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Examining Neuromuscular Control of the Vastus Medialis Oblique and Vastus Lateralis During Foundational Dance Movements

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Abstract

Elite dancers have higher rates of injury than college athletes; this may, in part, be due to improper alignment during dance movements. Electromyographic (EMG) activity at the vastus lateralis (VL) and vastus medialis oblique (VMO) may be important indicators of abnormal neuromuscular control at the patellofemoral joint in dancers. This study aimed to examine how turnout (maximal hip external rotation) impacts the activation of the VMO and VL during foundational dance movements in dancers. Thirty female collegiate dancers were recruited from intermediate and advanced ballet and modern technique classes. EMG was used to examine the activation of the VMO and VL during maximal isokinetic knee extensions and during demi-pliés and sautés in parallel and turned-out positions. Mean VMO:VL ratio was determined as a percent of the highest repetition of maximal extension. The VMO:VL ratio was significantly lower during parallel sautés (0.921 ±0.258) in comparison to turned-out sautés (1.008 ±0.384; $p=0.033$) and parallel pliés (1.185 ±0.509; $p=0.002$). No relationships were seen between VMO:VL ratio, injury history, and predominant style of dance. These findings suggest that dancers do not properly activate the VMO during jumps in parallel, which may cause improper patellar tracking and potential knee pathologies. Proprioceptive and neuromuscular training of the VMO might be warranted for collegiate dancers.

Introduction

Dancers often have higher rates of injury than college athletes, with 80-97% of professional and collegiate dancers reporting at least one musculoskeletal injury per year.[1-7] This high incidence of injury may be due to the repetitive nature of dance training involving movements which, when performed incorrectly, can lead to the development of chronic injuries over time.[8,9] Concert dance training is often practiced in high volume; in particular, a high volume of jumps are regularly performed, with over 200 jumps occurring in a typical 90-minute dance technique class.[10] Additionally, dance training rarely incorporates any principles of periodization, potentially linked to signs of physiological stress particularly close to performances, putting dancers at risk of overtraining and fatigue.[11,12] As such, improper alignment at the hip, knee, or ankle while performing dance movements is a risk factor for lower extremity injury.[13,14] Examining the potential impact of this malalignment may help to explain the increased risk of injury in dancers.

"Turnout," or maximal hip external rotation, is an essential aspect of ballet and modern dance technique but is frequently performed with improper alignment.[8] Turned-out positions are less stable than parallel positions, in which hip rotation is not present.[15] As maximal turnout is a desirable aspect of classical dance aesthetics, dancers sometimes force a stance that appears more turned-out by coupling their maximal hip external rotation with tibial rotation and ankle pronation, but this forced position is associated with higher risk of both traumatic and overuse injuries.[8,16] One factor that may contribute to malalignment in turned-out positions is improper patellar tracking associated with abnormal neuromuscular control of the vastus medialis oblique (VMO) and vastus lateralis (VL) muscles of the quadriceps, as this may lead to injuries including patellofemoral pain.[17,18] Neuromuscular control involves the integration of neural, physical, and behavioral contributions necessary to produce a desired movement.[19] Little is known about the neuromuscular control of these quadriceps muscles during functional movements in dance.

One previous study demonstrated that the VMO:VL activation ratio, assessed using electromyography (EMG), is lower in individuals experiencing patellofemoral pain (PFP) than in healthy individuals during functional activities.[20] The VMO also shows a delayed activation in comparison to the

VL in individuals with PFP during dynamic movements.[20,21] Since most dance movements develop lateral quadriceps muscles more than medial muscles due to the prevalence of turnout,[22] VL and VMO EMG activity may be important indicators of abnormal neuromuscular control in dancers. As the strength of individual quadriceps muscles cannot be assessed in vivo, EMG can be used to examine the neuromuscular control of individual muscles rather than their strength.[23,24]

Given the paucity of data exploring the neuromuscular activation of the VMO and VL during foundational dance movements, the purpose of this study was to examine how turnout (maximal hip external rotation) impacts the activation of the VMO and VL during foundational dance movements in collegiate dancers. It was hypothesized that dancers would display less activation of the VMO while performing dance movements in turned-out positions.

Methods

Participants for this study were 30 female collegiate dancers currently enrolled in intermediate- or advanced-level ballet or modern dance technique classes. Participants were able to perform all aspects of this study without pain and did not have any hip or knee injuries within the last month, which was defined as any injury that prohibited the dancer from fully participating in their training. This injury definition is based on previous studies,[25,26] the International Performing Arts Injury Reporting System,[27] and various other athletic and occupational injury definitions.[28-32] This definition was also used to obtain injury history data via questionnaire. Additionally, the participants' time-based dance exposure was obtained via questionnaire, where dance exposure was defined as the number of hours per week of "any participation in a class, rehearsal, or performance in which the dancer was exposed to the possibility of a dance injury".[25,26] This study was approved by the college's Institutional Review Board (IRB#1901-789), and all participants provided written informed consent prior to testing.

Experimental Trial

Participants performed a five-minute warm-up on a cycle ergometer at a self-selected pace before the testing trials, which consisted of two phases: a maximal knee extension phase and a foundational dance movement phase. The order of these two phases was counterbalanced (Figure 1). Unlike most dance studios, both phases of testing took place in a lab that did not have mirrors or sprung floors.

