






# The impact of velocity-based movement on electromyography activity in standard lower-limb strength exercises

-  **Ana Ferri-Caruana.** *Department of Physical Education and Sport. Faculty of Science of Physical Activity and Sport. University of Valencia. Spain.*
-  **Elena Muñoz-Gómez.** *UBIC. Department of Physiotherapy. Faculty of Physiotherapy. University of Valencia. Spain.*
-  **Sara Mollà-Casanova**  *UBIC. Department of Physiotherapy. Faculty of Physiotherapy. University of Valencia. Spain.*
- Pablo Camarón-Mallén.** *Department of Physical Education and Sport. Faculty of Science of Physical Activity and Sport. University of Valencia. Spain.*
-  **Pilar Serra-Añó.** *UBIC. Department of Physiotherapy. Faculty of Physiotherapy. University of Valencia. Spain.*

## ABSTRACT

Previous research has shown that the velocity of movement can influence muscle activation. However, no studies have investigated the impact of movement velocity under the same load conditions on electromyography (EMG) activity in knee and hip extensors. This study aims to compare the mean muscle activation of gluteus maximus [GM], biceps femoris [BF], semitendinosus [ST] and rectus femoris [RF] in three hip extension exercises (i.e., squat [SQ], hip thrust [HT] and Bulgarian squat [BS]) with two different movement velocities (i.e., maximum velocity [MV] and controlled velocity [CV]). Fifteen physically active students participated. The mean EMG activity of all targeted muscles was measured. Maximum Voluntary Isometric Contraction was used to normalize EMG muscle activation. All muscles were activated to a greater extent in BS at MV than in the same exercise performed at CV. However, during the SQ exercise, EMG differences between velocities were only obtained for BF and GM, and in HT, only for GM ( $p < .05$ ). In conclusion, higher velocity involves higher activation of the lower-limb muscles, depending on the physical test, and this can be used to better plan the functional recovery of injury, taking it into consideration for intensity progression and avoiding the risks of overly strenuous exercises.

**Keywords:** Sport medicine, Maximum velocity, Strengthening exercise, Hamstring injury prevention.

### Cite this article as:

Ferri-Caruana, A., Muñoz-Gómez, E., Mollà-Casanova, S., Camarón-Mallén, P., & Serra-Añó, P. (2023). The impact of velocity-based movement on electromyography activity in standard lower-limb strength exercises. *Scientific Journal of Sport and Performance*, 2(3), 314-325. <https://doi.org/10.55860/MXQO3997>



**Corresponding author.** *UBIC. Department of Physiotherapy. Faculty of Physiotherapy. University of Valencia. Spain.*

E-mail: [sara.molla@uv.es](mailto:sara.molla@uv.es)

Submitted for publication May 09, 2023.

Accepted for publication June 05, 2023.

Published June 20, 2023.

[Scientific Journal of Sport and Performance](#). ISSN 2794-0586.

©Asociación Española de Análisis del Rendimiento Deportivo. Alicante. Spain.

doi: <https://doi.org/10.55860/MXQO3997>

## INTRODUCTION

Resistance training is very important in sports performance, injury prevention and rehabilitation (Alcaraz-Ibañez & Rodríguez-Pérez, 2018; Bourne et al., 2018; Buckthorpe & Roi, 2017; Ferri Caruana et al., 2020). Previous research has shown that several uncontrollable factors (i.e., muscle size and length, joint angle, myotatic reflex and muscle elasticity (Cronin et al., 2008; Kuriki et al., 2012; Watanabe & Akima, 2011)) and controllable factors (i.e., exercise intensity (Keogh et al., 1999), the velocity of movement (Sakamoto & Sinclair, 2012), fatigue (Sakamoto & Sinclair, 2012), mental focus (Snyder & Fry, 2012), movement phases (van den Tillaar et al., 2012) and stability conditions) may affect the degree of muscle activation in dynamic contractions. Therefore, in order to control exercise performance, it is important to understand the impact of each of these controllable factors on muscle activation since they are the key improving training efficiency (Stastny et al., 2017).

Although the effect of most of the controllable factors, such as exercise load, fatigue, mental focus, movement phases and stability condition, has been widely studied (Cochrane & Barnes, 2015; Hassani et al., 2006; Krzysztofik et al., 2019; Pincivero et al., 2006; Smilios et al., 2010; van den Tillaar et al., 2019; van den Tillaar & Sousa, 2019), there is controversy in research about the effect of movement velocity on muscle activation. Physiologically, a rapid contraction produces rapid recruitment of motor units (Farina et al., 2004; Felici, 2006), reduces the required time for cross-bridge formations (Jones et al., 2004), increases the velocity of movement (Carpentier et al., 1996; Enoka, 2008) and decreases the fatigue resistance of fast-twitch motor units which are preferentially recruited in dynamic actions (Hunter et al., 2005). All of this could reflect higher muscle electromyography (EMG) activity (Jakobsen et al., 2013; Tsoukos et al., 2021) regardless of the load applied (Sakamoto & Sinclair, 2012; van den Tillaar et al., 2019).

