Accepted Article

J Musculoskelet Neuronal Interact 2024

Journal of Musculoskeletal and Neuronal Interactions JMNI

Original Article

Ischemic Preconditioning Improves Hip Abductor Strength and Power in Patients with Symptomatic Knee Osteoarthritis

Shraddha Sudhir[1], Kharma C. Foucher[2], Pim Jetanalin[3], Lindsay Slater Hannigan[1]

[1]Department of Physical Therapy, University of Illinois at Chicago, Chicago, Illinois, United States;
[2]Department of Kinesiology and Nutrition, University of Illinois at Chicago, Chicago, Illinois, United States;
[3]Department of Rheumatology, University of Illinois at Chicago, Chicago, Illinois, United States

Abstract

Objective: To investigate the effect of ischemic preconditioning (IC) on bilateral hip abductor strength, fatigue, and power in patients with knee osteoarthritis (KOA). **Methods**: Participants (n=10) with KOA completed isokinetic and isometric hip abductor assessments on a Biodex dynamometer both before and after IC. IC was administered during a single session and consisted of 5 minutes of inflation (225mmHg) followed by 5 minutes of reperfusion for 50 minutes. Changes in strength and endurance measures before and after IC were compared using paired t-tests and magnitude of significant differences were reported using Cohen's *d* effect sizes. **Results**: Isokinetic hip abductor peak torque (d=.42, p=.027) and average power (d=.57, p=.029) in the involved limb, and isokinetic peak torque (d=.37, p=.044) in the uninvolved limb increased significantly after IC compared to baseline. There were no changes in isokinetic average power in the uninvolved limb, or isometric peak torque and fatigue index in both limbs after IC (p=.13-.77). **Conclusions**: A single session of IC improved hip abductor strength in both limbs and power in the involved limb in KOA patients. IC should continue to be investigated as a safe and clinically convenient intervention that can supplement traditional modalities to improve muscle function in KOA.

Keywords: Blood Flow Restriction, Function, Knee Pain, Muscle

Introduction

Knee osteoarthritis (KOA) is one of the most common joint disorders in the world and has a prevalence of about 14-45%[1-3]. KOA causes morphological changes and presents with pain as a primary symptom that affects activities of daily living and quality of life[4]. Exercise therapy, especially through prescribed walking, is one of the most cost-effective treatment options for KOA[5-8]. However, changes in gait mechanics and compensatory behaviors including increased trunk lean in individuals with KOA[9] may, directly or indirectly, impair their ability to engage in exercise. In fact, research has demonstrated that greater fatigability, which may be linked to energetically costly gait compensations like trunk lean, as well as certain gait alterations are associated with lower levels of physical activity in people with KOA[10,11].

Changes in gait mechanics, and in turn, decreases in physical activity, may also be related to decreased muscle strength. In addition to decreased knee flexor and extensor strength, which is linked to reduced physical activity[12], individuals with KOA have hip abductor weakness[13,14]. Hip abductor weakness is associated with KOA disease severity and progression[15], presumably through its effect on medial compartment knee joint loading. Therefore, hip abductor strengthening and walking is often prescribed as a treatment option in KOA aiming to improve pelvic control, functional outcomes, and pain[16,17].

Although improved hip abductor strength in those with KOA improves function and pain[18,19], exercise interventions have a high dropout rate due to common barriers, such as

The authors have no conflict of interest.

Corresponding author: Shraddha Sudhir, Department of Physical Therapy, University of Illinois at Chicago, Chicago, Illinois, United States. 1640 W Roosevelt Rd, DHSP 307, Chicago, IL 60607
E-mail: ssudhi5@uic.edu

Edited by: G. Lyritis
Accepted 1 July 2024

time and economic constraints[20,21]. Home exercise programs, although lacking the constraints of other exercise programs, still need to address compliance issues in this population[6,21]. There is a need for more effective and clinically convenient interventions that improve functional outcomes with minimal pain. Ischemic preconditioning (IC), which exposes the limb to brief periods of ischemia followed by reperfusion in repeated cycles[22,23], has the potential to improve outcomes alone or in conjunction with other interventions. In stroke patients, IC has been shown to improve muscle hypertrophy and strength with both local and systemic benefits[24,25]. IC may therefore also benefit people with KOA who exhibit significant strength deficits. Thus, the purpose of this study was to investigate the effect of a single session of IC on bilateral hip abductor strength and endurance in participants with symptomatic KOA. We hypothesized that hip abductor strength, endurance, and power would increase after a single session of IC in both the involved and uninvolved limbs.

Table 1. Participant demographic and clinical characteristics at baseline (N = 10).