Neuromuscular Activation

EMG activity was used to assess the neuromuscular activation of the VL and VMO in both testing phases. A BIOPAC MP36 system was used to monitor surface EMG activity.[33] Prior to testing phases, each participant's skin was abraded with gauze and then cleaned with alcohol. Six EMG electrodes were then applied to the participant's right leg (Figure 2): the VMO and VL each had two electrodes affixed, 20 mm apart, on the muscle belly and parallel to the muscle fibers, at approximately 25% of the total thigh length above the superior border of the patella.[33,34] Two ground electrodes were applied: one just below the right tibial tubercle and one on the right fibular head.[35] All electrodes and wires were secured with surgical tape.[36]

Maximal Knee Extension Phase

During maximal knee extensions, the participants were seated and secured into the chair of a HUMAC NORM Cybex isokinetic dynamometer.[37,38] Each participant performed 3 repetitions of isokinetic concentric knee extensions at an angular velocity of 60°/second to familiarize themselves with the protocol. After a moment of rest, 5 maximal repetitions were performed to obtain maximal EMG activity and peak torque values. Participants received verbal encouragement as well as visual feedback of their force output on the computer monitor to encourage maximal performance;[39] this feedback was provided in a consistent manner across participants. Peak torque (Nm) was recorded and normalized to body weight.

Dance Movement Phase

Two foundational dance steps were examined: pliés and sautés (jumps). To perform a plié, the knees bend in order to lower their torso, then return to the original standing position by straightening the legs while keeping the torso upright and the heels in contact with the floor throughout. Jumps are performed from the bottom of the plié position and land in the same position; in the air, the knees extend and ankles plantar-flex while the torso is kept upright. A metronome was set to 60 bpm to keep time. Participants were instructed to perform pliés by taking two beats to descend and two beats to rise and to perform jumps at one repetition per beat (including rising and descending phases). These are common dance movements, so participants were familiar with the proper execution of these movements prior to testing. Pliés were always performed before jumps, as this follows the progression of a standard dance class.

These two dance steps were each performed in two conditions: a parallel position with no hip rotation (feet placed hip-width apart) and a turned-out position with maximal hip external rotation and heels together (ballet first position). The order of the parallel and turned-out conditions was counterbalanced. Participants performed five consecutive repetitions to familiarize themselves with the proper timing of the movements and then three repetitions of pliés and five repetitions of sautés in each condition, with breaks in between the four different steps, while EMG was continuously recorded. Unlike the maximal knee extension trials, no verbal encouragement was provided during the dance movements as this would not be common practice during dance technique classes.

EMG Analysis

The EMG leads were set up with one channel assigned to each muscle.[33] Data was sampled at a rate of 2.000 kHz with high and low pass filters of 5 and 1000 Hz and gain set at 1000x. EMG data was full-wave rectified and the mean amplitude, in millivolts, was recorded for each repetition in each condition. The maximal contraction with the largest mean value was recorded as the maximal EMG value for each muscle.[20] The mean EMG activity for the three pliés in each condition were assessed for each participant. Only the second, third, and fourth jumps in each condition were included in data analysis to eliminate the effects of initiating or stopping repeated jumps. The mean EMG output in each condition was then converted to percent of maximum and the percentages were used to calculate the VMO:VL ratio, with the maximal VMO:VL set as 1:1. All EMG analysis was completed by a single investigator in order to maintain consistency between movements and participants.

Statistical Analysis

The parallel and turned-out conditions were compared using within-subjects paired t-tests. Independent sample t-tests and Pearson correlations were used to compare or relate EMG data to factors including predominant style of dance studied and injury history. All data was analyzed using IBM SPSS

Statistics 25.0. Significance for all tests was determined at □=0.05. All data is presented in mean ± standard deviation.

Results

Dance Exposure

Participants had a mean time-based dance exposure of 16.4 (±9) hours per week; full participant demographics are displayed in Table 1. Each dancer was classified as focusing predominantly in either Ballet (n=14) or Modern (n=16) technique based on the time spent weekly in technique classes of each style. The groups did not differ in the total number of dance exposure minutes, but each group participated in more minutes of technique class in their respective style than the other group (Figure 3). Seven of the 14 ballet dancers also took modern technique, and two of the 16 modern dancers also took ballet technique.

Injury History

A total of 51 injuries were reported, with 73% occurring in the lower extremity. Nineteen participants (63%) reported experiencing at least one lower extremity injury. Of the participants that reported a lower extremity injury, the average number of injuries of the lower extremity reported was 2 (±0.9). Eight participants did not report injuries from any point in their dance career.

Neuromuscular Activation

During maximal knee extension trials, mean maximal VMO activation was 0.4042 (±0.187) mV, and mean maximal VL activation was 0.5698 (±0.293) mV. There was a moderate correlation between peak torque and EMG amplitude for both VMO ($R=0.470$, $p=0.009$) and VL ($R=0.635$, $p<0.001$). These values resulted in an absolute VMO:VL ratio of 0.771 (±0.338) during the maximal knee extension trials. When the maximum ratio was normalized to 1:1, none of the VMO:VL ratios during the dance protocol, determined as percentages of the maximal values, were significantly different from the absolute maximum ratio ($p>0.05$).

When comparing parallel and turned-out conditions for pliés and sautés, both the VMO and VL were more activated in the turned-out positions (Figure 4). The VMO:VL ratio was significantly greater during turned-out jumps compared to parallel jumps ($p=0.033$), but this difference was not observed during pliés (p=0.358; Figure 5). Furthermore, the VMO:VL ratio was significantly greater in parallel pliés compared to parallel jumps (p=0.002) but this difference did not occur in the turned-out positions (p=0.072; Figure 5).

