Project title: Effects of 8 weeks of free-weight and machine-based resistance training on neuromuscular function

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1. Introduction:

Resistance training is essential for maintaining physical fitness (Westcott, 2012) and improving athletic performance (Harries et al., 2012). Many studies have shown that long-term resistance training can increase muscle mass (Krzysztofik et al., 2019), reduce the risk of injury (Fleck & Falkel, 1986), improve posture (Kim et al., 2015), increase bone mineral density (Hong & Kim, 2018), improve well-being and quality of life (Leitão et al., 2022), and enhance neuromuscular function such as strength, power and muscle coordination (Peitz, Behringer, & Granacher, 2018, Romanazzi, Galante, & Sforza, 2015 and American College of Sports Medicine, 2009).

The most popular training methods used in gyms are free weights (barbell, dumbbell, etc.) and machines (lat pulldown, cable machine, etc.). However, the choice between free weights and machines is widely debated by coaches, athletes and fitness enthusiasts (Haugen et al., 2023). Free weights are often preferred by powerlifters and weightlifters because they provide a relatively unstable load and may engage more muscle groups near the torso (Haff, 2000). In contrast, machine exercises are more stable, require less technique, and are therefore generally considered easier for beginners to use (Haff, 2000).

Several studies have addressed the differences in strength, power and muscle hypertrophy between long-term free weight training and machine training (Schott, Johnen, & Holfelder, 2019, Prieto González & Sedlacek, 2021). However, few studies have investigated the effects of free weight and machine training on muscle activation, especially at the level of the motor unit or intermuscular coordination. Examples of cross-sectional studies include a study by Schwanbeck and colleagues (Schwanbeck, Chilibeck, & Binsted, 2009) which examined surface electromyography (EMG) differences between barbell squats and Smith squats, and a study by Schick and colleagues (Schick et al., 2010) which examined surface electromyography (EMG) differences between barbell bench press and Smith bench press. Although these studies all provide reference of differences in neuromuscular activation, the results of these studies cannot be used to infer long-term neuromuscular adaptations to different training methods. Therefore, the aim of this study is to determine the effects of free weight versus machine training on features of neuromuscular control and function of the lower limb.

<u>**Objectives**</u>

1. The primary objective of the study is to compare the effects of free weight training (barbell squats) and machine training (leg press) on neuromuscular function and motor unit behaviour of lower limb muscles over an 8-week period.
2. To investigate whether there are significant differences in maximum strength, intermuscular coordination, motor unit behavior, and other related neuromuscular adaptations between the Barbell Squat (BS) and Leg Press (LP) groups following the 8-week intervention.

<u>Expected outcomes</u>

After the 8-week training period, we hypothesize:

1. Based on measurements from conventional surface EMG and a force plate, the BS group will show greater improvements in vertical jump performance (including countermovement jump and squat jump) and intermuscular coordination compared to the LP group.
2. Based on high-density surface EMG and Biodex isokinetic dynamometer measurements, the increases in maximal isometric, eccentric, and concentric knee extension force, as well as quadriceps motor unit recruitment levels, are expected to be similar between the BS and LP groups. However, the BS group may show more significant increases in rate of force development (RFD).
3. Compared to baseline, the BS group may exhibit more pronounced early adaptations at each assessment point (2 weeks, 4 weeks).

2. Proposed Research Methodology:

2.1 Participants:

We will recruit a total of 54 participants, divided equally between the BS and LG groups for a total of 27 participants per group. Eligibility criteria are shown in Table 1.

Table 1 Eligibility criteria

	Barbell Squat Group (n=27)	**Leg Press Group (n=27)**
Inclusion criteria	- Healthy adult males aged between 18 and 35 years. - No history of major sports injuries to the spine or lower limb joints, such as severe sprains, fractures, or tendon ruptures. - No history of lower limb or spine surgery, and no current or recent chronic pain or functional limitations. - A BMI ranging from 18.5 to 29.9, covering the normal to slightly overweight categories. - No chronic diseases that could affect study outcomes, such as diabetes, cardiovascular diseases, respiratory conditions, or other systemic illnesses. - Not taking any medications that could influence the study results, including but not limited to steroids, antihypertensive drugs, or glucocorticoids.	