Demographic Variable	Mean ± Standard Deviation
Age (years)	68.70 ± 5.89
Sex (female), n (%)	4 (40%)
Height (m)	1.70 ± 0.10
Body Mass (kg)	84.40 ± 15.05
Body Mass Index (kg/m²)	28.93 ± 4.24
Affected/Involved Knee (right), n (%)	7 (70%)
KOOS – Symptoms	69.11 ± 17.46
KOOS – Pain	63.06 ± 12.43
KOOS – ADL	68.75 ± 16.84
KOOS – Sports/Recreation	36.50 ± 20.15
KOOS – QOL	48.13 ± 20.42

Abbreviations: m, meters; kg, kilograms; ADL, activities of daily living; QOL, quality of life.

Methods

Participants

An *a priori* power analysis, using data from a prior study, showed that ten participants were sufficient to identify strength differences of 12.8±10.3Nm from a pilot study with a large effect size (d > 0.70), with alpha level set at .05 and 90% power[26]. Thus ten individuals (Table 1) were recruited from the community and a rheumatology practice, and had a diagnosis of KOA with radiographic confirmation. Individuals with a history of knee surgery, intraarticular corticosteroid injection within 6 months, inability to walk without assistive devices, and any other neurological or muscular conditions affecting lower limb function were excluded from the study. In cases where participants had KOA in both knees, the involved limb was determined based on the knee with more severe symptoms. Before participating, all participants provided written informed consent approved by the university's institutional review board for biomedical sciences and participants' rights were protected.

Procedure

Participants reported to the laboratory for a single session, wearing athletic clothing and shoes. Following providing written informed consent, participants completed a health history questionnaire, self-reported pain assessment using a visual analog scale (VAS) for both knees, and the knee osteoarthritis outcome score (KOOS) questionnaire[27,28]. After finishing the questionnaires, participants underwent a baseline assessment of concentric isokinetic and isometric hip strength and endurance using the Biodex System 4 Pro Dynamometer (Biodex Medical Systems Inc, Shirley, NY). Hip abduction was performed standing because it is the most appropriate physiological and functional position to compare to everyday activities and has good test-retest reliability[29-31]. Participants stood in a neutral position with the center of the dynamometer axis aligned with the anterior superior iliac spine (ASIS) of the side being tested[15,19]. Prior to testing, participants were allowed a brief warmup to familiarize themselves with the testing procedures. Subsequently, participants performed five repetitions of isokinetic hip abduction and adduction at 60 degrees/second with range of motion set from approximately 0 degrees to 30 degrees of hip abduction[19,32]. Verbal encouragement was provided throughout the repetitions.

Participants then completed isometric hip abductor strength and endurance testing while standing with their leg positioned and secured at 15 degrees of hip abduction[19,32]. Participants were instructed to maximally abduct the hip and sustain the isometric contraction for 30 seconds. Verbal encouragement was given only during the first five seconds of the isometric hold. Both isokinetic and isometric strength and endurance testing were completed on the involved limb first to allow for participants to adjust to the weight-bearing nature of the test, followed by assessments on the contralateral limb (uninvolved limb).

Following baseline hip abductor strength and endurance assessments, IC was administered on the involved leg in accordance with other studies that have used IC as an intervention[24,33]. IC was administered by the same member of the research team in a laboratory setting. A rapid inflation cuff (Hokanson SC12D cuff) was placed on the involved thigh while the patients were supine. The cuff was inflated to 225 mmHg for 5 minutes and then released for a 5-minute recovery period to allow for reperfusion. The cycle of inflation and reperfusion was repeated 5 times, for a total of 50 minutes[24]. Upon completion of IC, participants repeated the isokinetic and isometric standing hip abduction assessments of strength and endurance on the instrumented dynamometer, using the same protocols as previously described.

