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# Comparison of concentric and eccentric resistance training in terms of changes in the muscle contractile properties

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ABSTRACT

The habitual use of resistance exercises involving concentric and eccentric contractions can increase muscle strength, speed and endurance. However, current knowledge has limited potential to fully understand the application of such resistance training and the muscle changes that occur to differentiate these two types of training. The aim of this study was to compare the effects of concentric contraction (CON) and eccentric contraction (ECC) during an acute bout of resistance training on the hamstring contractile properties. A group of 20 female recreational athletes were divided into two equal groups, CON training and ECC training. The contractile properties of the muscles on both sides of the body were assessed using tensiomyography (TMG): biceps femoris (BF) and semitendinosus (ST). The muscles were assessed twice, before and after 10 maximal repetitions of either concentric or eccentric isotonic contractions. The results indicate a greater change in TMG parameters with ECC training, with $p < 0.001$ (Td and Tc). An acute bout of resistance training induces changes in the muscle hamstrings contractile properties in both CON and ECC training. Eccentric training causes greater changes than concentric training, shortening contraction time (Td, Tc), increase radial displacement velocity (Vrd) and affecting changes in muscle belly displacement (Dm), so may be more effective in training.

## 1. Introduction

The efficiency of the muscular system is a crucial determinant of sports performance, injury prevention, and physical fitness (Bompa & Buzzichelli, 2021). Therefore, many studies have focused on designing resistance training programs that would enhance muscle capabilities. Resistance training can be oriented towards different goals, leading to various adaptations in the muscle system, depending on the applied stimulus. For example, it can be aimed at building strength, hypertrophy, or muscular endurance (Fleck & Kraemer, 2014; Unlu et al., 2020).

Skeletal muscles, which are attached to bones and move them relative to each other, can have two types of contraction during muscle activation: concentric (CON) or eccentric (ECC). In the case of CON, the muscle attachments are brought closer together, while in ECC, they move away from each other (Franchi et al., 2017). During a CON contraction, the muscle shortens and exerts force, which is transmitted through the tendon to the joint, enabling movement and causing a change in the joint angle. ECC contractions also occur during everyday movements, allowing for the dissipation of mechanical energy during the deceleration of body movements (Konow & Roberts, 2015). This type of contraction occurs, for example, during landing from a jump or descending stairs, in which the quadriceps muscles generate force by lengthening and decelerating the movement. ECC contractions also enable the conversion of kinetic energy into elastic energy stored in the tendons, partially recovering energy and resulting in less muscle work (Hoppeler, 2014). During traditional resistance training, which involves lifting or lowering external weight, people combine CON muscle work during lifting and ECC work during lowering the weight.

Eccentric muscle contraction is a fundamental process of human movement, but surprisingly, it is an area of exercise science that has been poorly studied. It is believed that ECC contractions may induce greater muscle strength and hypertrophy than CON contractions, as they generate greater muscular force (Franchi et al., 2017; Maeo et al., 2018; Mendez-Villanueva et al., 2016). However, some authors argue that

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there are no differences between ECC and CON resistance training (Gonzalez-Izal et al., 2014; Schoenfeld et al., 2017). Concentric resistance training can effectively reduce pain (Vincent & Vincent, 2020), which can limit an organism's mobility (Skorupska, 2018; Skorupska et al., 2013). ECC training, on the other hand, is characterized by the production of higher torque (Hollander et al., 2007), while generating lower bioelectrical muscle activity (Borysiuk et al., 2018; Pakosz & Konieczny, 2020; Westing et al., 1991). Additionally, ECC training may result in better muscle adaptation in elite athletes in a shorter period of time (Mendez-Villanueva et al., 2016). There is also evidence to suggest that properly conducted ECC training can prevent injuries (Hu et al., 2023). Despite many positive aspects, ECC training can cause pain, swelling, and reduced range of motion due to muscle fiber damage, which can result in muscle weakness (Kibler & Armstrong, 1990; Paulsen et al., 2019). Therefore, the impact of ECC and CON exercises on muscle parameters is still a matter of debate, and the mechanisms regulating these adaptations have not been fully elucidated.

The hamstring muscles are key muscles responsible for athlete's movement in many sports disciplines and are also among the most frequently injured muscles (Brukner, 2015; Đorđević et al., 2022; Ekstrand et al., 2011). Their primary function is knee flexion, but they also perform eccentric work to absorb force during knee extension movements, slow down momentum during late swing phase of sprinting, and prepare the foot for ground contact. Therefore, ensuring the strength of the hamstring muscles, especially in eccentric contractions, is important to maintain the overall functional capacity of the muscle group and prevent overuse injuries (Schache et al., 2009; Yu et al., 2008).

