent inter-session, except for distal RF channels (Figure 4).

Surface EMG (sEMG) is commonly used in clinical and research settings to understand quadriceps excitation. Generally, single-channel bipolar sEMG is used on each superficial muscle head (RF, VL, VM) to represent overall muscle excitation. We aimed to optimise a multi-channel sEMG configuration specific for quadriceps femoris to enable the study of complex within-muscle coordination, and to establish the intra- and inter-session reliability of a novel low-density, high surface area, multi-channel sEMG (LDmEMG) design.

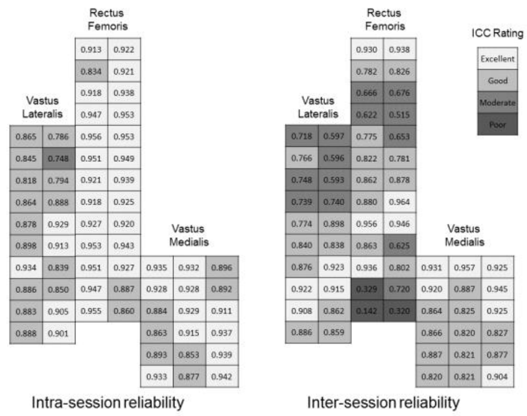

Figure 4. Intra- and Inter-Session Reliability for Individual LDmEMG Channels.

Overall, we observed good to excellent intra- and inter-session reliability for overall quadriceps, VM, VL, and RF. Single-channel reliability also showed good to excellent intra-session reliability and moderate to excellent inter-session reliability, apart from the distal ends of RF, which had poor reliability. VL reliability was slightly lower than the other muscles for both the whole muscle and single channels. The reliability of the LDmEMG design is similar to bipolar sEMG of the quadriceps reported previously (ICC=0.75–0.97) (14-16). Therefore, we propose the use of the LDmEMG approach as reliable for measurement of regional excitation within the quadriceps muscles.

Intra-session reliability of VL was slightly lower than other muscles for both the overall

VL and individual channel levels. This was specifically occurring within the medio-proximal channels. This might be because of high structural variability within VL and its connection with vastus intermedius (VI), especially at the proximal end (17). We speculate that the interaction between VL and VI might be slightly changing throughout repetitions and causing relatively lower reliability values when compared to RF or VM. Anatomically, VL thickness is greater in the proximal region of the thigh (9); therefore, a greater change in muscle structure would be expected in the proximal VL during a contraction (18), which may result in a higher variability of recorded sEMG. There is also a general tendency to place the VL electrodes close to the RF (19). We tried our best to place the grids along the VL longitudinal line, using ultrasound to avoid crossing muscle borders. However, there is still a chance of crosstalk from RF, especially since there is evidence that RF muscle is moving laterally during contractions (18). Our reliability results for distal VL were consistently high, where the change in muscle shape and crosstalk would be expected to be lower. Therefore, the lower variability within the medio-proximal channels of the VL may be due to the greater movement of the muscle and potential lateral shifting of the RF during contraction. In addition, the relatively lower reliability observed for the VL may be attributed to greater subcutaneous tissue thickness which can influence signal quality and electrode placement consistency. Future work should focus on optimizing electrode placement and improving signal acquisition for the vastus lateralis to enhance measurement reliability.

There was poor inter-session reliability for the RF distal electrodes, and lower reliability for the remaining individual RF electrodes relative to the excellent reliability of the total RF. A slight change in the longitudinal placement of the LDmEMG grids on two different test sessions might explain overall reliability being excellent but individual channel reliability being lower. The poor reliability values at the distal end may also be the result of different levels of muscle shifting under the electrodes on two different test days; during isometric exercise, the muscles are shifting under the skin for up to 1 cm during contractions (20). This shifting would be expected to be greatest during maximum contractions. As we placed the array based on the distal border of the muscle, variations in muscle location and muscle shifting during the MVIC likely explain the poor reliability at distal channels.

High reliability of force can be assumed as the primary requirement for reliable sEMG values; reliability of sEMG generally decreases with increased effort (21), caused by greater force instability at higher force levels (22), and geometrical artefacts (20) resulting from the three-dimensional nature of muscle contraction, changing pennation angle, length and thickness/width (23). Our inter-session reliability for MVIC was only good; therefore, this might have changed the structural destruction of the muscles, as well as their excitation levels. Further, relative contribution of VL, VM and RF to overall quadriceps force is changing with increasing force (24, 25). VL and VM are contributing relatively more at higher contraction levels, with VL contributing more than VM to overall force (25). Therefore, VL might be affected by the change in MVIC more than VM, reflecting the lower reliability in the VL compared to the VM.

EMG signals were not normalized in this study because the primary objective was to examine measurement reliability of the 64-channel configuration. Future studies including task- or population-based comparisons should consider normalization to a reference contraction (e.g., %MVIC) to enhance between-subject comparability.