In this line, only three studies compared different exercise velocities using the same load. Calatayud *et al.* (Calatayud et al., 2018) found that in the bench press exercise and using 50% 1-repetition maximum (1-RM) of load, maximum EMG activity of the pectoralis major and the triceps brachii muscles was higher when movement was performed at maximum velocity (MV) compared to a controlled movement velocity (CV). In the same way, Sakamoto *et al.* (Sakamoto & Sinclair, 2012) concluded that EMG amplitudes were greater under faster and heavier bench press conditions.

In contrast, Gentil *et al.* (Gentil et al., 2017) examined the effects of movement velocity on muscle EMG activity during a no-load resistance training exercise and they did not find higher EMG activity during higher velocities compared to slower velocities. However, study participants were asked to sustain maximum contraction during the full range of motion, without any external load, therefore the transferability of results to the clinical or sports performance setting is difficult.

Besides these controllable factors that have an effect on performance, it is further essential to select exercises suited to the goal set, for example, avoiding those too physically demanding that may jeopardize healing program goals. Hip extension is the most trained movement, since it is important for accelerating the body's upward and forward movement such as during sprinting and jumping (Neumann, 2010). In this regard, the squat (SQ) (Clark et al., 2012), Bulgarian squat (BS) (Appleby et al., 2019), and hip thrust (HT) (Contreras et al., 2015, 2017) are often used in training to increase force production during hip extension, since these exercises produce high activation in lower key limb muscles (i.e., rectus femoris [RF], biceps femoris [BF], gluteus maximus [GM] and semitendinosus [ST]). However, no studies have compared muscle activation using different movement velocities in regular hip exercises.

Taking into account what has been discussed above, this study aimed to compare the mean muscle activation of the GM, BF, ST and RF in three hip extension exercises (i.e., SQ, BS and HT) using two different movement speeds: MV (maximum velocity) and CV (controlled velocity).

## **METHODS**

### ***Study design***

This cross-sectional study compares the mean EMG activity of different lower-limb muscles (i.e., RF, BF, ST and GM) normalized by Maximum Voluntary Isometric Contraction (MVIC) during three resistance exercises (i.e., SQ, HT and BS) at two different movement velocities: MV and CV.

### ***Participants***

Healthy active University students were recruited. Inclusion criteria were i. aged 18 years or older; and ii. regular resistance training (> 3 h per week). Exclusion criteria were i. a history of lower-limb or low back injury in the 6 months before the study, ii. any acute or chronic pain in the lower body or low back, iii. neurological or vestibular disease, and iv. any contraindication for exercise. Moreover, participants were asked to refrain from caffeine intake and any unaccustomed or intensive exercise during the 72 h before the assessment sessions.

### ***Procedures***

The study was carried out following the guidelines contained in the Declaration of Helsinki and was approved by the University of Valencia Research Ethics Committee (1552264). All eligible candidates who agreed to take part in the study provided written informed consent.

During the week before measurements, participants were assessed for anthropometric parameters (i.e., body mass and height), and they were familiarized with all exercises (Supplementary Material). In this session, participants were instructed to use the proper technique throughout the exercises, and the pace of the exercise was also practiced before assessment and controlled using a metronome. The exercises were chosen based on existing scientific research to ensure lower-limb training (Appleby et al., 2019; Neumann, 2010).

The second visit was a 60-minute testing session. It began following a 10-min warm-up protocol involving dynamic stretching, jogging, double leg squats and jumping exercises. Then, MVIC from each muscle was obtained. The dominant (preferred kicking) limb was selected for data collection.

For MVIC, two 5-s maximum contractions with 1-minute resting intervals between trials were performed, and the highest mean EMG activity over 5 seconds was recorded as the MVIC. The MVIC test for knee flexors (i.e., BF and ST) was performed with participants lying in the prone position with their knees flexed 45°. Manual resistance was then applied at the ankle as the volunteer attempted to flex the knee. In addition, the MVIC for GM was taken with the subjects in a prone position and their knee flexed 90°. In this position, the subject was stabilized holding the uninvolved leg and the upper body and manual resistance was placed at the distal part of the femur, while the volunteer performed a hip extension. Finally, the MVIC for RF was taken with the subject on a quad extension machine, with the hip and torso firmly against the seat, 90° knee angle and a strap around the foot providing the fixed resistance, while the volunteer performed a knee extension.

After 3 minutes rest, exercises were carried out in a pre-established order: SQ (as bilateral and multiarticular exercise), HT (as bilateral and hip-dominant exercise) and BS (as unilateral exercise). However, the order of

exercise methods (i.e., CV and MV) was randomized using the simple randomization method according to <https://www.randomizer.org/>. At the end of each exercise, a 3-min rest was taken to allow full recovery.

Finally, the mean EMG activation of the GM, BF, ST and RF were recorded using the MVIC method for normalizing EMG data (in percentage).

### **Description of strength training methods and velocities**

Training procedures are shown in the Supplementary Material. For the SQ, HT and BS at CV, 1 series of 6 repetitions was performed using a metronome to guide the pace (3 s during the eccentric phase, 1 s during the isometric phase, and 2 s during the concentric phase with a constant velocity) (Calatayud et al., 2018). For SQ, HT and BS conducted at MV, volunteers were asked to do 1 set of 4 repetitions at a faster velocity (1 s during the eccentric phase, 1 s during the isometric phase and maximum velocity during the concentric phase). The number of repetitions was chosen in accordance with the type of training and time under tension commonly performed in a regular resistance training session (Baechle & Earle, 2008).

