







Synergism between vastus lateralis and vastus medialis oblique during gait after anterior cruciate ligament reconstruction

Sinergismo entre o vasto lateral e vasto medial oblíquo durante a marcha após a reconstrução do ligamento cruzado anterior

 Gustavo Leporace^{1,2},  Gabriel Gollner Zeitoune^{1,3},  Thiago Vivacqua¹,  Leonardo Metsavaht¹,  Liszt Palmeira de Oliveira⁴,  Luiz Alberto Batista⁵

ABSTRACT

Objective: The aim of this study was to compare vastus lateralis and vastus medialis oblique (VL/VMO) muscle co-contraction (MCC) and activation ratio during gait between healthy subjects - control group (CG), and those with anterior cruciate ligament reconstruction (ACLR). **Methods:** Twenty-three subjects participated in this study, 14 CG and 9 ACLR. The myoelectric activities of the VL and VMO were captured to calculate the MCC. The VL/VMO ratio was obtained by dividing the normalized signals of these two muscles at each point of the curve. The MCC values and the activation ratio in the initial double limb stance, single limb stance, terminal double limb stance and swing were obtained by calculating the arithmetic mean of the intensity values of the common curve in each interval. **Results:** MCC was significantly lower in the ACLR group during the initial double limb stance phase ($p=0.001$), with a high effect size (1.72). No significant differences were found for the other comparisons. **Conclusions:** The results of this study showed that the VL and VMO muscles co-contraction in the initial double limb stance phase of gait was different between the healthy and ACLR individuals. This finding may be related to lower patellofemoral stability during the loading response, increasing the potential risk for the development of injuries in this joint.

Keywords: Electromyography, Anterior Cruciate Ligament, Patellofemoral Pain Syndrome/rehabilitation

RESUMO

Objetivo: O objetivo deste estudo foi comparar a co-contração muscular (CCM) e ativação dos músculos vasto lateral (VL) vasto medial oblíquo (VMB) durante a marcha e uma amostra saudável - grupo controle (GC) e pacientes submetidos a reconstrução do ligamento cruzado anterior (RLCA). **Métodos:** Vinte e três indivíduos participaram neste estudo, 14 GC e 9 RLCA. A atividade mioelétrica do VL e VMO foram captados para cálculo da CCM. A razão VL/VMO foi obtida dividindo o sinal normalizado desses dois músculos em cada ponto da curva. O valor da CCM e a relação de ativação na fase de apoio duplo, fase de apoio simples, fase de apoio terminal e fase de balanço foram obtidas pelo cálculo da média aritmética dos valores de intensidade da curva comum em cada intervalo. **Resultado:** CCM foi significativamente menor no grupo RLCA durante a fase de apoio dupla ($p=0.001$), efeito máximo (1.72). Não foram encontradas diferenças entre as outras comparações. **Conclusão:** O resultado desse estudo mostrou que a contração dos músculos VL e o VMO na fase inicial de apoio duplo da marcha foi diferente entre indivíduos saudáveis e submetidos a RLCA. Este achado pode estar relacionado a diminuição da estabilidade patelofemoral durante a resposta a carga, aumentando o potencial risco de desenvolver lesões nesta articulação.

Palavras-chave: Eletromiografia, Ligamento Cruzado Anterior, Síndrome da Dor Patelofemoral/reabilitação

¹Instituto Brasil de Tecnologias da Saúde – IBTS

²Departamento de Diagnóstico por Imagem, Universidade Federal de São Paulo – UNIFESP

³Programa de Engenharia Biomédica (PEB-COPPE), Universidade Federal do Rio de Janeiro - UFRJ

⁴Laboratório de Artroscopia, Universidade do Estado do Rio de Janeiro – UERJ

⁵Laboratório de Biomecânica e Comportamento Motor (LaBiCoM), Universidade do Estado do Rio de Janeiro – UERJ

Mailing address:

Gustavo Leporace

E-mail: gustavo@biocinetica.com

Submitted: May 18, 2020

Accepted: June 02, 2020

How to cite

Leporace G, Zeitoune GG, Vivacqua T, Metsavaht L, Oliveira LP, Batista LA. Synergism between vastus lateralis and vastus medialis oblique during gait after anterior cruciate ligament reconstruction. 2019;26(4):199-203.