No differences were present in VMO and VL activation or VMO:VL ratio between the Ballet and Modern groups (Table 2). Furthermore, there were no differences between dancers with and without lower extremity injuries (Table 3), nor correlations with the number of injuries (Table 4).

Discussion

Overall, the VMO and VL both displayed more activation in the turned-out positions during pliés and jumps. Lower levels of VMO activation, relative to VL, were observed during parallel jumps in comparison to parallel pliés and turned-out jumps. These findings contradict the hypothesis that dancers would display less activation of the VMO when performing dance movements in turned-out positions. Additionally, this low VMO activation during parallel jumps indicates that dancers specifically have poor neuromuscular control during this movement. There were no relationships seen between the VMO:VL ratios during fundamental dance movements and injury history, nor with predominant style of dance studied.

The low VMO:VL ratio observed during parallel jumps may indicate a lack of neuromuscular control of the VMO. Participants specifically failed to fully activate the VMO while jumping in a parallel position, which puts them at a higher risk for lower extremity injuries.[13,14] A typical 90-minute dance technique class regularly involves over 200 jumps, more than half of which land unilaterally; this repetitive load can stress the hip, knee, and ankle joints, especially when movements are performed with improper alignment.[10,13] Low VMO:VL ratios can indicate improper patella tracking,[17,18] leading to lower extremity injuries including patellofemoral pain.[20,21,40] A study by Kamenski & Fu reported that the overdevelopment of lateral quadriceps muscles and underdevelopment of medial quadriceps muscles that can occur with dance training are contributing factors to the high rates of knee injuries seen in dancers.[41] While no relationship was observed between VMO or VL activation and injury history in this study, these results are still indicative of malalignment during sauté jumps in a parallel position, a fundamental motor pattern utilized in both ballet and modern dance disciplines. Interestingly, the VMO was more activated during exercises in the turned-out positions, which was unexpected based on previous studies that indicated either no change or a decrease in VMO:VL ratio with hip external rotation.[40,42,43]

The VMO:VL ratio was significantly greater during parallel pliés and turned-out jumps, indicating that greater activation of the VMO during jumps in parallel may be physiologically possible for these dancers. This discrepancy between pliés and jumps may be associated with decreased proprioception in the lower extremity, indicating a need for increased neuromuscular control. The dance movements performed in the current study examined only fundamental dance movements; when multiple dance movements are combined to create the complex movement patterns found in concert dance performance, there is a possibility for even more VMO:VL imbalance to occur due to the increased variability and unpredictability of movement patterns. Focusing on proper VMO activation and strong lower extremity proprioception, specifically in parallel positions and during complex movement patterns, may be appropriate for injury prevention and training in collegiate dancers.

Miller et al. found that external rotation of the hips is associated with a lower VMO:VL ratio during unilateral step-up/step-down and modified wall slide exercises (bending the knees to 75° flexion) in student athletes.[40] This is in contradiction with the data from the present study, possibly due to differences in how dancers and athletes may approach movements due to highly specific aesthetic constraints of dance techniques.[13] Additionally, previous studies that have examined the VMO:VL ratio have utilized isolated and closed-chain movements rather than more complex movements.[40,42,43] Jumps introduce braking ground reaction forces, which may put dancers at a higher risk of injury, especially when landing in unilateral positions.[9,44,45] More information is needed to determine possible imbalances between the VMO and VL during complex movements, specifically within the constraints of dance technique.

Bose et al. reported that the majority of fibers that make up the proximal tendon of the VMO originate from the same tendon as the adductor magnus.[46] This similar origin point may provide one explanation as to why VMO activation was greater during turned-out versus parallel jumps as, with proper dance technique, some hip adduction should occur during the rising phase of jump in a turned-out position.[47]

Furthermore, the VMO:VL ratio has been shown to be higher during a single-legged jump compared to a double-legged jump, indicating that the VMO may play a role in maintaining stability.[48] Massó et al. reported that the soleus shows greater EMG activity when standing in a turned-out position in comparison to a parallel position, indicating that the turned-out position is less stable.[15] Therefore, a dancer may rely on increased VMO activation to maintain adequate stability when jumping in turned-out positions as these are inherently less stable than parallel positions. This may help to explain the discrepancies seen between the data in the current study and previously published literature.[40,42,43]

No differences in VMO:VL ratios were observed when comparing ballet and modern dancers in any testing conditions. In a typical technique class, ballet dancers spend most of the time working in a turned-out position while modern dancers shift between parallel and turned-out positions.[10] Because of this difference in technical training, it is possible that ballet- and modern-focused dancers may develop different strength and endurance abilities in the hip external rotation.[49] However, this difference in technical training did not appear to impact the activation of the VMO and VL during pliés and jumps. There was also no difference in muscle activation between dancers with and without a history of lower extremity injury, nor a correlation between activation and number of injuries. However, injuries were self-reported and therefore information about injury history in these participants comes with a degree of uncertainty. Regardless, the inactivation of the VMO during parallel jumps appears to be a fundamental issue observed in dancers across a variety of concert dance forms, regardless of injury history.