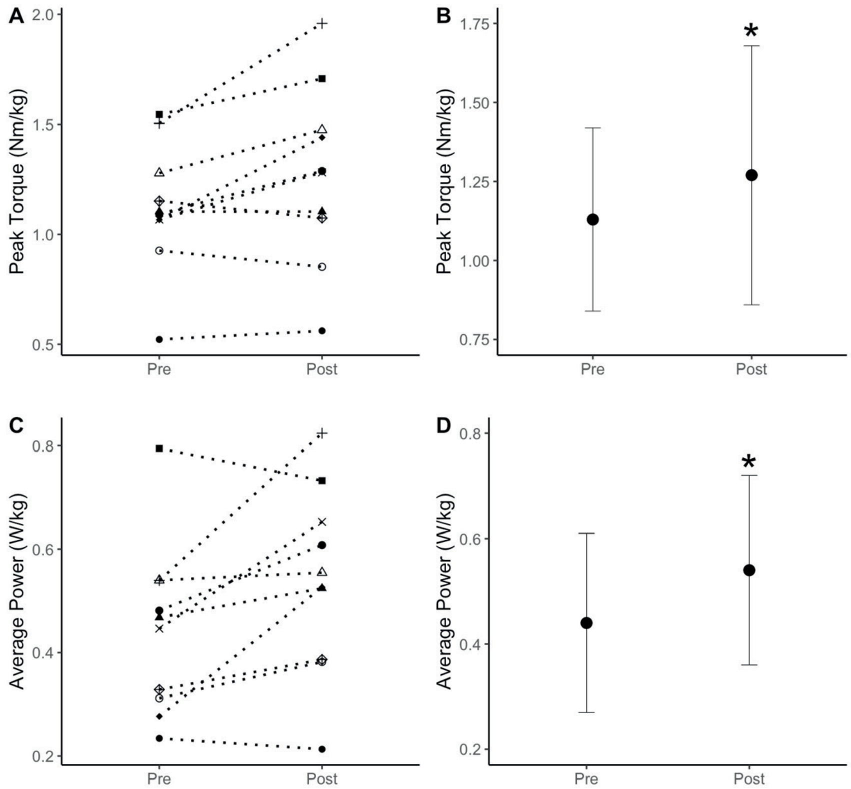

Figure 1. Changes in isokinetic measures, normalized to body mass, from pre- to post-IC in the involved limb. An asterisk indicates significantly different from pre-IC (p ≤ 0.05) A. Individual changes in isokinetic peak torque. Each symbol represents a separate participant. B. Group average with standard deviation of isokinetic peak torque pre- and post-IC. C. Individual changes in isokinetic average power. Each symbol represents a separate participant. D. Group average with standard deviation of isokinetic average power pre- and post-IC. Abbreviations: Nm, newton meter; kg, kilogram; W, watts.

Data Analysis

Isokinetic peak torque, isokinetic average power, and isometric peak torque were normalized to mass. A fatigue index (FI) percentage was calculated for hip abduction endurance using the area under the force time curve ($AUFC_{0\text{-}30}$) during the 30 second isometric contraction and the maximal torque generated during the first five seconds of the 30 second isometric contraction ($F_{max0\text{-}5}$) as follows[34]:

$$FI\ (\%)=\left[1-\frac{AUFC_{0\text{-}30}}{F_{max\ 0\text{-}5}\ X\ 30}\right]X\ 100.$$

A lower fatigue index value was indicative of greater hip abductor endurance whereas a higher fatigue index value was indicative of reduced hip abductor endurance.

Statistical Analysis

The Shapiro-Wilk test was used to verify normality of all outcome measures. Paired *t*-tests were used to determine the changes in hip abductor strength, power, and endurance. Mean differences were calculated, and the magnitude of pre-post differences were estimated using Cohen's *d* effect sizes. Cohen's *d* effect sizes were interpreted as *weak* (<0.21), *small* (0.21-0.39), *medium* (0.4-0.69), or *large* (≥0.7)[35]. Statistical significance for all analyses was set at p≤.05 *a priori*. All statistical analyses were performed in SPSS (version 28, IBM, Armonk, NY).

Results

All variables were normally distributed based on the Shapiro-Wilk test (p>.05). Isokinetic peak torque (p=.027) and isokinetic average power (p=.025) in the involved limb significantly increased after IC when compared to baseline (Figure 1). Isometric peak torque (p=.134) and fatigue index (p=.769) in the involved limb did not change significantly from pre- to post-IC (Table 2). In the uninvolved limb, isokinetic peak torque increased significantly after IC compared to baseline (p=.044) (Figure 2). There were no significant