DOI: 10.11606/issn.2317-0190.v26i4a168198



©2019 by Acta Fisiátrica
This work is licensed under a
Creative Commons - Attribution 4.0 International

INTRODUCTION

Anterior cruciate ligament (ACL) injury is among the most common injuries to the knee joint with equally high incidence in recreational and professional athletes.¹ In the United States, approximately 200,000 people sustain ACL injuries per year, of which approximately 50% undergo ligament reconstruction surgery.²

Quadriceps weakness, arthrogenic inhibition and knee osteoarthritis are common complications after ACL reconstruction (ACLR).^{3,4} There is evidence that disturbances in muscle activity manifested during daily activities may be associated with the early degenerative process in the knee.⁵ Decreased quadriceps function has been hypothesized to increase the risk for osteoarthritis and among the most cited changes, the lack of synergy between different heads of the quadriceps has been highlighted.^{5,3} Beyond the potential collaboration with the degenerative process, such changes have been also related to an increased risk of anterior knee pain.⁶

Indeed, the etiology of anterior knee pain is multifactorial. Activation imbalance between the lateral and medial vastus muscles ranks among possible factors⁶ This causal relationship is most likely related to the biomechanical function of these muscles; the vastus medialis oblique (VMO) pulls the patella medially, while the force generated by the vastus lateralis (VL) pulls it laterally.⁷

Fang et al.⁷ found an association of an inadequate activation of the VMO to the patellar malalignment in the initial angles of knee flexion in individuals with PFPs. Sheehan et al.⁸ in a prospective study, induced VMO weakness and evidenced important changes in the patellofemoral kinematics and even subtle changes as lateral inclination of patella have been related to patellofemoral osteoarthritis.^{8,9} The lower limb neuromuscular activation through electromyography (EMG) have been performed under different tasks and intensities in patients with ACL reconstruction.¹⁰

According to Norkin and Levangie,¹¹ muscle co-contraction (MCC) is a phenomenon characterized by the simultaneous contraction of two or more muscles around a joint, which is considered an event of crucial importance in maintaining dynamic joint stability. However, no studies have been performed on the VL-VMO co-contraction and activation ratio during gait.

The role of adequate muscle activity rehabilitation may have been underestimated after ACLR surgery. Despite the non-linear relationship with force production, myoelectric activity studies may be of help identifying such imbalances and provide orthopedic surgeons and physiotherapists valuable information for a more accurate rehabilitation approach.

OBJECTIVE

The objective of this study was to compare the MCC and VL-VMO activation ratio between ACLR and healthy individuals during gait. It was hypothesized that ACLR individuals would present lower co-contraction between these two muscles, but without differences in VL-VMO ratio when compared with healthy individuals.

METHODS

Twenty-three subjects, 14 in the control group (CG) and nine in the ACLR group, with similar anthropometric characteristics participated in this study (Table 1). The inclusion criteria for the CG were scoring over 90% of the maximum in the subjective evaluation questionnaires International Knee Documentation Committee (IKDC) Subjective Knee Form¹² and Lower Extremity Functional Scale¹³ with ages between 20 and 40 years. Subjects with history of neurological and orthopedic injuries or lower limb pain were excluded from the CG.

The inclusion criteria for ACLR group were individuals that underwent unilateral ACL reconstruction due to complete tear evidenced by magnetic resonance images, knee instability identified on clinical examination, and complete discharge from physical

therapy, with ages between 20 and 40 years. Exclusion criteria were history of any neurologic condition or previous relevant injury or surgery to any of the lower limbs. All surgeries were performed by the same surgeon with the single-bundle trans-tibial hamstrings autografts and underwent similar rehabilitation programs.

The mean time from surgery was 11.2 ± 2.4 months (ranging between 8 and 15 months) and all subjects presented complete knee extension-flexion range of motion, at least 85% of contralateral quadriceps force, no clinical signs of knee instability and reported to be able to return to sports participation. This study was approved by the Research Ethics Council and all participants signed an informed consent.