A 20-kg barbell and discs with various weights were used to adjust the load for each subject. The weight used in each exercise (the same for both methods) was obtained by calculating 60% of the 1-RM (Castillo et al., 2012). The 1-RM of each subject was estimated using the Vitruve Teams App (version 1.11.2) at the end of the warm-up session. Subjects performed 10 repetitions of each of the exercises at maximum velocity with two loads: 40 kg and 60 kg. Rest periods were 2 min between warm-up sets. Load-velocity profiles and validity of 1-RM prediction methods in different exercises using the Vitruve linear position transducer have been proven reliable (Kilgallon et al., 2022; Pérez-Castilla et al., 2019).

### **Instrumentation**

The mean muscle activation of GM, BF, ST and RF were monitored through surface EMG. For registering EMG signal, the skin was shaved, rubbed, and cleaned with alcohol. Electrodes were placed in pairs 1.5-2 cm apart and parallel to the muscle fibres. Electrode placement was according to SENIAM guidelines (Hermens et al., 1999). To ensure identical positioning of the electrodes, all EMG data were collected in a single session.

The EMG activity was recorded with two portable two-channel devices from the Shimmer group (Realtime Technologies Ltd, Dublin, Ireland) with a 16-bit analogue/digital (A/D) conversion. The sampling frequency was programmed at 1024 Hz. Moreover, during registration, the EMG signal was monitored using the mDurance software (mDurance Solutions S.L., Granada Spain) for Android and stored in a cloud server for further analysis. The application was installed on a ZTE BLADE device, model A506 with the Android 6.0.1 Marshmallow operating system (ZTE Corporation., Shenzhen, China).

A high-pass 20 Hz filter was used (De Luca et al., 2010) and the root mean square (RMS) was calculated from a window showing the duration of test execution and both movement phases were used for the analysis (i.e., concentric and eccentric). To obtain the EMG average, the four middle repetitions for each exercise at CV were used, while all the four repetitions of exercises at MV were used.

Further, to collect hip motion data, a sensor was placed in the middle of the thigh, 5 cm distal to the electrodes of the RF and in line with the patella. Hip range of motion was used to ensure that the SQ and the HT were performed at a similar range of motion through instant feedback to the researcher (5-10°) and to delimit duration of movement.

In order to compare values of different muscle activation patterns, EMG data were normalized as a percentage of the EMG signal recorded during MVIC tests as explained above.

**Statistical analysis**

Statistical data analysis was conducted using SPSS v26 (Inc. IBM., Chicago, IL, USA). Data were presented as mean and standard deviation (SD). A Repeated Measures T-test with the within-subjects factor ‘training method’ was used to search for differences between the two training methods (i.e., MV and CV) in the mean EMG activity of the key muscles (i.e., GM, BF, ST and RF). Type I error was set at 5% ( $p \leq .05$ ).

**RESULTS**

Fifteen physically active University students (5 females and 10 males) participated in this study. Demographic data are shown in Table 1.

Table 1. Demographic data.

	<b>Age (years)</b>	<b>Height (metres)</b>	<b>Weight (kilogrammes)</b>
Men	21.20 (0.63)	1.80 (0.08)	75.75 (9.90)
Women	20.20 (1.64)	1.65 (0.09)	62.00 (13.56)
Total	20.87 (1.13)	1.75 (0.11)	71.17 (12.67)