Future Research

Sreekar Kumar Reddy et al. reported increased activation of the VL during isometric contraction with the ankle pronated in comparison to neutral placement with difference was seen in VMO activation.[50] Weight-bearing ankle pronation causes the tibia to rotate internally, increasing the Q-angle of the knee, causing joint laxity and rotary stress that can cause patellofemoral pain.[50] Kinematic variables, such as the degrees of ankle pronation and knee valgus, were not analyzed in this study, but it is plausible that either or both may have occurred during jumping. In particular, the maximal hip external rotation required by the turned-out position can encourage ankle pronation and subsequent knee valgus, especially when dancers force the positioning of their feet beyond their maximal hip external rotation.[8,16] Focusing on proper alignment of the foot, ankle, and knee when landing and pushing off jumps may be a useful tool in improving VMO and VL activation and risk of injury in dancers. Additionally, similar protocols could be used to examine other dance movements, especially more complex jumping sequences, that may be associated with improper neuromuscular control of the VMO and VL and therefore pose a risk of injury.

Limitations

While EMG can be used to analyze neuromuscular control of the VMO and VL, it is not an actual predictor of the force, the balance of forces, or patellar tracking at the knee joint.[23] The muscle cross-sectional area, specific tension, quadriceps geometry and muscle stiffness all contribute to the forces on the patellofemoral joint by these muscles without having an effect on EMG.[23,51-54] In order to limit the influences of these factors, percent of maximum activation was used for analysis (rather than EMG amplitude) to calculate VMO:VL ratio,[20] and analysis between dance steps were performed within-subject. While an imbalance of forces on the patella cannot be directly inferred from the results of EMG analysis, there is currently no method of estimating these forces from individual quadriceps muscles *in vivo*.[23,24] EMG is currently the most appropriate method to estimate this, as a low VMO:VL is associated with improper patella tracking and PFP.[20,21]

Additionally, the lab used for data collection did not have a mirror as most dance studios do and did not have sprung floors. While participants were instructed to perform the dance movements with proper technique, they may not have been as concentrated on achieving proper classical dance aesthetics during their trials as they would in a typical dance class. Therefore, the execution of pliés and jumps that was recorded in this study may have been different from how they are normally performed in class.

Conclusion

The present data suggest that collegiate dancers do not fully activate the VMO during jumps in a parallel position in comparison to turned-out jumps and to pliés in parallel. Additionally, the VL and VMO were both significantly more activated in turned-out positions in comparison to parallel positions. These results appear to be common to both ballet- and modern-focused collegiate dancers and are not correlated with injury history. Focus on proprioceptive and neuromuscular training of the VMO is recommended for collegiate dancers in order to improve activation of the VMO and limit the risk of future injuries. Future studies should continue to examine the relationships between VMO and VL neuromuscular activation, improper alignment, and injury rates in foundational and complex dance movements.

References

1. Davenport KL, Air M, Grierson MJ, Krabak BJ. Examination of static and dynamic core strength and rates of reported dance related injury in collegiate dancers: A cross-sectional study. J Dance Med Sci. 2016;20(4):151-161.
2. Garrick JG, Requa RK. Ballet injuries: an analysis of epidemiology and financial outcome. Am J Sports Med. 1993;21:586-590.
3. Hamilton LH, Hamilton WG, Meltzer JD, Marshall P, Molnar M. Personality, stress, and injuries in professional ballet dancers. Am J Sports Med. 1989;17:263-267.
4. Hincapié CA, Morton EJ, Cassidy JD. Musculoskeletal injuries and pain in dancers: A systematic review. Arch Phys Med Rehabil. 2008;89(9):1819-1829.
5. Jacobs C, Hincapié CA, Cassidy JD. Musculoskeletal injuries and pain in dancers: A systematic review update. J Dance Med Sci. 2012;16:74-84.
6. Shah S, Weiss D. Issues relating to dancers. Arch Phys Med Rehabil. 2004;85:75-78.
7. Shah S, Weiss DS, Burchette RJ. Injuries in professional modern dancers: Incidence, risk factors, and management. J Dance Med Sci. 2012;16(1):17-25.
8. Armstrong R, Relph N. Screening tools as a predictor of injury in dance: Systematic literature review and meta-analysis. Sports Med Open. 2018:4(33).
9. Fietzer A, Chang Y, Kulig K. Dancers with patellar tendinopathy exhibit higher vertical and braking ground reaction forces during landing. J Sports Sci. 2012;30:1157-1163.
10. Liederbach M, Dilgen FE, Rose DJ. Incidence of anterior cruciate ligament injuries among elite ballet and modern dancers: a 5-year prospective study. Am J Sports Med. 2008;36(9):1779-1788.
11. Edmonds R, Wood M, Fehling P, DiPasquale S. The impact of a ballet and modern dance performance on heart rate variability in collegiate dancers. Sports. 2019;7:3.
12. Wyon M. Preparing to perform: Periodization and dance. J Dance Med Sci. 2010:14(2):67-72.
13. Bowerman EA, Whatman C, Harris N, Bradshaw E. A review of the risk factors for lower extremity overuse injuries in young elite female ballet dancers. J Dance Med Sci. 2015;19(2):51-56.