Exclusion criteria	- History of major lower extremity injury or surgery (e.g., fracture, ligament tear, tendon rupture, etc.) - Existing leg pain, swelling, or functional limitation which may affect the safety and effectiveness of resistance training - Diagnosis of severe osteoarthritis or osteoporosis - Any bone or joint disorders known to limit movement of the lower extremities - History of cardiovascular disease, such as coronary heart disease, heart failure, uncontrolled hypertension, or recent cardiac surgery - History of neurological conditions such as stroke, multiple sclerosis, or spinal cord injury - Any neurological disorder that may affect muscle control or coordination - Severe chronic medical conditions, such as diabetes, kidney disease, or uncontrolled thyroid dysfunction

2.2 Procedures:

During the entire experimental period, participants will complete 19 sessions: 12 conventional training sessions, 2 deload sessions, 1 familiarization session, and 4 data collection sessions. Details of the data collection sessions are shown in Table 2 - Neuromuscular function measurements and procedures (see below).

2.3 Intervention training program

Both the Barbell squat and Leg press groups will undergo an 8-week progressive overload resistance training intervention, with training sessions held twice weekly, spaced 48-72 hours apart. One week prior to the intervention, participants will visit the laboratory twice: once for familiarization with the procedures and once for baseline data collection. Each training session will follow a standard warm-up, after which participants will complete 5x5 training sets with a 3-1-X tempo (concentric-isometric-eccentric) and 3 minutes of rest between sets. The initial training load will be set at 70% of the estimated 1RM. Training intensity will be progressively increased as participants successfully complete the prescribed repetitions, under the guidance of a qualified strength and conditioning coach. To manage fatigue, a deload week will be implemented after every three weeks of training, during which the first session's intensity will be reduced to aid recovery. A second assessment will be conducted 48-72 hours later to collect outcome measures. Details of the schedule of training sessions are shown in Table 3 - Progressive resistance training program (see below).

2.4 Statistical analysis:

To ensure sufficient statistical power and account for potential dropouts, we conducted an a priori power analysis with G*Power, setting a power of 0.80, a significance level of 0.05, and an effect size of 0.25 based on prior research. The analysis determined that 24 participants per group were needed for a repeated measures ANOVA with within factors across four time points. To adjust for potential data loss, we increased the sample size by 10%, resulting in a target of 27 participants per group. A total of 54 participants will eventually be recruited. Analyses will be conducted using SPSS version 29.0, with a significance level set at $p < 0.05$ for all tests.

Data normality for changes in 1RM measurements will be assessed using the Shapiro–Wilk test, and Mauchly's Test will evaluate sphericity prior to statistical analysis. Due to the different exercises involved, direct comparison of 1RM changes between groups will not be made; instead, paired samples t-tests will assess within-group changes. If sphericity is violated, the Greenhouse-Geisser correction will be applied to the mixed-design ANOVA. Effect sizes will be calculated to estimate the magnitude of observed effects. Should the ANOVA indicate significant effects, a Bonferroni correction will address multiple comparisons.

3. Significance of project:

This project investigates neuromuscular adaptations to resistance training through an 8-week experimental intervention. The study will assess participants' neuromuscular function using advanced tools including Biodex, surface electromyography (sEMG), high-density electromyography (HD-EMG), and force plateform measurements. Participants will participate in a progressive resistance training program and be randomized into groups that perform barbell squats or leg presses to compare the effectiveness of free weight training and machine-based training. Assessments conducted before, during, and after the intervention will track immediate and sustained changes in neuromuscular performance. The results of the study will be published in a peer-reviewed journal, and these results will inform athletic training and rehabilitation practices, providing coaches, athletes, and related practitioners with evidence-based insights to enhance strength development and injury prevention strategies. By utilizing experimental data, my research aims to combine theoretical research with practical applications to ultimately improve athletic performance and physical fitness in diverse populations.