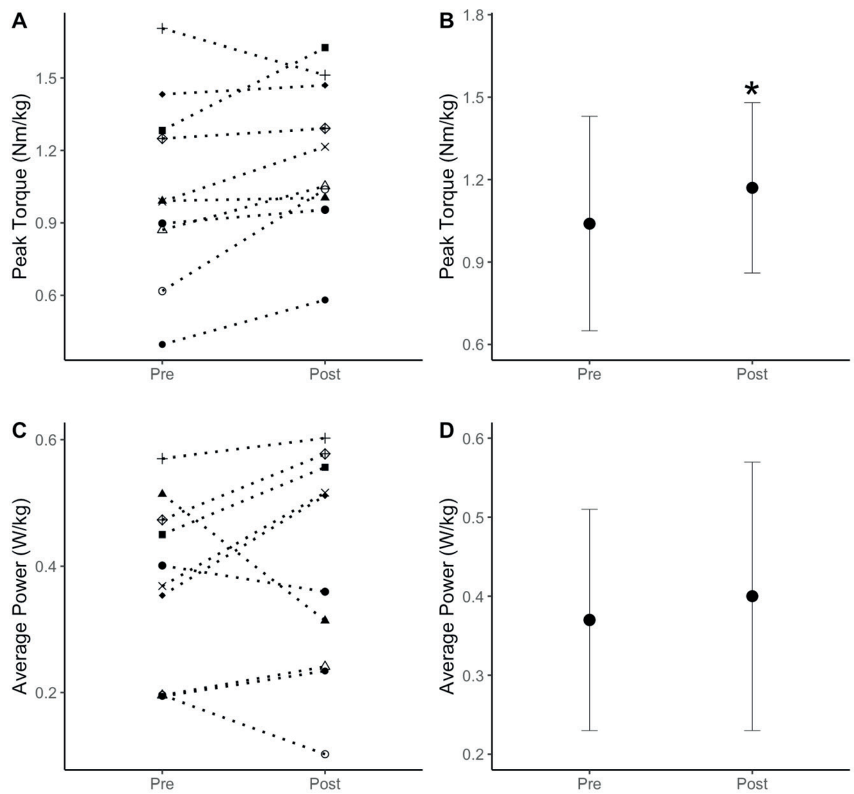

Figure 2. Changes in isokinetic measures, normalized to body mass, from pre- to post-IC in the uninvolved limb. An asterisk indicates significantly different from pre-IC ($p \leq 0.05$) **A**. Individual changes in isokinetic peak torque. Each symbol represents a separate participant. **B**. Group average with standard deviation of isokinetic peak torque pre- and post-IC. **C**. Individual changes in isokinetic average power. Each symbol represents a separate participant. **D**. Group average with standard deviation of isokinetic average power pre- and post-IC. Abbreviations: Nm, newton meter; kg, kilogram; W, watts.

changes in isokinetic average power (p=.424) (Figure 2), isometric peak torque (p=.369), or fatigue index (p=.267) in the uninvolved limb from pre- to post-IC (Table 3). Effect sizes for the outcome measures on both limbs ranged from weak to medium (Tables 2 and 3).

Discussion

The purpose of this study was to investigate the effect of a single session of IC on hip abductor strength in participants with symptomatic KOA. Participants demonstrated increased strength, as evidenced by greater peak torque and average power in the involved limb, with an average 12.39% increase in isokinetic peak torque. This is comparable to other studies that have reported a 11.1% increase in isometric hip abductor strength after a 12-week hip abductor strengthening program[36] and 15.5% increase in isokinetic hip abductor strength after a 6-week intensive hip abductor strengthening program[37]. Follow-up measurements in the second study reported that subjects maintained this strength increase through the 12th week, reporting a 12.9% increase in hip abductor strength from baseline measured 6 weeks after completion of the strengthening program[37]. The strength increase reported at week 12 following the 6 week strengthening program is very comparable to the 12.39% increase in hip abductor strength seen in the current study, possible after only a single session of IC. This suggests that a single session of IC may be as beneficial as some strengthening programs, but further research needs to be completed comparing the two interventions in this population.

The results also partially supported our secondary hypothesis showing significant increases in isokinetic hip abductor strength in the uninvolved limb after IC which was similar to other studies that have reported systemic effects of IC[25]. The systemic effect of IC can improve hip abductor strength in both limbs in individuals with KOA which could potentially address some of the compensatory behaviors employed in the contralateral (uninvolved) limb in this population. Increased hip strength can potentially improve pelvic control allowing for more trunk stability during

Table 2. Average strength and endurance measures at baseline and post IC and changes in outcome measures reported as mean differences and effect sizes in the involved limb.

Outcome Measure	Pre IC	Post IC	Mean Difference	Effect Size
Isokinetic Peak Torque (Nm/kg)	1.13 (0.29)	1.27 (0.41)*	0.15	0.42
Isokinetic Average Power (W/kg)	0.44 (0.17)	0.54 (0.18)*	0.10	0.57
Isometric Peak Torque (Nm/kg)	0.97 (0.35)	1.07 (0.24)	0.10	0.33
Fatigue Index (%)	21.19 (5.41)	20.32 (6.16)	-0.87	-0.15

*Abbreviations: Nm, newton meter; kg, kilogram; W, watts. Values are reported as mean (SD). *Indicates significant increase from baseline.*

Table 3. Average strength and endurance measures at baseline and post IC and changes in outcome measures reported as mean differences and effect sizes in the uninvolved limb.