14. Murphy DF, Connolly DAJ, Beynnon BD. Risk factors for lower extremity injury: a review of the literature. Br J Sports Med. 2003;37(1):13-29.
15. Massó N, Germán A, Rey F, Costa LL, Romero D, Guitart S. Study of muscle activity during relevé in first and sixth positions. J Dance Med Sci. 2004;8(4);101-107.
16. Lohr C, Schmidt T. Turnout in classical dance: Is it possible to enhance the external rotation of the lower limb by a myofascial manipulation? A pilot study. J Dance Med Sci. 2017;21(4):168.
17. Chen H, Chien C, Wu S, Liau J, Jan M. Electromechanical delay of the vastus medialis obliquus and vastus lateralis in individuals with patellofemoral pain syndrome. J Orthop Sport Phys. 2012;42(9):791-796.
18. Park K, Chun S, Oh D, Kim S, Chon S. The change in vastus medialis oblique and vastus lateralis electromyographic activity related to shoe heel height during treadmill walking. J Back Musculoskelet. 2010;23:39-44.
19. O'Sullivan SB, Schmitz TJ. *Physical Rehabilitation*, 5th ed. F.A. Davis, Philadelphia, PA, 2007.
20. Kim H, Song CH. Comparison of the VMO/VL EMG ratio and onset timing of VMO relative to VL in subjects with and without patellofemoral pain syndrome. J Phys Ther Sci. 2012;24:1315-1317.
21. Akkurt E, Salli A, Ozerbil OM, Ugurlu H. The effect of isokinetic exercise on symptoms, functional status and EMG activation onset time of the vastus medialis oblique and vastus lateralis in female patients with patellofemoral pain syndrome. Isokinet Exerc Sci. 2010;18:157-161.
22. Sciosia TN, Griffin JR, Fu FH. Knee ligament and meniscal injuries in dancers. J Dance Med Sci. 2001;5(1):11-15.
23. Hug F, Hodges PW, Tucker K. Muscle force cannot be directly inferred from muscle activation: Illustrated by the proposed imbalance of force between the vastus medialis and vastus lateralis in people with patellofemoral pain. J Orthop Sport Phys. 2015;45(5) 360-365.
24. Sczepanski TL, Gross MT, Duncan PW, Chandler JM. Effect of contraction type, angular velocity, and arc of motion on VMO:VL EMG ratio. Journal of Orthop Sport Phys. 1991;14(6):256-262.

25. Liederbach M, Richardson M. The importance of standardized injury reporting in dance. J Dance Med Sci. 2007;11(2):45-48.
26. Liederbach M, Hagins M, Gamboa JM, Welsh TM. Assessing and reporting dancer capacities, risk factors, and injuries: Recommendations from the IADMS standard measures consensus initiative. J Dance Med Sci. 2012;16(4):139-153.
27. Liederbach M. IPAIRS: an injury tracking system for dance. Proceedings of the Annual Conference of the International Association for Dance Medicine and Science, 1995.
28. Alles WF, Powell JW, Buckley W, Hunt EE. The national athletic injury/illness reporting system three-year findings of high school and college football injuries. J Orthop Sport Phys. 1979;1(2):103-108.
29. Caine G, Caine D, Lindner K. *Epidemiology of Sports Injuries*. Champaign, IL: Human Kinetics, 1996.
30. Dick RW. *NCAA Injury Surveillance System*. Overland Park, KS: National Collegiate Athletic Association, 2001.
31. Nordin M, Andersson GBJ, Pope MH. *Musculoskeletal Disorders in the Workplace: Principles and Practice*. St. Louis: Mosby Publishers, 1997.
32. Powell JW, Dompier TP. Analysis of injury rates and treatment patterns for time-loss and non-time-loss injuries among collegiate student athletes. J Athl Training. 2004;39(1):56-70.
33. Ebersole KT, Housch TJ, Johnson GO, Evetovich TK, Smith DB, Perry SR. MMG and EMG responses of the superficial quadriceps femoris muscles. J Electromyogr Kines. 1999;9:219-227.
34. 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. Eur J Appl Physiol. 2017;117:1085-1094.
35. Gilleard W, McConnell J, Parsons D. The effect of patellar taping on the onset of vastus medialis obliquus and vastus lateralis muscle activity in persons with patellofemoral pain. Phys Ther. 1998;78:25-32.

36. Oliveira ASC, Corvino RB, Goncalves M, Caputo F, Dendai BS. Maximal isokinetic peak torque and EMG activity determined by shorter ranges of motion. Hum Mov Sci. 2012;13(2):102-108.

37. Impellizzeri FM, Bizzini M, Rampinini E, Cereda F, Maffiuletti NA. Reliability of isokinetic strength imbalance ratios measured using the Cybex NORM dynamometer. Clin Physiol Funct Imaging. 2008:28(2):113–119.

38. Li RC, Wu Y, Maffulli N, Chan KM, Chan JL. Eccentric and concentric isokinetic knee flexion and extension: a reliability study using the Cybex 6000 dynamometer. Br J Sports Med. 1996;30(2):156–160.

39. Campenella B, Mattacola CG, Kimura IF. Effect of visual feedback and verbal encouragement on concentric quadriceps and hamstrings peak torque of males and females. Isokinet Exerc Sci. 2000;8;1-6.

40. Miller JP, Sedory D, Croce RV. Leg rotation and vastus medialis oblique/vastus lateralis electromyogram activity ratio during closed chain kinetic exercise prescribed for patellofemoral pain. J Athl Training. 1997;32(3):216-220.

41. Kamenski R, Fu F. Dance and the arts. In: Stone DA, Fu FH (eds): *Sports Injuries.* Baltimore, MD: Williams & Wilkins, 1994.