This study has some limitations. First, the sample size was relatively small, which may limit the generalizability of the results. Although the sample size was adequate for preliminary reliability analysis, larger cohorts are needed to confirm these findings across different participant characteristics and activity levels. Second, only healthy asymptomatic individuals were included; therefore, the applicability of this configuration in clinical populations remains unknown. Finally, electrode placement and skin preparation were performed by the same investigator, which, while improving standardization, may underestimate variability of application in clinical and research settings.

The generalizability of the present findings is limited by the participant characteristics. Most participants were male, and the age range was relatively narrow (27–33 years), which restricts the applicability of the results to other age groups and to females. Future studies should include larger and more diverse samples with balanced sex distribution to confirm these findings across broader populations.

Because this was a preliminary study with a small sample size (n=7) and a large number of channels (64 per participant), only ICC values were reported to describe reliability. Calculation of Bland–Altman plots or SEM for each channel was not feasible and will be addressed in future studies with larger samples.

The overall behaviour of the muscle may not be reflected fully with a single site of measurement, commonly used with bipolar sEMG, as the values will depend on the site of observation. Increasing the number of recording electrodes and averaging the sEMG signals has previously been shown to decrease within-subject variability and increase reliability (26, 27). Advancing this approach, our results showed good to excellent intra- and inter-session reliability for most of the LDmEMG channels, although some minor site-specific problems were observed with low reliability. We are planning to address these problems by (i) increasing the VL coverage in medio-lateral direction, and (ii) decreasing the RF longitudinal grid size. Future investigations will also use lower contraction levels to minimize force-related variability.

CONCLUSION AND RECOMMENDATIONS

LDmEMG enables the recording of spatial excitation patterns of quadriceps heads simultaneously. It is a reliable tool to measure quadriceps muscle excitation, although minor improvements are needed for measuring VL and RF. Future work will seek to improve VL and RF reliability with slightly different grid designs and create 2D EMG maps of quadriceps femoris to identify regional excitation differences.

Strengths of the Study

This study provides a significant contribution to the literature by introducing an innovative LDmEMG configuration that captures the structural heterogeneity of the quadriceps, which traditional bipolar EMG often overlooks. The methodological rigor is further enhanced by using ultrasound-guided electrode placement, ensuring that the spatial activation patterns are anatomically accurate and minimizing the risk of signal crosstalk.

Limitations of the Study

The main limitations of this study include the relatively small sample size and the focus on isometric contractions; however, these effects were mitigated by recruiting a homogenous cohort and employing strict normalization and distribution testing.

Author Contributions

B.T.; Investigation, Conceptualization, Data Curation, Formal Analysis, Methodology, Writing - Original Draft, Writing - Review & Editing, Project Administration. **D.M.;** Methodology, Writing - Review & Editing, Supervision. **S.C.M.;** Conceptualization, Formal Analysis, Methodology, Writing - Review & Editing, Supervision, Project Administration. **All authors have read and agreed to the published version of the manuscript.**

Funding

This research received no external funding.

Data Availability

The data that support the findings of this study are available from the corresponding author, [B.T.], upon reasonable request.

Declarations

Ethical Approval and Consent

This study was conducted in accordance with the guidelines set forth in the Declaration of Helsinki, and all procedures involving research participants were approved by the Queen Mary University of London Ethics of Research Committee on 01.10.2018 with protocol number QMREC2014/24/173. Written informed consent was obtained from all participants.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