Table 1. Anthropometric data and p values for the comparison between the two groups. Values are reported as the mean (standard deviation)

	CG	ACLR-R	p value
Age (years)	27.3 (2.7)	33.1 (11.1)	0.288
Body mass (kg)	82.1 (9.5)	82.1 (7.4)	0.365
Height (cm)	180.4 (4.4)	182.3 (2.9)	0.771

CG: Control Group; ACLR-R: Anterior cruciate ligament reconstruction group

Subjects walked six times at a self-selected speed along an eight meters walkway. The first three trials were not measured to allow familiarization with the task and instrumentation. The last three trials were collected to determine the myoelectric activity during three gait cycles, using the right lower limb in the CG group and the injured limb in the ACLR group. The walk speed was similar in both of groups.

The myoelectric activity analysis was performed using surface electromyography technique. The signals were captured using Acqknowledge software version 3.5, at a sample rate of 1.8 kHz (TEL 100D, BIOPAC System®, Santa Barbara, USA) with a bipolar differential amplifier (input impedance = 2 MΩ, Common Mode Rejection Ratio > 110 db, gain = 1000), and they were converted from analog to digital (12 bit, MP100WSW, BIOPAC Systems®).

Ag/AgCl electrodes (Kobme, Protect Bio®, Korea) were positioned on the VMO and VL according to Cram et al.¹⁴ they describe VMO electrodes fixation three cm medial to the upper border of the patella at an oblique angle, and VL electrodes position five cm from the lateral border of the patella at an oblique angle. The electrodes were positioned with an inter-electrode distance of two cm, parallel to the muscle fibers. The reference electrode was positioned on the spinous process of the seventh cervical vertebra.

Before application of the electrodes, the skin was prepared by shaving the area and cleansing it with alcohol to reduce surface impedance. To prevent movement artifacts, all electrodes cables were fixed to the skin using adhesive tape (3M Ltda, Brazil). The raw EMG signals from the first three successful collected cycles of each muscle were filtered by a 2nd order Butterworth filter (20 Hz to 400 Hz); the filter was applied in the direct and reverse directions to avoid phase distortions and then full wave rectified and filtered again by a low-pass 2nd order recursive Butterworth filter with cut-off frequency of 12 Hz.

The magnitude of the signals was normalized by the arithmetic mean of the three highest EMG peaks for each muscle found in the processed cycles. To determine the time interval of each gait cycle, a footswitch was positioned on the heel area and another under the first metatarsal head only of the analyzed limb (FootPress, LaBiCOM®). At the time of data collection there were only two footswitches available at the laboratory.

On contact to the ground the circuit generated an electrical signal for each area of the foot that was captured by a BIOPAC (UMI 100B, BIOPAC Systems®) synchronized to the EMG signal and pointing the exact moment the heel and the toe touched the ground. The footswitches allowed identification of the stance and swing phases of the limb (Figure 1). The stance subphases (initial double limb stance [IDLs], single limb stance [SLS], terminal double limb stance [TDLS]) were defined according to the recommendations of Perry and

Burnfield¹ and already used by Favre et al.¹⁵ The IDLS, SLS and TDLS were defined as the time elapsed between the initial 17%, 17% and 83%, and 83% and 100% of the stance phase, respectively.

The MCC was determined by the value of the common area between the VMO and VL normalized EMG curves of each gait cycle. The intersection area between these curves represents the intensity of simultaneous muscle activation, referred to as the MCC of muscles tested.¹⁰ The curve resulting from this process allows an average intensity value of the MCC developed during a certain period to be obtained. The MCC average values were obtained by calculating the arithmetic mean of the intensity values of the common curve for each gait phase as described above.

The VL/VMO activation ratio was obtained by dividing each point of the normalized activation curve of the vastus lateralis by those of the vastus medialis oblique and calculating the arithmetic mean in each gait phase. All data were processed using Matlab 7.04 (The Mathworks, USA).

Demographic data, MCC and VL-VMO ratio in each gait phase were compared between the two groups using a Mann-Whitney test. The effect size was calculated for all variables according to Cohen.¹⁶ Values greater than 0.8 were considered high, and those below 0.5 were considered low.¹⁶ The level of significance was set at $\alpha = 0.05$. To test the reliability of the MCC signals and VL/VMO ratio in both groups in each gait cycle phase over the three collected cycles, the intraclass correlation coefficient (ICC type 2,1) was used. The GraphPad Prism software was used for statistical analyses.