Outcome Measure	Pre IC	Post IC	Mean Difference	Effect Size
Isokinetic Peak Torque (Nm/kg)	1.04 (0.39)	1.17 (0.31)*	0.13	0.37
Isokinetic Average Power (W/kg)	0.37 (0.14)	0.40 (0.17)	0.03	0.19
Isometric Peak Torque (Nm/kg)	0.94 (0.24)	0.98 (0.31)	0.04	0.14
Fatigue Index (%)	24.85 (8.17)	21.12 (4.94)	-3.73	-0.55

*Abbreviations: Nm, newton meter; kg, kilogram; W, watts. Values are reported as mean (SD). *Indicates significant increase from baseline.*

gait[36]. Hip strengthening exercises can also have functional implications, such as improved walking distance, improved performance on the sit to stand test, and reduced symptoms and pain, which leads to improved quality of life[19,36,38]. The use of IC as a noninvasive intervention to potentially reduce knee pain and improve mechanics may allow patients with KOA to remain active, which can be the first step to breaking the vicious cycle that leads to inactivity in this population. Therefore, IC may be an effective intervention to improve quality of life in persons with KOA.

Although there were changes in strength and power, there were no significant changes in hip endurance in either limb. Hip endurance is particularly important for patients with KOA because these patients have a high risk of developing secondary joint disorders, such as hip OA and low back pain. Lack of endurance in the hip musculature can increase compensatory behaviors involving the low back muscles, and allow for load transfer, thereby increasing comorbidity[39]. Decreased hip muscle endurance can thus lead to a pain avoidance behavior which can cause low back muscle weakness and chronic low back pain[39]. Reduced endurance can potentially also have implications on balance in patients with KOA. A single session of IC, although beneficial to strength, may induce temporary priming effects of muscles due to increased oxygenation and reperfusion. Perhaps chronic exposure to repeated cycles of ischemia and reperfusion is necessary to see endurance effects.

There could be many mechanisms that led to the increase in strength, such as physiological changes and temporary hypertrophy of the hip abductors. Hypertrophy from muscle ischemia has been previously observed from the metabolic stress induced during ischemia which leads to the accumulation of metabolites[40]. Combined with increased oxygenation and rate of deoxygenation of the hemoglobin and myoglobin during the reperfusion phase of IC, it is possible that type II muscle fibers benefited more from IC because of their lower microvascular oxygen partial pressure[22]. Furthermore, ischemia leads to increased activation of type II fibers after chronic IC, however it is unknown if these changes are just temporary and whether similar effects are seen after acute IC in individuals with KOA[41,42]. Future work in this area may consider the use of a muscle biopsy to confirm these physiologic changes in muscle fibers and evaluate whether acute IC can have lasting hypertrophy effects.

Another potential mechanism for the strength and power increases following IC could be attributed to neural adaptation, resulting in an engaged and overactive autonomic nervous system. IC has been shown to activate the group III and group IV afferents, which are sensitive to ischemia, leading to the release of neuromodulators such as serotonin and norepinephrine from the brain stem centers[43,44]. These neuromodulators increase the excitability of spinal motoneurons and potentially the excitability of weaker muscles[45]. Increased activation of atrophied hip abductors in KOA patients could contribute to the observed increase in strength. Our data also suggests a potential systemic effect of IC based on the increase in peak torque observed in the uninvolved limb. Other studies have reported similar systemic effects[46] which could be an adaptation of the nervous system to ischemia[44].

Despite the mechanism for improved strength, IC may be a useful intervention in conjunction with physical therapy as a pre-therapy agent, allowing patients to be more functionally mobile for their sessions. This can help patients get more benefits from their physical therapy sessions and complete exercises with reduced pain. Further, IC may help improve pain-related non-adherence to exercise and prescribed walking, and can help keep this population motivated. Overall, IC, when used in conjunction with other treatment options, can help alleviate several barriers that limit persons with KOA from existing treatment options, and improve their functional mobility, gait, and overall quality of life.

Limitations

There were some limitations in the current study. First, our study sample consisted mostly of men (60%), which may not accurately represent the incidence and prevalence of KOA in women, or their associated severity in the population[47]. Typically, the incidence of KOA is about 1.5 to 2 times higher in women than in men and women also exhibit greater KOA severity[47-49]. Response to IC based on sex differences is currently unknown. Future studies should consider sex differences in the response to IC in persons with KOA.