42. Davlin CD, Holocomb WR, Guadagnoli MA. The effect position and electromyographic biofeedback training on the vastus medialis oblique:vastus lateralis ratio. J Athl Training. 1999;34(4):342-349.

43. Roth H, Voorhies J, Bambenek M, Boyd M, Bird M. Quadriceps muscle activity during an isometric contraction with lateral hip rotation. Missouri Journal of Health, Physical Education, Recreation and Dance. 2007;17:101-107.

44. Chockley C. Ground reaction force comparison between jumps landing on the full foot and jumps landing en pointe in ballet dancers. J Dance Med Sci. 2008;12(1):5-8.

45. McPherson AM, Schrader JW, Docherty CL. Ground reaction forces in ballet: Differences resulting from footwear and jump conditions. J Dance Med Sci. 2019;23(1):34-39.

46. Bose K, Kanagasuntheram R, Osman MBH. Vastus medialis oblique: An anatomic and physiologic study. Orthopedics. 1980;3(9):880-883.
47. Trepman E, Gellman RE, Micheli LJ, de Luca CJ. Electromyographic analysis of grande-plié in ballet and modern dancers. Med Sci Sport Exer. 1998;30(12):1708-1720.
48. Toumi H, Poumarat G, Benjamin M, Best T F'Guyer S, Fairclough J. New Insights into the function of the vastus medialis with clinical implications. Med Sci Sport Exer. 2007;39(7):1153-1159.
49. van Merkensteijn GC, Quin EQ. Assessment of compensated turnout characteristics and their relationship to injuries in university level modern dancers. J Dance Med Sci. 2015;19(2):57-62.
50. Sreekar Kumar Reddy R, Siva kumar B, Vamsidhar N, Haribabu G. Electromyographic actiof the vastus medialis oblique and vastus lateralis during maximum voluntary isometrics in different weight bearing positions of the foot. Int J Physiother. 2014;1(3):120-126.
51. Souza RB, Powers CM. Differences in hip kinematics, muscle strength, and muscle activation between subjects with and without patellofemoral pain. J Orthop Sports Phys Ther. 2009;39:12-19.
52. Kan JH, Heemskerk AM, Ding Z, Gregory A, Mencio G, Spindler K, Damon BM. DTI-based muscle fiber tracking of the quadriceps mechanism in lateral patellar dislocation. J Magn Reson Imaging. 2009;29:663-670.
53. Hart HF, Ackland DC, Pandy MG, Crossley KM. Quadriceps volumes are reduced in people with patellofemoral joint osteoarthritis. Osteoarthritis Cartilage. 2012;20:863-868.
54. D'Antona G, Lanfranconi F, Pellegrino MA, Brocca L, Adami R, Rossi R, Moro G, Miotti D, Canepari M, Bottinelli R. Skeletal muscle hypertrophy and structure and function of skeletal muscle fibres in male body builders. J Physiol. 2006;570:611-627.

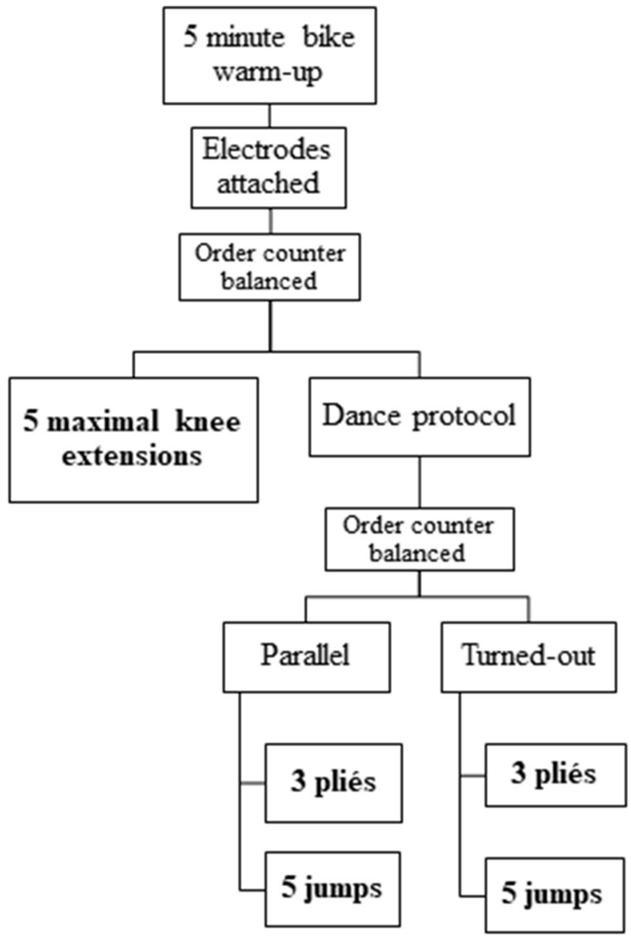

Figure 1: Experimental protocol

Figure 2: Electrode placement

Table 1: Participant demographics (N=30)

	Mean	±SD
Age (years)	20.3	±1.4
Height (cm)	165.0	±5.1
Weight (kg)	58.5	±6.3
BMI (kg/m^2)	21.5	±2.4
Dance exposure (hours/week)	16.4	±9.0
Peak relative torque (Nm/kg)	2.9	±0.5
Number of injuries reported	1.7	±1.2
Number of injuries in college	0.7	±0.8