However, the effect of eccentric and concentric muscle contractions on the hamstring, measured directly after an acute bout of resistance training, remains unclear. Research in this area is significant because optimal muscle contraction ability is crucial for training quality and performance outcomes (Bompa & Buzzichelli, 2021). To assess the muscular system's ability, a relatively new method for monitoring muscle contraction function, called tensiomyography (TMG), has been developed. TMG is a non-invasive technique that uses a portable device to measure the properties of individual superficial muscles by recording an isometric muscle contraction induced externally by electrostimulation (Pakosz et al., 2021). TMG can provide information about muscle parameters during the contraction and muscle belly deformation (Macgregor et al., 2018). It can also monitor muscle fiber composition, tension of individual muscles, fatigue of these muscles, muscular imbalance in joints, or between both sides of the body (Pakosz et al., 2021). Tensiomyography (TMG) is a modern diagnostic tool that allows the examination of isolated muscles or even muscle actones (Macgregor et al., 2018), which is also achievable with electromyography (EMG) but requires effort from the subject being tested. This is important for monitoring athletes' physiological status to assess training effectiveness, but such monitoring requires initial muscle assessment and continuous monitoring (Muñoz-López et al., 2022).

Despite numerous studies conducted, the effects of CON and ECC training on changes in the muscle contractile properties are still unknown. Such an assessment can help coaches utilize the differences in muscle profile during training, which can lead to the development of the most appropriate training program to enhance muscle growth and prevent injuries. Therefore, the aim of this study was to compare the effects of CON vs ECC training on changes in muscle parameters measured by means of TMG. The hypothesis was formulated that different training stimuli, such as CON or ECC training, would induce different adaptations in hamstring muscle contractile properties after an acute bout of resistance training. We expected ECC training to produce greater changes than CON training, according to literature.

## 2. Methods

### 2.1. Study design

This study contributes to the knowledge of the effects of resistance training using concentric (CON) and eccentric (ECC) contractions, the effects of which are known but still poorly understood. A repeated measures design was used to determine the temporal response of the muscle during CON or ECC training. Tensiomyography (TMG) was used as a tool to measure the mechanical response of the muscle. The participants had no previous femoral injuries and were randomly assigned to two equal groups of 10, either CON or ECC training. On the day of the study, the athletes were asked to refrain from physical activity and stimulant-containing products.

### 2.2. Participants

The study group comprised of 20 young female athletes (age = 21.3 ± 0.9, body mass = 65.4 ± 5.4 kg, body height = 168.4 ± 9.6) who exercised recreationally 3 times a week. The recreational training lasted approximately an hour and a half, and encompassed various physical activities aimed at improving overall fitness and health. The training program included aerobic elements such as jogging, stationary cycling, and treadmill exercises to enhance cardiovascular endurance. Additionally, strength exercises such as weightlifting and machine-based strength training were incorporated to build muscle strength. The recreational training also aimed to develop motor skills, coordination, and flexibility. The athletes also engaged in stretching, pilates, and gymnastics exercises to improve muscle flexibility and mobility. All participants were right-footed and provided informed consent to participate in the tests, approved by the Bioethics Commission of the Chamber of Physicians in Opole No. 260, following the guidelines specified in the Declaration of Helsinki on human experimentation.

### 2.3. Procedure

The hamstring TMG test was performed twice per athlete: at rest and after eccentric or concentric muscle resistance training. The resistance test and measurement were performed on both lower limbs of the hamstring muscles: biceps femoris (BF) and semitendinosus (ST). During the first test, the athlete had a TMG measurement taken after 10 min of rest from any activity, followed by a 10-minute warm-up on a stationary bike to prepare the hamstring muscles for the test. The load on the stationary bike was 100 W (10 MET), adhering to a rhythm between 60 and 70 revolutions per minute (rpm). The warm-up was followed by the actual resistance test. The athletes were randomly assigned to either an eccentric exercise group (ECC) or a concentric exercise group (CON), so that there were equal numbers of people in each group. Prior to the testing procedure, participants were instructed to lie face down on the examination table, with their feet freely hanging beyond the edge. Subsequently, the appropriate testing procedures were conducted, and muscle responses were recorded. Introducing this specific research position helped minimize disruptions and ensured appropriate and comparable results among the participants. Tests consisted of 10 maximal concentric or eccentric repetitions of hamstring muscle work. Manual resistance was adjusted by an one experienced researcher to match the strength level of each participant and was gradually increased as training progressed, so that the last repetition was performed with difficulty and the participant was unable to perform another repetition (Fig. 1). Athletes reached a level of fatigue of 9–10 on the 10-point OMNI-RES scale during the test. The tempo of each trial was 3 s at maximum load, followed by 1 s of rest, 1 s of return to the starting position, and 1 s of rest. In the concentric test, the lower limb was fully extended, followed by a resistance movement where the subject moved their heel close to the buttock until 90 degrees of knee flexion was reached, with the hip joint straight. The eccentric test was performed