Second, we did not control for the severity in KOA, which may have affected the response to IC. As the first study to explore the use of IC to improve hip strength in this population, we included a wider range of participants with symptomatic KOA rather than limit participation based on a Kellgren and Lawrence grade. Future studies should confirm KOA severity and determine if the effects of IC vary with KOA severity and exercise history.

Conclusion

A single session of IC increased hip abductor isokinetic peak torque in the involved and uninvolved limbs, and isokinetic average power in the involved limb. The increased strength and power after IC can be beneficial to KOA patients by improving pain related physical function and mobility, and thereby increasing their quality of life. These changes can potentially improve pain related non-adherence to other treatment options like prescribed walking and allow for better outcomes from strengthening and physical therapy sessions. Clinicians and clinical researchers may consider the use of IC as a passive, non-invasive, accompanying modality to help with muscle strength and as a treatment option for patients with KOA.

Ethics approval

The study protocol was approved by the Institutional Review Board at the University of Illinois at Chicago on January 25, 2023 (IRB # 2022-1600).

Funding

This work was supported by the University of Illinois at Chicago's Center for Clinical and Translational Science Pilot Grant.

Authors' Contributions

SS was responsible for IRB submission, study conception and design, participant recruitment, data collection and analysis, and manuscript preparation and revision. KCF was responsible for assisting with data analysis and manuscript preparation and revision. PJ was responsible for participant recruitment and manuscript preparation and revision. LSH provided oversight over IRB submission, study conception and design, data collection and analysis, and was responsible for manuscript preparation and revision.

References

1. Guccione AA. Arthritis and the process of disablement. Physical Therapy 1994;74(5):408-414.
2. Kramer JS, Yelin EH, Epstein WV. Social and economic impacts of four musculoskeletal conditions. Arthritis & Rheumatism: Official Journal of the American College of Rheumatology 1983;26(7):901-907.
3. Heidari B. Knee osteoarthritis prevalence, risk factors, pathogenesis and features: Part I. Caspian journal of internal medicine 2011;2(2):205.
4. Vitaloni M, Botto-van Bemden A, Sciortino Contreras RM, Scotton D, Bibas M, Quintero M, Monfort J, Carné X, de Abajo F, Oswald E. Global management of patients with knee osteoarthritis begins with quality of life assessment: a systematic review. BMC musculoskeletal disorders 2019;20(1):1-12.
5. Bennell KL, Hinman RS. A review of the clinical evidence for exercise in osteoarthritis of the hip and knee. Journal of science and medicine in sport 2011;14(1):4-9.
6. Evcik D, Sonel B. Effectiveness of a home-based exercise therapy and walking program on osteoarthritis of the knee. Rheumatology international 2002;22(103-106.
7. Ettinger Jr WH, Afable RF. Physical disability from knee osteoarthritis: the role of exercise as an intervention. Medicine and science in sports and exercise 1994; 26(12):1435-1440.
8. Bieler T, Siersma V, Magnusson S, Kjaer M, Beyer N. OP0006-HPR Even in The Long Run Nordic Walking Is Superior To Strength Training and Home Based Exercise for Improving Physical Function in Older People with Hip Osteoarthritis-An RCT. BMJ Publishing Group Ltd; 2016.
9. Iijima H, Shimoura K, Ono T, Aoyama T, Takahashi M. Proximal gait adaptations in individuals with knee osteoarthritis: A systematic review and meta-analysis. Journal of biomechanics 2019; 87(127-141.
10. Aydemir B, Huang CH, Foucher KC. Gait speed and kinesiophobia explain physical activity level in adults with osteoarthritis: A cross-sectional study. Journal of Orthopaedic Research® 2023;41(12):2629-2637.
11. Foucher KC, Aydemir B, Huang C-H. Walking energetics and fatigue are associated with physical activity in