*Note. Data are expressed in mean (standard deviation).*

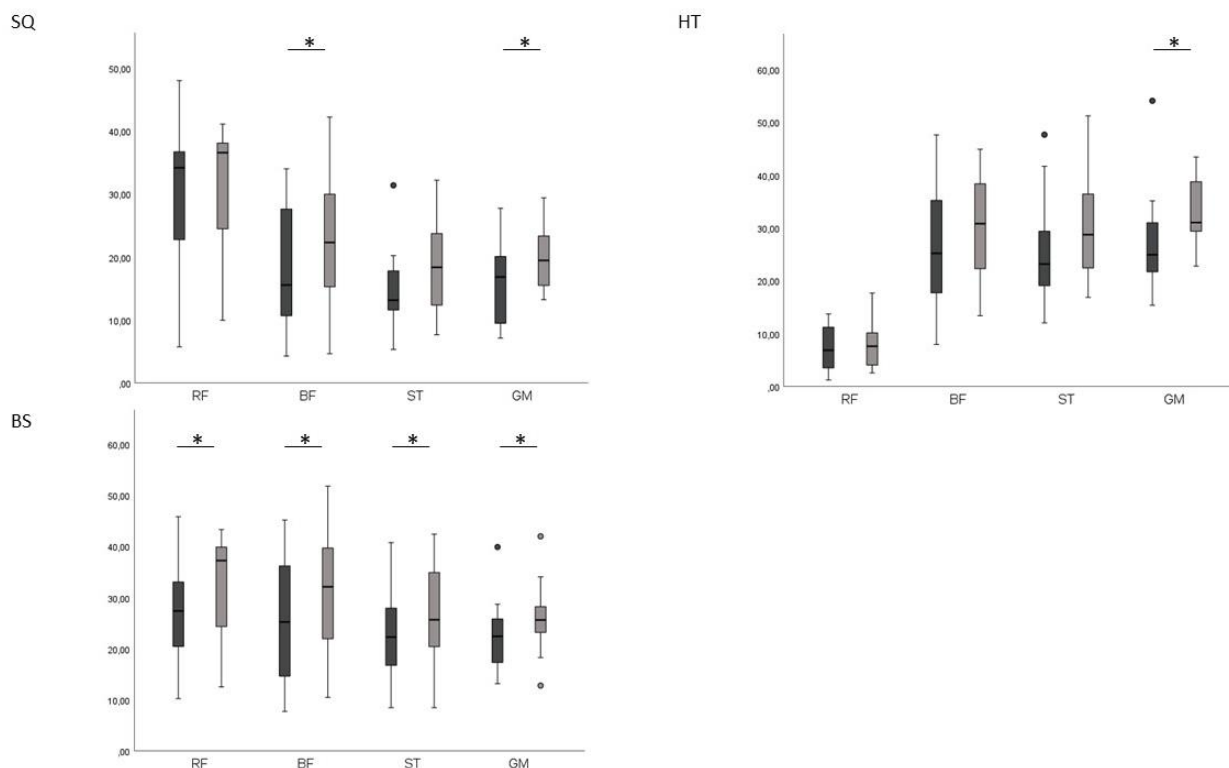


Figure 1. Comparison of mean EMG activity of the RF, BF, ST and GM muscles for SQ, HT and BS exercises using CV (dark bars) and MV (light bars).

Results of mean EMG activity in each muscle are shown in Figure 1. BF and GM obtained significantly higher values at MV compared to CV in SQ exercise, but ST and RF showed no differences between movement velocities in this exercise. With regard to HT, only GM showed significantly higher mean EMG activity at MV; for the other muscles there were no differences between movement velocities. For BS, all muscles exhibited significantly higher EMG activity at MV compared to CV.

## DISCUSSION

This is the first study to analyse EMG activity of the knee flexor and hip extensor muscles (i.e., RF, BF, ST and GM) during SQ, HT and BS exercises using two velocities (i.e., MV and CV). We investigated whether the increased velocity is enough to improve EMG activity of the muscles and thus avoid high-load strength training that has been related to injuries (Keogh & Winwood, 2017). Overall, significantly higher mean EMG activity was found at MV compared to CV for all muscles assessed except for RF.

Previous studies that assess the bench press exercise similarly compared different velocities (e.g., Sakamoto *et al.* (Sakamoto & Sinclair, 2012) compare slow 5.6 s/repetition, medium 2.8 s/repetition, fast 1.9 s/repetition, and MV; and Calatayud *et al.* and Gentil *et al.* (Calatayud *et al.*, 2018; Gentil *et al.*, 2017) compared CV vs MV), using the same load for each velocity. Their results were not consistent since not all muscles exhibited an increase in EMG amplitude when faster velocities were used to perform the exercises. Calatayud *et al.* and Sakamoto *et al.* (Calatayud *et al.*, 2018; Sakamoto & Sinclair, 2012) reported higher EMG activity for the pectoralis major, deltoid and triceps brachii muscles when higher speed was used, while Gentil *et al.* found no differences between movement velocities for the biceps and triceps brachii (Gentil *et al.*, 2017). Despite this controversy, earlier literature using other tools to assess differences between movement velocities in terms of muscle response (i.e., hypertrophy, strength, tensiomyography and other physiological parameters) supports that MV movements exhibit higher hormonal and neurological responses (Kojić *et al.*, 2021; Pryor *et al.*, 2011; Wilk *et al.*, 2018), while muscles are subject to a greater work load (Cormie *et al.*, 2009, 2010), as compared to lower movement velocities.

In this study, the average (minimum and maximum) increment in EMG activity when performing the exercises at MV was 17.41% (1.08%-25.49%) compared to CV. Although not entirely comparable, these values are slightly higher than those reported by Calatayud *et al.* (Calatayud *et al.*, 2019), which showed increments of EMG activity when performing the bench press exercise at MV of about 9% for the pectoralis major and 14% for the triceps brachii. This difference might be because they used a lower load (i.e., 50% 1-RM load compared to 60% 1-RM in our study). In the same line, Sakamoto *et al.* (Sakamoto & Sinclair, 2012) found an overall increment of EMG activity (around 20%) similar to our study when high velocity of movement was used for pectoralis major, triceps brachii and anterior deltoid exercises with a 60% 1-RM load.

When comparing muscle activation between velocities (i.e., MV or CV), in each of the exercises, SQ rendered a higher mean increment of EMG activity for BF and GM at MV. A rapid contraction produces higher muscle EMG activity through faster recruitment of motor units (Farina *et al.*, 2004; Felici, 2006), decreasing the required time for cross-bridge formations (Jones *et al.*, 2004) and fast-twitch motor units (Hunter *et al.*, 2005), and increasing velocity of movement (Carpentier *et al.*, 1996; Enoka, 2008). These results suggest that most of the main muscles involved in exercise performance significantly increase their activation when higher speeds are applied to the execution of the movement (i.e., BF and GM) (McCaw & Melrose, 1999).