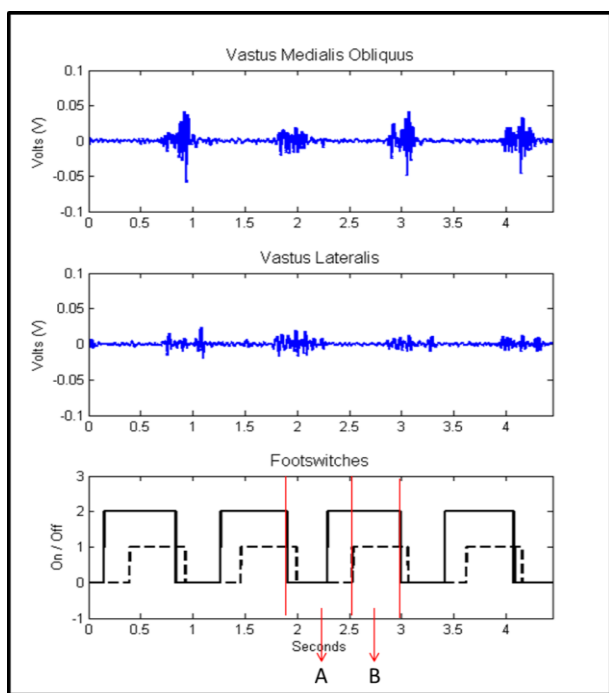


Figure 1. Data collection example, with the raw signals of the muscles collected in the two top lines and the footswitch signals collected in the bottom line (0 = ground contact, 1 = no forefoot contact with the ground, 2 = no heel contact with the ground). A: Stance Phase B: Swing Phase. On the bottom, the solid line represents the heel, and the dotted line represents the forefoot

RESULTS

The reliability of the MCC and VL-VMO ratio was considered moderate to high. All values were above ranged from 0.60-0.93, and the majority was above 0.80 (Table 2). Regarding the MCC, a significant higher value for the control group was found in the initial double limb stance phase (IDLS) ($p = 0.001$), with a high effect size (1.01) (Table 3).

No significant differences were found in the MCC in other analyzed gait cycle phases ($p > 0.05$) (Table 3). For the VL/VMO ratio, no differences were found in any of the gait phases (Table 4).

Table 2. Intraclass correlation coefficient (ICC) for the dependent variables in the study. Values are expressed as the mean (95% IC)

Gait Phases	Muscle co-contraction (%)		VL/VMO ratio	
	CG	ACL-R	CG	ACL-R
IDLS	0.842 (0.757 – 0.935)	0.660 (0.074 – 0.912)	0.630 (0.067 – 0.873)	0.722 (0.135 – 0.932)
SLS	0.906 (0.768 – 0.967)	0.753 (0.298 – 0.937)	0.951 (0.882 – 0.983)	0.745 (0.205 – 0.938)
TDLS	0.762 (0.435 – 0.916)	0.881 (0.634 – 0.971)	0.765 (0.434 – 0.918)	0.638 (0.395 – 0.913)
Swing	0.882 (0.714 – 0.959)	0.873 (0.606 – 0.969)	0.868 (0.674 – 0.954)	0.903 (0.709 – 0.976)

IDLS: Initial Double Limb Stance; SLS: Single Limb Stance; TDLS: Terminal Double Limb Stance; VL: Vastus Lateralis; VMO: Vastus medialis oblique; CG: Control Group; ACL-R: Anterior cruciate ligament reconstruction group.

Table 3. Co-contraction between the VL and VMO [mean (standard deviation)], p value and effect size for each gait cycle phase

Gait Phases	Muscle co-contraction		p value	Effect size
	CG	ACL-R		
IDLS	0.399 (0.112)	0.302 (0.073)	0.040	1.01
SLS	0.084 (0.045)	0.102 (0.029)	0.284	0.48
TDLS	0.045 (0.028)	0.041 (0.020)	0.976	0.18
Swing	0.067 (0.026)	0.074 (0.024)	0.520	0.27

IDLS: Initial Double Limb Stance; SLS: Single Limb Stance; TDLS: Terminal Double Limb Stance; VL: Vastus Lateralis; VMO: Vastus medialis oblique; CG: Control Group; ACL-R: Anterior cruciate ligament reconstruction group.