people with knee osteoarthritis. Clinical Biomechanics 2021;88(105427.
12. Aydemir B, Huang CH, Foucher KC. Strength and physical activity in osteoarthritis: the mediating role of kinesiophobia. Journal of Orthopaedic Research® 2022;40(5):1135-1142.
13. Hinman RS, Hunt MA, Creaby MW, Wrigley TV, McManus FJ, Bennell KL. Hip muscle weakness in individuals with medial knee osteoarthritis. Arthritis care & research 2010;62(8):1190-1193.
14. Deasy M, Leahy E, Semciw AI. Hip strength deficits in people with symptomatic knee osteoarthritis: a systematic review with meta-analysis. journal of orthopaedic & sports physical therapy 2016; 46(8):629-639.
15. Chang AH, Chmiel JS, Almagor O, Hayes KW, Guermazi A, Prasad PV, Moisio KC, Zhang Y, Szymaszek J, Sharma L. Hip muscle strength and protection against structural worsening and poor function and disability outcomes in knee osteoarthritis. Osteoarthritis and cartilage 2019; 27(6):885-894.
16. Hislop AC, Collins NJ, Tucker K, Deasy M, Semciw AI. Does adding hip exercises to quadriceps exercises result in superior outcomes in pain, function and quality of life for people with knee osteoarthritis? A systematic review and meta-analysis. British journal of sports medicine 2020;54(5):263-271.
17. Selistre LFA, Gonçalves GH, Nakagawa TH, Petrella M, Jones RK, Mattiello SM. The role of hip abductor strength on the frontal plane of gait in subjects with medial knee osteoarthritis. Physiotherapy Research International 2019;24(4):e1779.
18. Thorp L, Wimmer M, Foucher K, Sumner D, Shakoor N, Block J. The biomechanical effects of focused muscle training on medial knee loads in OA of the knee: a pilot, proof of concept study. J Musculoskelet Neuronal Interact 2010;10(2):166-73.
19. Sled EA, Khoja L, Deluzio KJ, Olney SJ, Culham EG. Effect of a home program of hip abductor exercises on knee joint loading, strength, function, and pain in people with knee osteoarthritis: a clinical trial. Physical therapy 2010;90(6):895-904.
20. McKnight PE, Kasle S, Going S, Villanueva I, Cornett M, Farr J, Wright J, Streeter C, Zautra A. A comparison of strength training, self-management, and the combination for early osteoarthritis of the knee. Arthritis Care & Research: Official Journal of the American College of Rheumatology 2010;62(1):45-53.
21. Chen H, Zheng X, Huang H, Liu C, Wan Q, Shang S. The effects of a home-based exercise intervention on elderly patients with knee osteoarthritis: a quasi-experimental study. BMC musculoskeletal disorders 2019;20(1):1-11.
22. Paradis-Deschênes P, Joanisse DR, Billaut F. Ischemic preconditioning increases muscle perfusion, oxygen uptake, and force in strength-trained athletes. Applied Physiology, Nutrition, and Metabolism 2016;41(9):938-944.
23. Heusch G, Bøtker HE, Przyklenk K, Redington A, Yellon D. Remote ischemic conditioning. Journal of the American College of Cardiology 2015;65(2):177-195.
24. Hyngstrom AS, Murphy SA, Nguyen J, Schmit BD, Negro F, Gutterman DD, Durand MJ. Ischemic conditioning increases strength and volitional activation of paretic muscle in chronic stroke: a pilot study. J Appl Physiol (1985) 2018;124(5):1140-1147.
25. Hyngstrom AS, Nguyen JN, Wright MT, Tarima SS, Schmit BD, Gutterman DD, Durand MJ. Two weeks of remote ischemic conditioning improves brachial artery flow mediated dilation in chronic stroke survivors. Journal of Applied Physiology 2020;129(6):1348-1354.
26. Sudhir S, Foucher KC, Jetanalin P, Slater L. Ischemic Preconditioning Improves Muscle Performance In Participants With Knee Osteoarthritis: 2930. Medicine & Science in Sports & Exercise 2023;55(9S):981-982.
27. Roos EM, Lohmander LS. The Knee injury and Osteoarthritis Outcome Score (KOOS): from joint injury to osteoarthritis. Health and quality of life outcomes 2003;1(1):1-8.
28. Hawker GA, Mian S, Kendzerska T, French M. Measures of adult pain: Visual analog scale for pain (vas pain), numeric rating scale for pain (nrs pain), mcgill pain questionnaire (mpq), short-form mcgill pain questionnaire (sf-mpq), chronic pain grade scale (cpgs), short form-36 bodily pain scale (sf-36 bps), and measure of intermittent and constant osteoarthritis pain (icoap). Arthritis care & research 2011;63(S11):S240-S252.
29. Farrell M, Richards JG. Analysis of the reliability and validity of the kinetic communicator exercise device. Medicine & Science in Sports & Exercise 1986;18(1):44-49.
30. Cahalan TD, Johnson ME, Liu S, Chao EY. Quantitative measurements of hip strength in different age groups. Clin Orthop Relat Res 1989;(246):136-45.
31. Widler KS, Glatthorn JF, Bizzini M, Impellizzeri FM, Munzinger U, Leunig M, Maffiuletti NA. Assessment of hip abductor muscle strength. A validity and reliability study. J Bone Joint Surg Am 2009;91(11):2666-72.
32. Johnson ME, Mille ML, Martinez KM, Crombie G, Rogers MW. Age-related changes in hip abductor and adductor joint torques. Arch Phys Med Rehabil 2004;85(4):593-7.
33. Durand MJ, Boerger TF, Nguyen JN, Alqahtani SZ, Wright MT, Schmit BD, Gutterman DD, Hyngstrom AS. Two weeks of ischemic conditioning improves walking speed and reduces neuromuscular fatigability in chronic stroke survivors. Journal of Applied Physiology 2019; 126(3):755-763.
34. Surakka J, Romberg A, Ruutiainen J, Virtanen A, Aunola S, Mäentaka K. Assessment of muscle strength and motor fatigue with a knee dynamometer in subjects with multiple sclerosis: a new fatigue index. Clinical rehabilitation 2004;18(6):652-659.
35. Hopkins WG, Marshall SW, Batterham AM, Hanin J.