Table 2 Neuromuscular function measurements and procedures

Tasks	Outcomes	Task descriptions
Measurement of mid-thigh circumference	Thigh circumference	The participants' mid-thigh circumference will be measured first, following the recommendations in the "Standards for Anthropometry Assessment" chapter from the book Kinanthropometry and Exercise Physiology (Norton & Eston, 2019). Participants will stand in a relaxed posture. The researcher will palpate to locate the participant's anterior superior iliac spine (ASIS) and the lateral superior margin of the patella (LSMP), marking both points with a marker. The midpoint between these two landmarks is then located and marked. A tape measure is used to measure the circumference at the horizontal level of the midpoint, ensuring that the tape is in contact with the participant's skin but not pressing into it. The recorded value is accurate to 0.1 cm. The measurement is taken three times in total, and the average of the three recordings is used.
Countermovement Jump and Squat Jump test	Jump height, EMG amplitude and	The CMJ and SJ tests will be conducted using a force plate (BTS Bioengineering, Italy). Participants will stand on a single force platform, ensuring both take-off and landing occur on the platform.

Tasks	Outcomes	Task descriptions
	intermuscular coordination	For the CMJ test, participants will place their hands on their waist to minimize arm swing interference, quickly squat to a pre-determined depth at the researcher's cue ("3, 2, 1, jump"), and then jump vertically as high as possible. A 60-second rest will be provided between each CMJ attempt, with the procedure repeated five times. After completing the CMJ tests, participants will proceed with the SJ test, starting from a 90-degree knee flexion position. No practice jumps will be allowed before the official SJ trials, which will also consist of five repetitions. During each CMJ and SJ attempt, ground reaction forces will be collected using a force plate sampled at 500Hz. The data will be processed using MATLAB software to identify and analyze the propulsion phase, defined when the vertical ground reaction force drops below 10 N, indicating propulsion phase. The impulse-momentum method will be applied to calculate jump height. Additionally, we will calculate kinetic variables such as velocity and power for both CMJ and SJ to evaluate differences within and between groups before and after the intervention. All force-derived variables will be normalized to each participant's body mass to ensure accurate comparison of performance metrics across study groups. During CMJ and SJ assessments, surface electromyography (sEMG, BTS Bioengineering) signals were recorded at a sampling frequency of 1000 Hz from the vastus lateralis (VL), vastus medialis (VM), gluteus maximus (GM), long head of biceps femoris (BF), semitendinosus (ST), and rectus femoris (RF), tibialis anterior (TA), gastrocnemius medialis (GM) of the dominant leg. We will prepare the skin and place the electrodes according to SENIAM guidelines (Moir, 2008). We will utilize the SMART Capture software provided by BTS Bioengineering for the synchronization of sEMG and force plate measurements. In all CMJ and SJ attempts, the trial with the highest jumping height will be selected for data analysis. Raw EMG recordings will then be 4th order Butterworth band pass filtered (20–250 Hz) and full wave rectification will be performed prior to the data analysis. To quantify the level of muscle activation during the take-off phase, we will calculate the Root Mean Square (RMS) values of the EMG signals. We will employ Non-negative Matrix Factorization (NMF) to analyze muscle activation patterns during the CMJ and SJ by analysing the EMG signals into a set of muscle synergies (Lee & Seung, 2000). These synergies represent the coordinated activation of multiple muscles and will be extracted using an open-source NMF algorithm in MATLAB. Initially, the EMG signals will be normalized to the average amplitude over a 100-ms interval at the peak of the linear envelope, which captures the entire phase of CMJ and SJ,