Table 4. VL/VMO ratio [mean (standard deviation)], p value and effect size for each gait cycle phase

Gait Phases	VL/VMO activation ratio		p value	Effect Size
	CG	ACL-R		
IDLS	1.28 (0.26)	1.34 (0.52)	0.508	0.15
SLS	1.99 (1.25)	1.92 (0.95)	0.825	0.06
TDLS	1.86 (1.11)	1.82 (1.32)	0.875	0.03
Swing	1.80 (0.84)	1.81 (1.10)	0.549	0.01

IDLS: Initial Double Limb Stance; SLS: Single Limb Stance; TDLS: Terminal Double Limb Stance; VL: Vastus Lateralis; VMO: Vastus medialis oblique; CG: Control Group; ACL-R: Anterior cruciate ligament reconstruction group.

DISCUSSION

The objective of this study was to compare the MCC and the VL-VMO activation ratio between ACLR and healthy subjects during gait. The study of the MCC allowed the identification of simultaneous VMO and VL contraction over time, while the muscular ratio enabled the measurement of the activation rate of one muscle in relation to another.

In the present study, a lower MCC was found in ACLR subjects during the initial double limb stance phase, but not in other gait phases. These differences only in the loading response phase can be explained by the fact that the primary function of the quadriceps muscle in gait is to absorb mechanical loads during the eccentric control of knee flexion.² According to the literature, decreased quadriceps function is strongly related to degenerative changes on the knee joint after several years and increased risk for anterior knee pain.¹⁷

It is known that a coordinated muscle contraction around a joint is needed for the maintenance of dynamic joint stability.¹⁸ In the specific case of the patellofemoral joint, the muscular co-contraction and activation ratio between different portions of the quadriceps are responsible for physiological alignment of the patella in the trochlear groove during knee extension and the forces acting on this joint.¹⁹

However, the use of electromyography techniques do not allow the comparison of force production between these two muscles, but the ability to active muscles concomitantly during each gait phase.

This lower MCC between the VL and VMO found in the ACLR group could contribute for imbalance forces in coronal plane during the initial double limb stance phase of gait, what can contribute to increased patellofemoral overload.⁶⁻⁸ It has been proposed that ACL-R may lead to increased patellofemoral osteoarthritis ten years after surgery^{20,21} and knee function and activation may be one of the risk factors.²⁰

Hiemstra et al.²² found a deficiency of approximately 25% in the force generated by the quadriceps three years after surgery. Despite the nonlinear relationship between EMG and force production in dynamic activities, evidence suggests that lower myoelectric activity is related to a reduced muscle force generation qualitatively.²³

Regarding the VL-VMO ratio, no significant differences were found in any of the gait cycle phases, in accordance to the experimental hypothesis. These results show that the activation ratio between the dynamics patellar stabilizers in the frontal plane is normalized, at approximately 1.2:1 in initial double stance and 1.8:1 in the other phases after ACL reconstruction. This result agrees to previous studies that found a general inadequate function of quadriceps, without isolated inactivation or atrophy of VMO.²⁴

Although the four heads of the quadriceps have synergic function for knee extension, regarding active stabilization in the frontal plane and considering the horizontal components of muscular strength, the VL and VMO have antagonistic actions. The VL applies a horizontal component of force on the patella in the lateral direction, while the VMO applies a horizontal component of force in the medial direction.

Thus, in the phase of gait that the four heads of quadriceps have functional synergy, the relationship between VMO and VL is 1:1, consistent with the recommendations by Powers.²⁵

On single limb stance, terminal double limb stance and swing phase, the activation of the VL is almost twice the activation observed in the VMO in the ACLR group. However, the MCC is very low and the expected patellar instability in the dynamic frontal plane does not happen²⁶ (Table 3).

Patients were not analyzed before surgery, so we cannot infer if the MCC alterations were related to the surgical procedure or the primary lesion to the ACL, as well as the relationship with the results of MCC and the PFPS was not available.

The sample was only of male individuals, but that happened by chance and not by the selection process. Lastly, a small sample size should be noted.