Progressive statistics for studies in sports medicine and exercise science. Med Sci Sports Exerc 2009;41(1):3-13.
36. Bennell K, Hunt M, Wrigley T, Hunter D, McManus F, Hodges P, Li L, Hinman R. Hip strengthening reduces symptoms but not knee load in people with medial knee osteoarthritis and varus malalignment: a randomised controlled trial. Osteoarthritis and cartilage 2010; 18(5):621-628.
37. Wang J, Xie Y, Wang L, Lei L, Liao P, Wang S, Gao Y, Chen Y, Xu F, Zhang C. Hip abductor strength–based exercise therapy in treating women with moderate-to-severe knee osteoarthritis: a randomized controlled trial. Clinical Rehabilitation 2020;34(2):160-169.
38. Singh S, Pattnaik M, Mohanty P, Ganesh GS. Effectiveness of hip abductor strengthening on health status, strength, endurance and six minute walk test in participants with medial compartment symptomatic knee osteoarthritis. Journal of back and musculoskeletal rehabilitation 2016;29(1):65-75.
39. Kankaanpää M, Taimela S, Laaksonen D, Hänninen O, Airaksinen O. Back and hip extensor fatigability in chronic low back pain patients and controls. Archives of physical medicine and rehabilitation 1998;79(4):412-417.
40. Schoenfeld BJ. The mechanisms of muscle hypertrophy and their application to resistance training. The Journal of Strength & Conditioning Research 2010; 24(10):2857-2872.
41. Cleland SM, Murias JM, Kowalchuk JM, Paterson DH. Effects of prior heavy-intensity exercise on oxygen uptake and muscle deoxygenation kinetics of a subsequent heavy-intensity cycling and knee-extension exercise. Applied Physiology, Nutrition, and Metabolism 2012;37(1):138-148.
42. da Silva Novaes J, da Silva Telles LG, Monteiro ER, da Silva Araujo G, Vingren JL, Silva Panza P, Reis VM, Laterza MC, Vianna JM. Ischemic preconditioning improves resistance training session performance. Journal of Strength and Conditioning Research 2021; 35(11):2993-2998.
43. Sharma V, Marsh R, Cunniffe B, Cardinale M, Yellon DM, Davidson SM. From protecting the heart to improving athletic performance–the benefits of local and remote ischaemic preconditioning. Cardiovascular drugs and therapy 2015;29(573-588.
44. Cruz RSdO, Pereira KL, Lisbôa FD, Caputo F. Could small-diameter muscle afferents be responsible for the ergogenic effect of limb ischemic preconditioning? American Physiological Society Bethesda, MD; 2017. p. 718-720.
45. Surkar SM, Bland MD, Mattlage AE, Chen L, Gidday JM, Lee JM, Hershey T, Lang CE. Effects of remote limb ischemic conditioning on muscle strength in healthy young adults: A randomized controlled trial. PLoS One 2020;15(2):e0227263.
46. Allois R, Pagliaro P, Roatta S. Ischemic Conditioning to Reduce Fatigue in Isometric Skeletal Muscle Contraction. Biology (Basel) 2023;12(3).
47. Srikanth VK, Fryer JL, Zhai G, Winzenberg TM, Hosmer D, Jones G. A meta-analysis of sex differences prevalence, incidence and severity of osteoarthritis. Osteoarthritis and cartilage 2005;13(9):769-781.
48. Felson DT, Lawrence RC, Dieppe PA, Hirsch R, Helmick CG, Jordan JM, Kington RS, Lane NE, Nevitt MC, Zhang Y. Osteoarthritis: new insights. Part 1: the disease and its risk factors. Annals of internal medicine 2000; 133(8):635-646.
49. Hootman JM, Helmick CG. Projections of US prevalence of arthritis and associated activity limitations. Arthritis & Rheumatism: Official Journal of the American College of Rheumatology 2006;54(1):226-229.