Table 2: Mean (± standard deviation) VMO:VL ratio between Modern and Ballet dancers

	Modern (n=16)	Ballet (n=14)	p-value
Maximal (absolute)	0.822 ± 0.383	0.713 ± 0.280	0.387
Parallel pliés	1.129 ± 0.523	1.251 ± 0.503	0.519
Turned-out pliés	1.168 ± 0.593	1.123 ± 0.358	0.809
Parallel jumps	0.899 ± 0.292	0.946 ± 0.221	0.625
Turned-out jumps	1.026 ± 0.452	0.988 ± 0.294	0.791

Table 3: Difference in the mean (± standard deviation) VMO:VL ratio between dancers with and without reported lower extremity injury

VMO:VL	Injury history (n=19)	No injuries (n=11)	p-value
Maximal (absolute)	0.799 ± 0.374	0.716 ± 0.259	0.540
Parallel pliés	1.158 ± 0.440	1.241 ± 0.648	0.684
Turned-out pliés	1.145 ± 0.308	1.152 ± 0.757	0.977
Parallel jumps	0.929 ± 0.241	0.904 ± 0.302	0.810
Turned-out jumps	1.024 ± 0.392	0.978 ± 0.375	0.761

Table 4: Pearson correlation between the VMO:VL ratio and number of lower extremity injuries reported

VMO:VL	R-value	p-value
Maximal (absolute)	0.226	0.230
Parallel pliés	0.002	0.993
Turned-out pliés	0.032	0.866
Parallel jumps	0.121	0.524
Turned-out jumps	-0.017	0.930

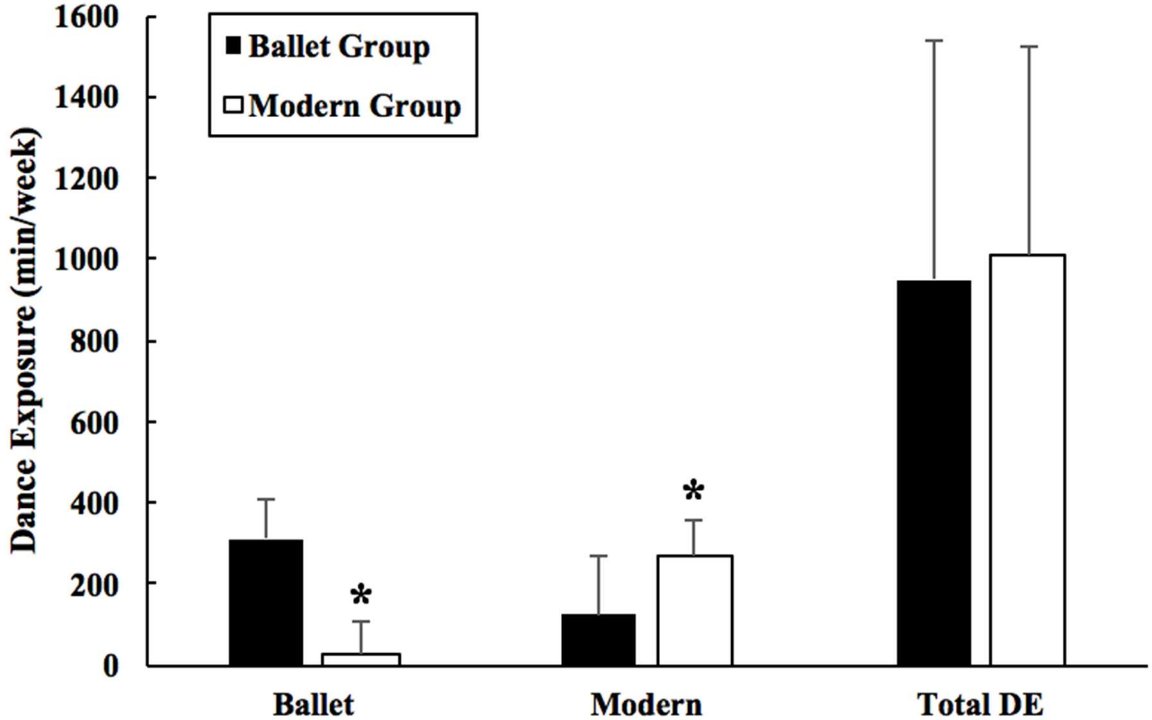

Figure 3: Mean (± standard deviation) minutes spent in ballet and modern technique classes and total dance exposure for Ballet (n=14) and Modern (n=16) groups. Asterisk (*) indicates a significant difference between the Ballet Group and the Modern Group ($p < 0.05$).