A wide range of effect size was observed in the current investigation. A larger sample size would reduce a chance of Type I error. Therefore, the results from the current investigation should be interpreted with caution. For future studies it would be recommended monitoring of the dynamic joint stability during the rehabilitation process and on long-term follow-up, through similar variables used in this study.

CONCLUSION

The results of this study showed that one-year after surgery the VL and VMO muscles co-contraction in the initial double limb stance phase of gait was reduced in ACLR individuals compared to healthy subjects and this may affect patellar dynamics, increasing the risk of patellofemoral dysfunction.

Conflict of interest

There are no conflicts of interest.

REFERENCES

- Perry J, Burnfield JM. Gait analysis: normal and pathological function. 2nd ed. New Jersey: SLACK Incorporated; 2010.
- Wilk KE, Macrina LC, Cain EL, Dugas JR, Andrews JR. Recent advances in the rehabilitation of anterior cruciate ligament injuries. *J Orthop Sports Phys Ther.* 2012;42(3):153-71. Doi: <https://www.jospt.org/doi/10.2519/jospt.2012.3741>
- Hubley-Kozey CL, Deluzio KJ, Landry SC, McNutt JS, Stanish WD. Neuromuscular alterations during walking in persons with moderate knee osteoarthritis. *J Electromyogr Kinesiol.* 2006;16(4):365-78. Doi: <https://doi.org/10.1016/j.jelekin.2005.07.014>
- Cinque ME, Dornan GJ, Chahla J, Moatshe G, LaPrade RF. High rates of osteoarthritis develop after anterior cruciate ligament surgery: an analysis of 4108 patients. *Am J Sports Med.* 2018;46(8):2011-9. Doi: <https://doi.org/10.1177%2F0363546517730072>
- Palmieri-Smith RM, Thomas AC. A neuromuscular mechanism of posttraumatic osteoarthritis associated with ACL injury. *Exerc Sport Sci Rev.* 2009;37(3):147-53. Doi: [10.1097/JES.0b013e3181aa6669](https://doi.org/10.1097/JES.0b013e3181aa6669)
- Petersen W, Ellermann A, Gösele-Koppenburg A, Best R, Rembitzki IV, Brüggemann GP, et al. Patellofemoral pain syndrome. *Knee Surg Sports Traumatol Arthrosc.* 2014;22(10):2264-74. Doi: <https://doi.org/10.2147/OAJSM.S133406>
- Lin F, Wang G, Koh JL, Hendrix RW, Zhang LQ. In vivo and noninvasive three-dimensional patellar tracking induced by individual heads of quadriceps. *Med Sci Sports Exerc.* 2004;36(1):93-101. Doi: <https://doi.org/10.1249/01.MSS.0000106260.45656.CC>
- Sheehan FT, Borotikar BS, Behnman AJ, Alter KE. Alterations in vivo knee joint kinematics following a femoral nerve branch block of the vastus medialis: Implications for patellofemoral pain syndrome. *Clin Biomech.* 2012;27(6):525-31. Doi: <https://doi.org/10.1016/j.clinbiomech.2011.12.012>
- Saper MG, Shneider DA. Diagnosis and treatment of lateral patellar compression syndrome. *Arthrosc Tech.* 2014;3(5): e633-e638. DOI: <https://dx.doi.org/10.1016%2Fj.eats.2014.07.004>
- Lustosa LP, Ocarino JM, Andrade MA, Pertence AE, Bittencourt NF, Fonseca ST, et al. Muscle co-contraction after anterior cruciate ligament reconstruction: Influence of functional level. *J Electromyogr Kinesiol.* 2011;21(6):1050-5. Doi: <https://doi.org/10.1016/j.jelekin.2011.09.001>
- Norkin CC, Levangie PK. Joint structure and function: a comprehensive analysis. Philadelphia: F.A. Davis; 2011.
- Metsavaht L, Leporace G, Riberto M, Mello Sposito MM, Batista LA. Translation and cross-cultural adaptation of the Brazilian version of the International Knee Documentation Committee Subjective Knee Form: validity and reproducibility. *Am J Sports Med.* 2010;38(9):1894-9. Doi: <https://doi.org/10.1177%2F0363546510365314>
- Metsavaht L, Leporace G, Riberto M, Sposito MM, Del Castillo L, Oliveira LP, et al. Translation and Cross Cultural Adaptation of the Lower Extremity Functional Scale into a Brazilian version and validation to patients with knee injuries. *J Orthop Sports Phys Ther.* 2012;42(11):932-9. Doi: <https://www.jospt.org/doi/10.2519/jospt.2012.4101>
- Cram J, Kasman G, Holtz J. Part III Atlas for electrode placement. In: Criswell E. Cram's introduction to surface electromyography. 2nd ed. London: Jones and Bartlett; 2011. p.365-7.
- Favre F, Hayoz M, Erhart-Hledik JC, Andriacchi TP. A neural network model to predict knee adduction moment during walking based on ground reaction force and anthropometric measurements. *J Biomech.* 2012;45(4):692-8. Doi: <https://www.doi.org/10.1016/j.jbiomech.2011.11.057>
- Cohen J. Statistical power analysis for the behavioral sciences. 2nd ed. Hillsdale: Lawrence Erlbaum Associates; 1988.