Tasks	Outcomes	Task descriptions
		including the Unloading, Breaking, Propulsion, Flight, and Landing stages. The normalized data will then be processed with NMF to identify the muscle synergies, which will be used to reconstruct the original EMG signals.
Ultrasonic muscle thickness testing	Muscle thickness of the vastus medialis (VM), vastus lateralis (VL), and rectus femoris (RF)	Muscle thickness of the vastus medialis (VM), vastus lateralis (VL), and rectus femoris (RF) were assessed using ultrasound (Logiq S8, GE Healthcare, USA). Participants will lie in supine with their legs extended and muscles relaxed. The researcher will apply a water-soluble gel to the probe to ensure proper acoustic contact and eliminate any muscle deformation caused by pressure. The ultrasound muscle thickness scan will be performed on the participants' dominant leg. The probe needs to be aligned parallel to the muscle fibers of the VL and VM and perpendicular to the skin. To locate the VL and VM, a line is drawn between the superior tip of the patella and the ASIS as the axis. The muscle thickness of the VL is measured at the point of greatest thickness halfway between the ASIS and the proximal end of the patella (Giles et al., 2015). The VM's muscle thickness is measured at three-quarters of the distance from the ASIS to the proximal end of the patella, ensuring the outer edge of the probe aligns with the inner part of the patella (Giles et al., 2015). Three images will be taken at each measurement point to minimize error. After completing the ultrasound scans, the muscle thickness of the VL and VM will be measured using the internal software of the Logiq S8 machine.
Maximum and submaximal voluntary contractions	HDsEMG data; Biomechanical data of knee extension under closed chain test and open chain test	Participants will be seated on a Biodex isokinetic dynamometer with the hip positioned at 85°. The maximum isometric knee extension angle will be set to 110°based on previous studies. After a warm-up, participants will perform three 3-5s knee extension MVCs, with 1-minute rest between trials. The highest recorded force will be used as the reference value. Following a 3-minute rest, participants will complete 8 trapezoidal contractions at 10%, 30%, 50%, and 70% MVC, aiming to match on-screen templates. Rest intervals will be 3 minutes between 50% and 70% MVC, and 1 minute between 10% and 30% MVC. After the isometric trapezoidal contraction, participants will rest for 3 minutes to prepare for the subsequent isokinetic concentric test. First, the range of motion for knee extension will be set to 0-60°, and the angular velocity will be set to 10°/s. Under the instruction of the researcher, participants will complete 2 attempts of concentric MVCs, with a 1-minute rest between attempts. The highest force value of the 2 concentric MVC attempts will be used as the reference value. After a 3-minute rest, participants will complete 4 isokinetic contractions at 10% and 50% MVC, both at 10°/s, aiming to match the template displayed on the screen, with a 1-minute rest

Tasks	Outcomes	Task descriptions
		between each contraction. After completing the concentric contractions, participants will rest for 3 minutes to prepare for the eccentric isokinetic contraction test. The setup for eccentric isokinetic contractions is the same as for concentric contractions, including 2 MVC tests and 4 isokinetic contractions at 10% and 50% to match the template on the screen. However, the Biodex mode will be set to eccentric, with the resistance set to a value higher than the participant's maximum isometric force to ensure they can complete the eccentric movement of the knee joint. After completing all knee extension tests on the Biodex, participants will rest for 3 minutes in preparation for the upcoming isometric mid-thigh pull (IMTP). The IMTP will be conducted using a Load Cell (RS, UK) along with a compatible platform. Participants will stand on the platform and hold the testing handle while the researcher secures both ends of the portable dynamometer to the handle and the platform on the ground using a metal hook and adjustable straps. Based on previous studies (Dos 'Santos et al., 2017), the researcher will adjust the strap length to ensure that the handle is positioned at the participant's mid-thigh (the midpoint between the ASIS and LSMP) and that the hip joint angle is maintained at 145° for optimal IMTP results. Following this, participants will perform 2 maximal effort IMTP tests, followed by 4 matching IMTP tests targeting 10% and 50% of their peak force, with a 1-minute rest between each set. During the matching tests, a portable screen will be placed in front of the participant, allowing them to monitor their force output in real-time to match the target force as accurately as possible. For example, if the participant's IMTP peak force is 1000N, the targets for the matching tests will be 100N and 500N, with an emphasis on maintaining a stable force output. HD-sEMG will be recorded from the VL, VM and RF of the dominant leg during maximal and submaximal isometric contractions, concentric and eccentric contractions, as well as during the isometric mid-thigh pull (IMTP) test. The skin will be prepared by shaving, abrading, and cleansing to optimize electrode-skin contact. Two-dimensional adhesive grid electrodes (13x5, 1mm diameter, 8mm spacing) from SPES Medica will be applied over the distal VL and VM muscles, aligned with muscle fibers. Data will be collected at 2048 Hz and amplified with gain settings of 150x for general conditions, 500x for 50% MVC, and 1000x for 30% MVC. Signals will be bandpass-filtered (10-500 Hz) using a 4th order Butterworth filter. EMG data will be synchronized with torque measurements from