Conversely, our results failed to report higher EMG activity during MV compared to CV in the SQ exercise for ST and RF, despite the major role of the latter muscle (McCaw & Melrose, 1999). RF has a particular



architecture, specifically its proportion of active type I and II fibres and its pennate architecture. On the one hand, RF has a higher proportion of fast-twitch muscle fibres and a lower proportion of slow-twitch muscle fibres compared to GM, ST and BF (Punkt, 2012). Accordingly, this muscle is more prepared to perform faster dynamic movements, without the need of increasing the EMG activity. On the other hand, when a pennate muscle, like RF, contracts and shortens, the penetration angle increases, allowing higher velocities without needing to increase muscle activity (Azizi et al., 2008).

Regarding the lack of significant differences between velocities in ST, it should be noted that ST has a more important intervention in single-limb SQ performance, as compared to double-limb SQ. During single-limb performance, less external hip rotation and greater knee abduction were recorded due to the repositioning of the body weight (Khuu et al., 2016). In this way, previous studies (McCurdy et al., 2018; Monajati et al., 2019) reported higher muscle activation of ST during the single-leg squat compared to the double-leg squat, while BF remains at a similar level of activation. Therefore, to better assess differences between velocities in this muscle, single-leg squat would be more appropriate, such as using the BS exercise.

For HT, only the GM muscle showed a significantly higher activation at MV compared to CV. In this case, MV produced higher EMG activation of those muscles most involved in the exercise performed; previous studies have shown that GM has a major role in the HT exercise execution, far more important than the role of other muscles involved (García et al., 2020; Neto et al., 2019). This main contribution is probably because HT produces greater bilateral extensor demand at the hip joint in comparison to the knee joint (Brazil et al., 2021) and, therefore, hip extensor muscles involving the knee joint (i.e., BF and ST) are activated to a smaller extent. In this way, the use of higher velocities may place a higher demand on the GM during the exercise, improving its EMG activation capacity with low loads, making this a feasible option for the recovery or prevention of hip injuries. Indeed, HT could be an ideal exercise for untrained people because it is a guided close-chain exercise, preventing unwanted movements, even at high velocities.

With regard to the BS exercise, higher mean EMG activity was registered at MV for all muscles. This single-leg squat exercise has shown to produce higher neuromuscular activation in both hamstring and quadriceps muscles as compared to other types of squats (i.e., double-leg squat and double-leg squat with Bosu) (Monajati et al., 2019) at a slow velocity. As with the HT exercise, the use of fast speeds during the performance of BS promoted higher EMG activity of the main muscles involved in execution (i.e., all assessed muscles). Thus, BS at MV could be useful to increase muscle activation in trained people, but further studies are needed to establish how higher speeds during BS may affect muscle activation in untrained people lacking the training skills of the former.

Overall, the findings suggest that the greater the difficulty or instability of the exercise, (i.e., BS) the higher the increase in muscle activation at high speeds for all the muscles involved.

There were some limitations in this study since all participants were active healthy individuals; thus, our results cannot be extrapolated to the sedentary population. Moreover, activation strategies not only vary among individuals but are unique to each individual (Hug et al., 2010). Our results support this idea based on the large standard deviations obtained. Accordingly, individual differences must be accounted for when setting SQ, HT and BS workout routines at MV or CV.

## CONCLUSION

This study supports that standard lower-limb exercises performed at MV generally achieve higher muscle activation compared to their CV performance using the same load. Larger increments were obtained in the more physically demanding exercises.

Therefore, SQ, HT and BF at MV could be an ideal option for achieving higher muscle activation of BF, ST and GM, while avoiding the risks of high-intensity training.

## AUTHOR CONTRIBUTIONS

Pilar Serra-Añó: conceptualization, data analysis, supervision, final article revision, and project administration. Ana Ferri-Caruana, Sara Mollà-Casanova, Elena Muñoz-Gómez: methodology, data analysis and article redaction. Pablo Camarón-Mallén: assessments and data acquisition.

## SUPPORTING AGENCIES

This work was partially supported by Grants from the Spanish Government (PID2021-125694OB-I00; co-financed by EU FEDER funds;), Generalitat Valenciana, Conselleria d'Innovació, Universitats, Ciència i Societat (CIAICO/2021/215); and from Universitat de València (INV19-01-13-07).

## DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

## ACKNOWLEDGMENTS

We would like to thank all the subjects who selflessly participated in the study and to Il·lustre Colegio Oficial de Fisioterapeutas de la CV.