REFERENCES

1. Watanabe K, Kouzaki M, Moritani T. Regional neuromuscular regulation within human rectus femoris muscle during gait. Journal of Biomechanics. 2014;47(14):3502-8.
2. Sakthibalan S, Twycross-Lewis R, Woledge R, Hao Y, Morrissey D. Low-density, high surface area electromyography of the hamstring muscles during running and kicking. British Journal of Sports Medicine. 2011;45(2):i-e1.
3. Staudenmann D, Kingma I, Daffertshofer A, Stegeman DF, van Dieën JH. Heterogeneity of muscle activation in relation to force direction: A multi-channel surface electromyography study on the triceps surae muscle. Journal of Electromyography and Kinesiology. 2009;19(5):882-95.
4. Zwarts MJ, Stegeman DF. Multichannel surface EMG: Basic aspects and clinical utility. Muscle & Nerve. 2003;28(1):1-17.
5. Gallina A, Ivanova TD, Garland SJ. Regional activation within the vastus medialis in stimulated and voluntary contractions. Journal of Applied Physiology. 2016;121(2):466-74.
6. Vieira TM, Botter A, Minetto MA, Hodson-Tole EF. Spatial variation of compound muscle action potentials across human gastrocnemius medialis. Journal of Neurophysiology. 2015;114(3):1617-27.
7. Farina D, Arendt-Nielsen L, Merletti R, Graven-Nielsen T. Assessment of single motor unit conduction velocity during sustained contractions of the tibialis anterior muscle with advanced spike triggered averaging. Journal of Neuroscience Methods. 2002;115(1):1-12.
8. Hegyi A, Péter A, Finni T, Cronin NJ. Region-dependent hamstrings activity in Nordic hamstring exercise and stiff-leg deadlift defined with high-density electromyography. Scandinavian Journal of Medicine & Science in Sports. 2018;28(3):992-1000.
9. Blazevich AJ, Gill ND, Zhou S. Intra- and intermuscular variation in human quadriceps femoris architecture assessed in vivo. Journal of Anatomy. 2006;209(3):289-310.
10. Farahmand F, Senavongse W, Amis AA. Quantitative study of the quadriceps muscles and trochlear groove geometry related to instability of the patellofemoral joint. Journal of Orthopaedic Research. 1998;16(1):136-43.
11. Martinez-Valdes E, Negro F, Falla D, De Nunzio AM, Farina D. Surface electromyographic amplitude does not identify differences in neural drive to synergistic muscles. Journal of Applied Physiology. 2018;124(4):1071-9.
12. Campenella B, Mattacola CG, Kimura IF. Effect of visual feedback and verbal encouragement on concentric quadriceps and hamstrings peak torque of males and females. Isokinetics and Exercise Science. 2000;8(1):1-6.
13. Koo TK, Li MY. A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research. Journal of Chiropractic Medicine. 2016;15(2):155-63.
14. Cavanaugh MT, Aboodarda SJ, Behm DG. Intrasession and Intersession Reliability of Quadriceps' and Hamstrings' Electromyography During a Standardized Hurdle Jump Test With Single Leg Landing. The Journal of Strength & Conditioning Research. 2017;31(6).
15. Fauth ML, Petushek EJ, Feldmann CR, Hsu BE, Garceau LR, Lutsch BN, et al. Reliability of Surface Electromyography During Maximal Voluntary Isometric Contractions, Jump Landings, and Cutting. The Journal of Strength & Conditioning Research. 2010;24(4).
16. Place N, Maffiuletti NA, Martin A, Lepers R. Assessment of the reliability of central and peripheral fatigue after sustained maximal voluntary contraction of the quadriceps muscle. Muscle & Nerve. 2007;35(4):486-95.
17. Willan PLT, Ransome JA, Mahon M. Variability in human quadriceps muscles: Quantitative study and review of clinical literature. Clinical Anatomy. 2002;15(2):116-28.
18. Finni T, Havu M, Sinha S, Usenius J-P, Cheng S. Mechanical behavior of the quadriceps femoris muscle tendon unit during low-load contractions. Journal of Applied Physiology. 2008;104(5):1320-8.
19. Finni T, Cheng S. Variability in Lateral Positioning of Surface EMG Electrodes. Journal of Applied Biomechanics. 2009;25(4):396-400.
20. Rainoldi A, Nazzaro M, Merletti R, Farina D, Caruso I, Gaudenti S. Geometrical factors in surface EMG of the vastus medialis and lateralis muscles. Journal of Electromyography and Kinesiology. 2000;10(5):327-36.
21. Kellis E, Katis A. Reliability of EMG power-spectrum and amplitude of the semitendinosus and biceps femoris muscles during ramp isometric contractions. Journal of Electromyography and Kinesiology. 2008;18(3):351-8.
22. Newell KM, Carlton LG. On the relationship between peak force and peak force variability in isometric tasks. Journal of Motor Behavior. 1985;17(2):230-41.

23. Roberts TJ, Eng CM, Sleboda DA, Holt NC, Brainerd EL, Stover KK, et al. The Multi-Scale, Three-Dimensional Nature of Skeletal Muscle Contraction. Physiology. 2019;34(6):402-8.

24. Pincivero DM, Coelho AJ. Activation linearity and parallelism of the superficial quadriceps across the isometric intensity spectrum. Muscle & nerve. 2000;23(3):393-8.

25. Zhang LQ, Wang G, Nuber GW, Press JM, Koh JL. In vivo load sharing among the quadriceps components. Journal of Orthopaedic Research. 2003;21(3):565-71.

26. Balshaw TG, Fry A, Maden-Wilkinson TM, Kong PW, Folland JP. Reliability of quadriceps surface electromyography measurements is improved by two vs. single site recordings. European Journal of Applied Physiology. 2017;117(6):1085-94.

27. Kasprisin JE, Grabiner MD. EMG variability during maximum voluntary isometric and anisometric contractions is reduced using spatial averaging. Journal of Electromyography and Kinesiology. 1998;8(1):45-50.