Tasks	Outcomes	Task descriptions
		a calibrated Biodex isokinetic dynamometer. After data collection, the EMG data will be analyzed offline using MATLAB. The 64 monopolar channels will be re-referenced to bipolar derivations to examine root mean square (RMS) amplitude, entropy and the y and x-axis coordinates of the EMG amplitude map. Additionally, the HDEMG signals will be decomposed to extract motor unit characteristics such as firing rate and recruitment thresholds.
Rate of force development test	Explosive force of knee extension	Rate of force development (RFD) is defined as the ability to increase force or torque as rapidly as possible during a voluntary contraction (Aagaard et al., 2002). This concept is particularly relevant to neuromuscular function, as it reflects the capacity to generate force quickly, which is crucial for activities requiring agility, balance, and rapid movement (Maffiuletti et al., 2016). Participants will rest for 5 minutes following the previous contractions to eliminate any fatigue. Subsequently, under the guidance of the researchers, participants will perform 2 rapid isometric contractions of knee extension. The participants will be verbally instructed to perform the isometric contractions “as quickly and explosively as possible,” with the objective of exceeding a preset horizontal cursor on the display (set at 75% of the MVC). The RFD will be determined by calculating the slope of the torque-time curve. The peak RFD will be defined as the maximum rate of torque increase within those time windows. The RFD peak-time will refer to the time required to reach the maximum RFD from the start of the contraction. Furthermore, by analyzing the increments of RFD in consecutive 50-millisecond time windows, a more detailed description of the changes in the rate of force development over time will be provided, specifically for intervals such as 0-50, 50-100, 100-150, 150-200, and 200-250 milliseconds.
One Repetition Maximum test	Maximum weight for barbell squat or leg press	The One Repetition Maximum (1RM) testing will then be conducted. Adhering to the guidelines provided by the National Strength and Conditioning Association (Miller, 2012), participants will initiate the 1RM test by completing 10 repetitions with a self-perceived weight of 50% of their estimated 1RM under the supervision of the researcher as a warm-up set. Subsequently, the weight will be progressively increased for the barbell or leg press machine to determine the participant's 3 to 5 repetition maximum (3 to 5RM) within a total of 5 sets, allowing for a 3-minute rest period between each set. To guarantee the safety of all participants and to ensure technical proficiency in resistance training, this study will utilize the weights corresponding to the 3 to 5RM to estimate the 1RM for all participants. EMG will not be acquired during this test.

Table 3 Progressive resistance training program

Week	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9
Session 1		5x5	5x5	5x5	Deload session	5x5	5x5	5x5	Deload session
Session 2	Baseline Testing session		Test session						
Session 3		5x5	5x5	5x5	Test session	5x5	5x5	5x5	Test session

4. Reference:

Westcott W. L. (2012). Resistance training is medicine: effects of strength training on health. Current sports medicine reports, 11(4), 209–216.

Harries, S. K., Lubans, D. R., & Callister, R. (2012). Resistance training to improve power and sports performance in adolescent athletes: a systematic review and meta-analysis. Journal of science and medicine in sport, 15(6), 532–540.

Krzysztofik, M., Wilk, M., Wojdała, G., & Gołaś, A. (2019). Maximizing Muscle Hypertrophy: A Systematic Review of Advanced Resistance Training Techniques and Methods. International journal of environmental research and public health, 16(24), 4897.

Fleck, S. J., & Falkel, J. E. (1986). Value of resistance training for the reduction of sports injuries. Sports medicine (Auckland, N.Z.), 3(1), 61–68.

Kim, D., Cho, M., Park, Y., & Yang, Y. (2015). Effect of an exercise program for posture correction on musculoskeletal pain. Journal of physical therapy science, 27(6), 1791–1794.

Hong, A. R., & Kim, S. W. (2018). Effects of Resistance Exercise on Bone Health. Endocrinology and metabolism (Seoul, Korea), 33(4), 435–444.