## REFERENCES

- Alcaraz-Ibañez, M., & Rodríguez-Pérez, M. (2018). Effects of resistance training on performance in previously trained endurance runners: A systematic review. *Journal of sports sciences*, 36(6), 613-629. <https://doi.org/10.1080/02640414.2017.1326618>
- Appleby, B. B., Cormack, S. J., & Newton, R. U. (2019). Specificity and transfer of lower-body strength: Influence of bilateral or unilateral lower-body resistance training. *The Journal of Strength & Conditioning Research*, 33(2), 318-326. <https://doi.org/10.1519/JSC.0000000000002923>
- Azizi, E., Brainerd, E. L., & Roberts, T. J. (2008). Variable gearing in pennate muscles. *Proceedings of the National Academy of Sciences*, 105(5), 1745-1750. <https://doi.org/10.1073/pnas.0709212105>
- Baechle, T. R., & Earle, R. W. (2008). *Essentials of strength training and conditioning*. Human kinetics.
- Bourne, M. N., Timmins, R. G., Opar, D. A., Pizzari, T., Ruddy, J. D., Sims, C., Williams, M. D., & Shield, A. J. (2018). An evidence-based framework for strengthening exercises to prevent hamstring injury. *Sports Medicine*, 48(2), 251-267. <https://doi.org/10.1007/s40279-017-0796-x>
- Brazil, A., Needham, L., Palmer, J. L., & Bezodis, I. N. (2021). A comprehensive biomechanical analysis of the barbell hip thrust. *PloS one*, 16(3), e0249307. <https://doi.org/10.1371/journal.pone.0249307>



- Buckthorpe, M., & Roi, G. S. (2017). The time has come to incorporate a greater focus on rate of force development training in the sports injury rehabilitation process. *Muscles, ligaments and tendons journal*, 7(3), 435. <https://doi.org/10.11138/mltj/2017.7.3.435>
- Calatayud, J., Casaña, J., Martín, F., Jakobsen, M. D., Andersen, L. L., & Colado, J. C. (2019). Electromyographic effect of using different attentional foci during the front plank exercise. *American journal of physical medicine & rehabilitation*, 98(1), 26-29. <https://doi.org/10.1097/PHM.0000000000001008>
- Calatayud, J., Vinstrup, J., Jakobsen, M. D., Sundstrup, E., Colado, J. C., & Andersen, L. L. (2018). Influence of different attentional focus on EMG amplitude and contraction duration during the bench press at different speeds. *Journal of sports sciences*, 36(10), 1162-1166. <https://doi.org/10.1080/02640414.2017.1363403>
- Carpentier, A., Duchateau, J., & Hainaut, K. (1996). Velocity-dependent muscle strategy during plantarflexion in humans. *Journal of Electromyography and Kinesiology*, 6(4), 225-233. [https://doi.org/10.1016/S1050-6411\(96\)00003-X](https://doi.org/10.1016/S1050-6411(96)00003-X)
- Castillo, F., Valverde, T., Morales, A., Pérez-Guerra, A., De León, F., & García-Manso, J. M. (2012). Maximum power, optimal load and optimal power spectrum for power training in upper-body (bench press): A review. *Revista Andaluza de Medicina del Deporte*, 5(1), 18-27. [https://doi.org/10.1016/S1888-7546\(12\)70005-9](https://doi.org/10.1016/S1888-7546(12)70005-9)
- Clark, D. R., Lambert, M. I., & Hunter, A. M. (2012). Muscle activation in the loaded free barbell squat: A brief review. *The Journal of Strength & Conditioning Research*, 26(4), 1169-1178. <https://doi.org/10.1519/JSC.0b013e31822d533d>
- Cochrane, D. J., & Barnes, M. J. (2015). Muscle activation and onset times of hip extensors during various loads of a closed kinetic chain exercise. *Research in Sports Medicine*, 23(2), 179-189. <https://doi.org/10.1080/15438627.2015.1005299>
- Contreras, B., Vigotsky, A. D., Schoenfeld, B. J., Beardsley, C., & Cronin, J. (2015). A comparison of gluteus maximus, biceps femoris, and vastus lateralis electromyographic activity in the back squat and barbell hip thrust exercises. *Journal of applied biomechanics*, 31(6), 452-458. <https://doi.org/10.1123/jab.2014-0301>
- Contreras, B., Vigotsky, A. D., Schoenfeld, B. J., Beardsley, C., McMaster, D. T., Reyneke, J. H., & Cronin, J. B. (2017). Effects of a six-week hip thrust vs. front squat resistance training program on performance in adolescent males: A randomized controlled trial. *Journal of strength and conditioning research*, 31(4), 999-1008. <https://doi.org/10.1519/JSC.0000000000001510>
- Cormie, P., McBride, J. M., & McCaulley, G. O. (2009). Power-time, force-time, and velocity-time curve analysis of the countermovement jump: Impact of training. *The Journal of Strength & Conditioning Research*, 23(1), 177-186. <https://doi.org/10.1519/JSC.0b013e3181889324>
- Cormie, P., McGuigan, M. R., & Newton, R. U. (2010). Adaptations in athletic performance after ballistic power versus strength training. *Med Sci Sports Exerc*, 42(8), 1582-1598. <https://doi.org/10.1249/MSS.0b013e3181d2013a>
- Cronin, N. J., Peltonen, J., Ishikawa, M., Komi, P. V., Avela, J., Sinkjaer, T., & Voigt, M. (2008). Effects of contraction intensity on muscle fascicle and stretch reflex behavior in the human triceps surae. *Journal of Applied Physiology*, 105(1), 226-232. <https://doi.org/10.1152/jappphysiol.90432.2008>
- De Luca, C. J., Gilmore, L. D., Kuznetsov, M., & Roy, S. H. (2010). Filtering the surface EMG signal: Movement artifact and baseline noise contamination. *Journal of biomechanics*, 43(8), 1573-1579. <https://doi.org/10.1016/j.jbiomech.2010.01.027>
- Enoka, R. M. (2008). *Neuromechanics of human movement*. Human kinetics.
- Farina, D., Merletti, R., & Enoka, R. M. (2004). The extraction of neural strategies from the surface EMG. *Journal of applied physiology*, 96(4), 1486-1495. <https://doi.org/10.1152/jappphysiol.01070.2003>