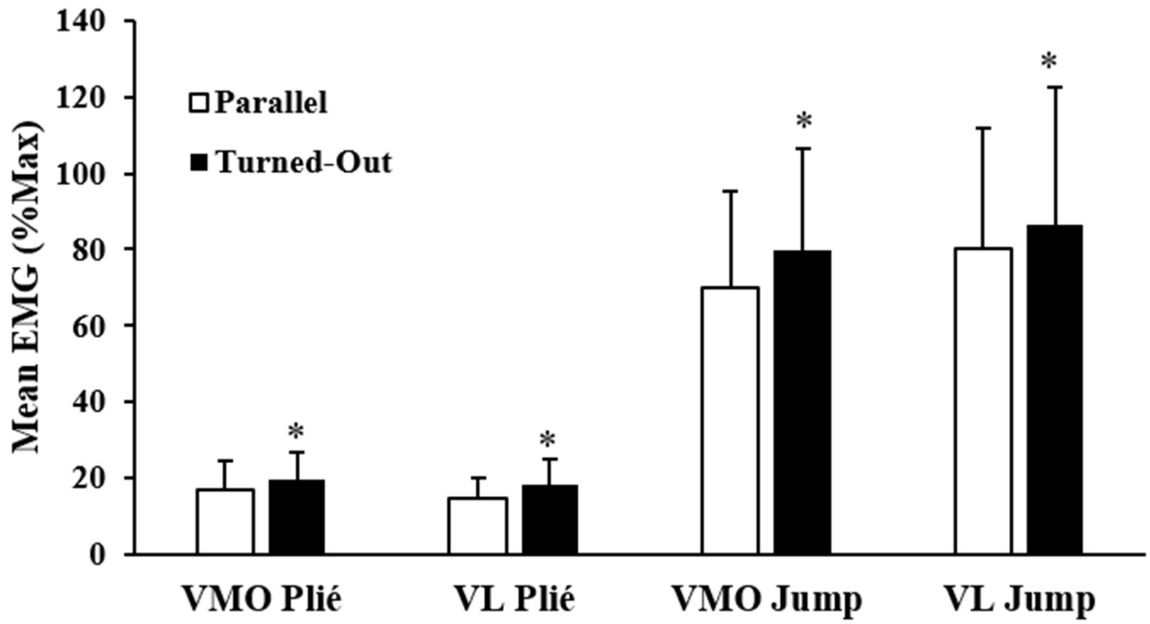

Figure 4: Mean (± standard error) VMO and VL activation during pliés and jumps expressed as a percent of maximal activation amongst female collegiate dancers (N=30). Asterisk (*) indicates increased activation in turned-out position in comparison to parallel ($p<0.05$).

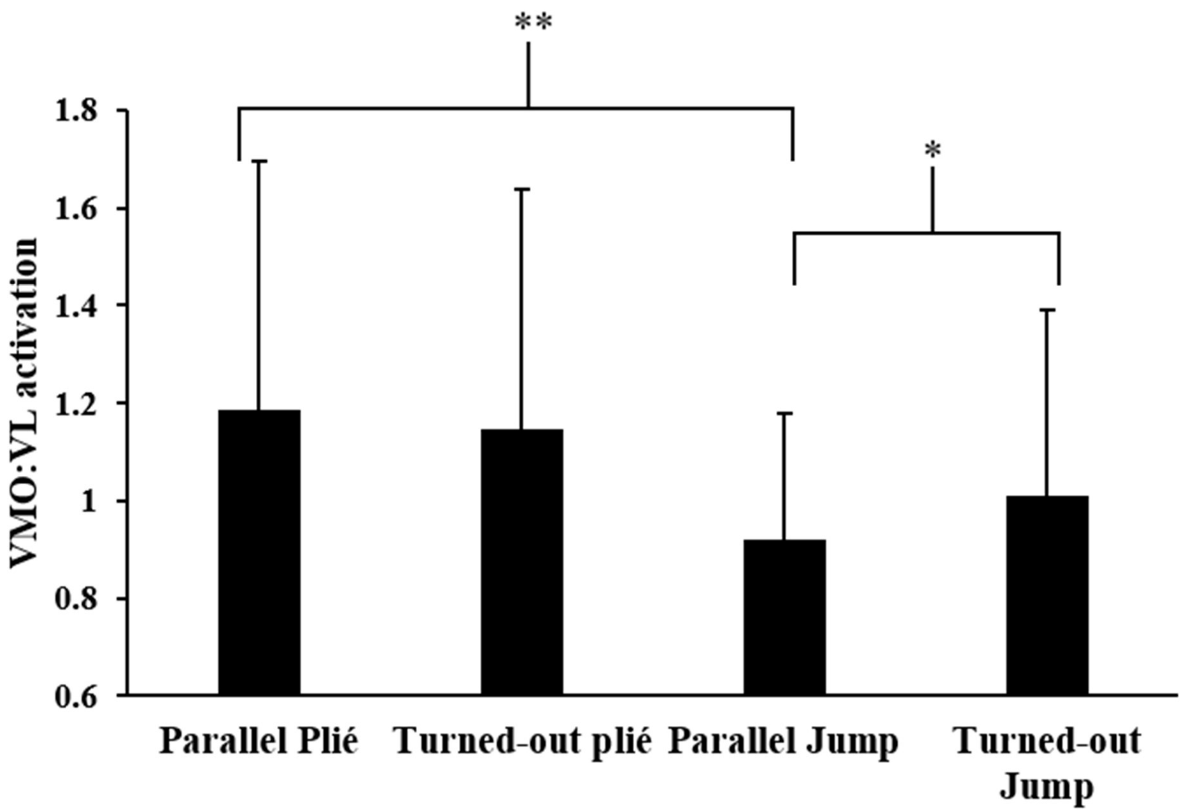

Figure 5: Mean (± standard deviation) VMO:VL ratio during pliés and jumps in parallel and turned-out conditions amongst female collegiate dancers (N=30). Asterisk (*) indicates significantly large ratio during turned-out jumps in comparison to parallel jumps (p=0.033); double asterisk (**) indicates significantly larger ratio in parallel pliés than in parallel jumps (p=0.002)