17. Ithurburn MP, Paterno MV, Thomas S, Pennell ML, Evans KD, Magnussen, RA, et al. Clinical measures associated with knee function over two years in young athletes after ACL reconstruction. *Knee*. 2019;26(2):355-3. Doi: <https://doi.org/10.1016/j.knee.2019.01.011>
18. Wong YM. Recording the vastii muscle onset timing as a diagnostic parameter for patellofemoral pain syndrome: Fact or fad? *Phys Ther Sport*. 2009;10(2):71-4. Doi: <https://doi.org/10.1016/j.ptsp.2009.02.001>
19. Elliott CC, Diduch DR. Biomechanics of patellofemoral instability. *Oper Tech Sports Med*. 2001;9(3):112-21. Doi: <https://doi.org/10.1053/otsm.2001.25157>
20. Scanlan SF, Chaudhari AMW, Dyrby CO, Andriacchi TP. Differences in tibial rotation during walking in ACL reconstructed and healthy contralateral knees. *J Biomech*. 2010;43(9):1817-22. Doi: <https://doi.org/10.1016/j.jbiomech.2010.02.010>
21. Culvenor AG, Øiestad BE, Holm I, Gunderson RB, Crossley KM, Risberg MA. Anterior knee pain following anterior cruciate ligament reconstruction does not increase the risk of patellofemoral osteoarthritis at 15-and 20-year follow-ups. 2017;25(1):30-3. Doi: <http://dx.doi.org/10.1016/j.joca.2016.09.012>
22. Hiemstra LA, Webber S, MacDonald PB, Kriellaars DJ. Contralateral limb strength deficits after anterior cruciate ligament reconstruction using a hamstring tendon graft. *Clin Biomech*. 2007;22(5):543-50. Doi: <https://doi.org/10.1016/j.clinbiomech.2007.01.009>
23. Disselhorst-Klug C, Schmitz-Rode T, Rau G. Surface electromyography and muscle force: limits in sEMG-force relationship and new approaches for applications. *Clin Biomech*. 2009;24(3):225-35. Doi: <https://doi.org/10.1016/j.clinbiomech.2008.08.003>
24. Giles LS, Webster KE, McClelland JA, Cook J. Atrophy of the quadriceps is not isolated to the vastus medialis oblique in individuals with patellofemoral pain. *J Orthop Sports Phys Ther*. 2015;45(8):613-9. Doi: <https://www.jospt.org/doi/10.2519/jospt.2015.5852>
25. Powers CM. Patellar kinematics, part I: the influence of vastus muscle activity in subjects with and without patellofemoral pain. *Phys Ther*. 2000;80(10):956-64. Doi: <https://doi.org/10.1093/ptj/80.10.956>
26. Santos GM, Say KG, Pulzato F, Oliveira AS, Bevilacqua-Grossi D, Monteiro-Pedro V. Integrated electromyographic ratio of the vastus medialis oblique and vastus lateralis longus muscles in gait in subjects with and without patellofemoral pain syndrome. *Br J Sports Med*. 2007;13(1):17-21. Doi: <https://doi.org/10.1590/S1517-86922007000100005>