- Felici, F. (2006). Neuromuscular responses to exercise investigated through surface EMG. *Journal of Electromyography and Kinesiology*, 16(6), 578-585. <https://doi.org/10.1016/j.jelekin.2006.08.002>
- Ferri Caruana, A. M., Prades Insa, B., & Serra Añó, P. (2020). Effects of pelvic and core strength training on biomechanical risk factors for anterior cruciate ligament injuries. *Journal of Sports Medicine and Physical Fitness*, 2020, vol. 60, p. 1128-1138. <https://doi.org/10.23736/S0022-4707.20.10552-8>
- García, C. L. C., Rueda, J., Luginick, B. S., & Navarro, E. (2020). Differences in the electromyographic activity of lower-body muscles in hip thrust variations. *The Journal of Strength & Conditioning Research*, 34(9), 2449-2455. <https://doi.org/10.1519/JSC.0000000000002859>
- Gentil, P., Bottaro, M., Noll, M., Werner, S., Vasconcelos, J. C., Seffrin, A., & Campos, M. H. (2017). Muscle activation during resistance training with no external load-effects of training status, movement velocity, dominance, and visual feedback. *Physiology & behavior*, 179, 148-152. <https://doi.org/10.1016/j.physbeh.2017.06.004>
- Hassani, A., Patikas, D., Bassa, E., Hatzikotoulas, K., Kellis, E., & Kotzamanidis, C. (2006). Agonist and antagonist muscle activation during maximal and submaximal isokinetic fatigue tests of the knee extensors. *Journal of electromyography and kinesiology*, 16(6), 661-668. <https://doi.org/10.1016/j.jelekin.2005.11.006>
- Hermens, H. J., Freriks, B., Merletti, R., Stegeman, D., Blok, J., Rau, G., Disselhorst-Klug, C., & Hägg, G. (1999). European recommendations for surface electromyography. *Roessingh research and development*, 8(2), 13-54.
- Hug, F., Turpin, N. A., Guével, A., & Dorel, S. (2010). Is interindividual variability of EMG patterns in trained cyclists related to different muscle synergies? *Journal of applied physiology*, 108(6), 1727-1736. <https://doi.org/10.1152/jappphysiol.01305.2009>
- Hunter, J. P., Marshall, R. N., & McNair, P. J. (2005). Relationships between ground reaction force impulse and kinematics of sprint-running acceleration. *Journal of applied biomechanics*, 21(1), 31-43. <https://doi.org/10.1123/jab.21.1.31>
- Jakobsen, M. D., Sundstrup, E., Andersen, C. H., Aagaard, P., & Andersen, L. L. (2013). Muscle activity during leg strengthening exercise using free weights and elastic resistance: Effects of ballistic vs controlled contractions. *Human movement science*, 32(1), 65-78. <https://doi.org/10.1016/j.humov.2012.07.002>
- Jones, D. A., Round, J. M., & De Haan, A. (2004). *Skeletal Muscle from Molecules to Movement: A Textbook of Muscle Physiotherapy for Sport*. Exercise and Physiotherapy: Edinburgh.
- Keogh, J. W., Wilson, G. J., & Weatherby, R. E. (1999). A cross-sectional comparison of different resistance training techniques in the bench press. *The Journal of Strength & Conditioning Research*, 13(3), 247-258. <https://doi.org/10.1519/00124278-199908000-00012>
- Keogh, J. W., & Winwood, P. W. (2017). The epidemiology of injuries across the weight-training sports. *Sports medicine*, 47(3), 479-501. <https://doi.org/10.1007/s40279-016-0575-0>
- Khuu, A., Foch, E., & Lewis, C. L. (2016). Not all single leg squats are equal: A biomechanical comparison of three variations. *International journal of sports physical therapy*, 11(2), 201.
- Kilgallon, J., Cushion, E., Joffe, S., & Tallent, J. (2022). Reliability and validity of velocity measures and regression methods to predict maximal strength ability in the back-squat using a novel linear position transducer. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*, 17543371221093188. <https://doi.org/10.1177/17543371221093189>
- Kojić, F., Ranisavljev, I., Ćosić, D., Popović, D., Stojiljković, S., & Ilić, V. (2021). Effects of resistance training on hypertrophy, strength and tensiomyography parameters of elbow flexors: Role of eccentric phase duration. *Biology of Sport*, 38(4), 587-594. <https://doi.org/10.5114/biolSport.2021.99323>