Leitão, L., Venturini, G. R. O., Junior, R. P., Monteiro, E. R., Telles, L. G., Araújo, G., Novaes, J., Tavares, C., Marques-Neto, S., & Mazini, M. (2022). Impact of Different Resistance Training Protocols on Balance, Quality of Life and Physical Activity Level of Older Women. International journal of environmental research and public health, 19(18), 11765.

Peitz, M., Behringer, M., & Granacher, U. (2018). A systematic review on the effects of resistance and plyometric training on physical fitness in youth- What do comparative studies tell us?. PloS one, 13(10), e0205525.

Romanazzi, M., Galante, D., & Sforza, C. (2015). Intralimb joint coordination of the lower extremities in resistance training exercises. Journal of Electromyography and Kinesiology, 25(1), 61-68.

American College of Sports Medicine (2009). American College of Sports Medicine position stand. Progression models in resistance training for healthy adults. Medicine and science in sports and exercise, 41(3), 687–708.

Haugen, M. E., Vårvik, F. T., Larsen, S., Haugen, A. S., van den Tillaar, R., & Bjørnsen, T. (2023). Effect of free-weight vs. machine-based strength training on maximal strength, hypertrophy and jump performance–a systematic review and meta-analysis. BMC Sports Science, Medicine and Rehabilitation, 15(1), 103.

Haff, G. G. (2000). Roundtable discussion: machines versus free weights. Strength & Conditioning Journal, 22(6), 18.

Schott, N., Johnen, B., & Holfelder, B. (2019). Effects of free weights and machine training on muscular strength in high-functioning older adults. Experimental gerontology, 122, 15-24.

Prieto González, P., & Sedlacek, J. (2021). Comparison of the efficacy of three types of strength training: Body, weight training machines and free weights. Apunts Educación Física y Deportes, 145, 9-16.

Schwanbeck, S., Chilibeck, P. D., & Binsted, G. (2009). A comparison of free weight squat to Smith machine squat using electromyography. The Journal of Strength & Conditioning Research, 23(9), 2588-2591.

Schick, E. E., Coburn, J. W., Brown, L. E., Judelson, D. A., Khamoui, A. V., Tran, T. T., & Uribe, B. P. (2010). A comparison of muscle activation between a Smith machine and free weight bench press. The Journal of Strength & Conditioning Research, 24(3), 779-784.

Norton, K., & Eston, R. (Eds.). (2019). Kinanthropometry and exercise physiology (pp. 68-137). London, UK:: Routledge.

Giles L. S., Webster K. E., Mcclelland J. A., Cook J. (2015). Can Ultrasound Measurements of Muscle Thickness Be Used to Measure the Size of Individual Quadriceps Muscles in People with Patellofemoral Pain? Phys. Ther. Sport 16, 45–52.

Moir, G. L. (2008). Three different methods of calculating vertical jump height from force platform data in men and women. Measurement in Physical Education and Exercise Science, 12(4), 207-218.

Dos'Santos T, Thomas C, Jones PA, McMahon JJ, and Comfort P. (2017). The effect of hip joint angle on isometric midthigh pull kinetics. J Strength Cond Res 31(10): 2748-2757.

Aagaard P, Simonsen EB, Andersen JL, Magnusson P, Dyhre-Poulsen P. Increased rate of force development and neural drive of human skeletal muscle following resistance training. J Appl Physiol (1985) 2002;93:1318–1326.

Maffiuletti, N. A., Aagaard, P., Blazevich, A. J., Folland, J., Tillin, N., & Duchateau, J. (2016). Rate of force development: physiological and methodological considerations. European journal of applied physiology, 116(6), 1091–1116.

Miller, T. A. (2012). NSCA's Guide to Tests and Assessments. Human Kinetics.

Craig, C. L., Marshall, A. L., Sjöström, M., Bauman, A. E., Booth, M. L., Ainsworth, B. E., Pratt, M., Ekelund, U., Yngve, A., Sallis, J. F., & Oja, P. (2003). International physical activity questionnaire: 12-country reliability and validity. Medicine and science in sports and exercise, 35(8), 1381–1395.