- Krzysztofik, M., Wilk, M., Wojdalla, G., & Gollaś, 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. <https://doi.org/10.3390/ijerph16244897>
- Kuriki, H. U., Mello, E. M., De Azevedo, F. M., Takahashi, L. S. O., Alves, N., & de Faria Negrão Filho, R. (2012). The relationship between electromyography and muscle force. Citeseer.
- McCaw, S. T., & Melrose, D. R. (1999). Stance width and bar load effects on leg muscle activity during the parallel squat. *Medicine and science in sports and exercise*, 31, 428-436. <https://doi.org/10.1097/00005768-199903000-00012>
- McCurdy, K., Walker, J., & Yuen, D. (2018). Gluteus maximus and hamstring activation during selected weight-bearing resistance exercises. *The Journal of Strength & Conditioning Research*, 32(3), 594-601. <https://doi.org/10.1519/JSC.0000000000001893>
- Monajati, A., Larumbe-Zabala, E., Goss-Sampson, M., & Naclerio, F. (2019). Surface electromyography analysis of three squat exercises. *Journal of human kinetics*, 67(1), 73-83. <https://doi.org/10.2478/hukin-2018-0073>
- Neto, W. K., Vieira, T. L., & Gama, E. F. (2019). Barbell hip thrust, muscular activation and performance: A systematic review. *Journal of sports science & medicine*, 18(2), 198.
- Neumann, D. A. (2010). Kinesiology of the hip: A focus on muscular actions. *Journal of Orthopaedic & Sports Physical Therapy*, 40(2), 82-94. <https://doi.org/10.2519/jospt.2010.3025>
- Pérez-Castilla, A., Piepoli, A., Delgado-García, G., Garrido-Blanca, G., & García-Ramos, A. (2019). Reliability and concurrent validity of seven commercially available devices for the assessment of movement velocity at different intensities during the bench press. *The Journal of Strength & Conditioning Research*, 33(5), 1258-1265. <https://doi.org/10.1519/JSC.0000000000003118>
- Pincivero, D. M., Gandhi, V., Timmons, M. K., & Coelho, A. J. (2006). Quadriceps femoris electromyogram during concentric, isometric and eccentric phases of fatiguing dynamic knee extensions. *Journal of biomechanics*, 39(2), 246-254. <https://doi.org/10.1016/j.jbiomech.2004.11.023>
- Pryor, R. R., Sforzo, G. A., & King, D. L. (2011). Optimizing power output by varying repetition tempo. *The Journal of Strength & Conditioning Research*, 25(11), 3029-3034. <https://doi.org/10.1519/JSC.0b013e31820f50cb>
- Punkt, K. (2012). *Fibre Types in Skeletal Muscles*. Springer Science & Business Media.
- Sakamoto, A., & Sinclair, P. J. (2012). Muscle activations under varying lifting speeds and intensities during bench press. *European journal of applied physiology*, 112(3), 1015-1025. <https://doi.org/10.1007/s00421-011-2059-0>
- Smilios, I., Häkkinen, K., & Tokmakidis, S. P. (2010). Power output and electromyographic activity during and after a moderate load muscular endurance session. *The Journal of Strength & Conditioning Research*, 24(8), 2122-2131. <https://doi.org/10.1519/JSC.0b013e3181a5bc44>
- Snyder, B. J., & Fry, W. R. (2012). Effect of verbal instruction on muscle activity during the bench press exercise. *The Journal of Strength & Conditioning Research*, 26(9), 2394-2400. <https://doi.org/10.1519/JSC.0b013e31823f8d11>
- Stastny, P., Gollaś, A., Blazek, D., Maszczyk, A., Wilk, M., Pietraszewski, P., Petr, M., Uhlir, P., & Zajac, A. (2017). A systematic review of surface electromyography analyses of the bench press movement task. *PloS one*, 12(2), e0171632. <https://doi.org/10.1371/journal.pone.0171632>
- Tsoukos, A., Brown, L. E., Terzis, G., Wilk, M., Zajac, A., & Bogdanis, G. C. (2021). Changes in EMG and movement velocity during a set to failure against different loads in the bench press exercise. *Scandinavian Journal of Medicine & Science in Sports*, 31(11), 2071-2082. <https://doi.org/10.1111/sms.14027>

- van den Tillaar, R., Andersen, V., & Saeterbakken, A. H. (2019). Comparison of muscle activation and kinematics during free-weight back squats with different loads. *PLoS One*, 14(5), e0217044. <https://doi.org/10.1371/journal.pone.0217044>
- van den Tillaar, R., Saeterbakken, A. H., & Ettema, G. (2012). Is the occurrence of the sticking region the result of diminishing potentiation in bench press? *Journal of sports sciences*, 30(6), 591-599. <https://doi.org/10.1080/02640414.2012.658844>
- van den Tillaar, R., & Sousa, C. (2019). Comparison of muscle activation and barbell kinematics during bench press with different loads. *Acta Kinesiologiae Universitatis Tartuensis*, 25, 37-50. <https://doi.org/10.12697/akut.2019.25.03>
- Watanabe, K., & Akima, H. (2011). Effect of knee joint angle on neuromuscular activation of the vastus intermedius muscle during isometric contraction. *Scandinavian journal of medicine & science in sports*, 21(6), e412-e420. <https://doi.org/10.1111/j.1600-0838.2011.01347.x>
- Wilk, M., Stastny, P., Golas, A., Nawrocka, M., Jelen, K., Zajac, A., & Tufano, J. (2018). Physiological responses to different neuromuscular movement task during eccentric bench press. *Neuroendocrinology Letters*, 39(1), 101-107.