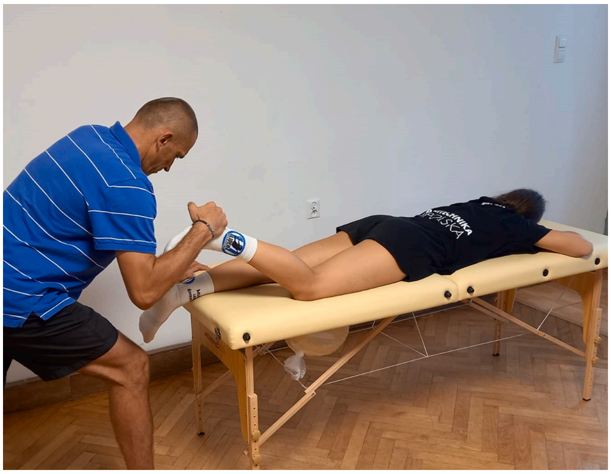

**Fig. 1.** Research setup during manual resistance test.

from 90 degrees of knee flexion and ended with full knee extension. In both cases, the examiner applied a load to the subject's heel, preventing flexion of the knee joint in the CON test and straightening the knee joint from 90 degrees to full extension in the ECC test. Verbal encouragement was given during all exercise tests to elicit maximum effort from the subject.

The following parameters of TMG were assessed in the study: muscle displacement (Dm), contraction time (Tc), and delay time (Td). To obtain a measure that is relatively independent of Dm (muscle belly displacement), the radial displacement velocity (Vrd) is calculated as the ratio ($mm \cdot s^{-1}$) between the radial displacement occurring within a specific time period of Tc(0.8 * Dm)/Tc * 1000. This formula is derived from the proposal by Valenčič & Knez (1997), where $Vr = \Delta dr/\Delta tr$, with $\Delta dr$ representing the difference in muscle belly displacement during the rise time, and $\Delta tr$ denoting the rise time. To record these parameters, a pressure sensor connected to a digital displacement converter was used. The sensor was mounted perpendicular to the belly of the muscle and had a controlled initial pressure of $1.5 \times 10^{-2}$ N/mm2. The digital displacement converter (GK 40 Panoptik d.o.o., Ljubljana, Slovenia) had a spring installed with a value of 0.17 N/mm. The sensor was placed on the thickest fragment of the muscle belly, which was determined visually and by palpation during voluntary contraction. The muscle was stimulated by two self-adhesive electrodes (Axelgaard, Pulse), which were spaced 2–5 cm apart and delivered a 1 ms pulse from an electrostimulator (TMG-S1, Furlan and Co. ltd.). The size and position of the electrodes were adjusted to isolate the contraction of the target muscle and avoid activation of nearby muscles. Electrical stimulation with a pulse duration of 1 ms and an initial current amplitude of 30 mA was applied, which was increased by 10 mA steps until reaching 100 mA (maximum output of the stimulator). A 10-second interval was maintained between each pulse. The digital TMG signal was taken directly from the MATLAB Compiler Toolbox at a sampling frequency of 1 kHz. The TMG signal was recorded and stored on a portable PC computer. The maximum amplitude of stimulation was determined as the minimum current required to induce the largest muscle displacement (Dm).

Based on previous research conducted by Pakosz et al. (2021), the reliability of measuring Dm, Tc, and Td was assessed in terms of both relative and absolute measures. The results indicated high reliability for all three measurements: Dm showed a relative reliability of 0.92 with a range of 0.80–0.97, a coefficient of variation (cv) of 6.5 %, and a standard error of measurement (SEM) of 7.35 %. Similarly, Tc demonstrated a relative reliability of 0.92 within a range of 0.80–0.96, a cv of 4.4 %, and an SEM of 4.37 %. Lastly, Td exhibited a relative reliability of 0.93 with a range of 0.84–0.97, a cv of 3.4 %, and an SEM of 2.89 %.

### *2.4. Statistical analyses*

The authors employed a repeated measures ANOVA to assess the significance of differences among the factors: Muscle (Biceps Femoris - BF, Semitendinosus - ST), Contraction (eccentric - ECC, concentric - CON), Side (Left, Right), and Time (Before, After). Significance was determined at $p \leq 0.05$. Additionally, eta squared (ηp2) was utilized as a measure of effect size in the ANOVA, with ηp2 values of ≥ 0.01 indicating a small effect, ≥0.06 indicating a medium effect, and ≥0.14 indicating a large effect. The sample size of 20 participants was sensitive enough to detect an effect size of f = 0.19, a power of 80 %, and a significance level of 5 %, as indicated by the GPower tool. The data was analysed using Jamovi 2.2.3 software.

## 3. Results

The results of parameter Td showed that the Contraction factor had a significant and large effect on muscle performance ($p < 0.001$, ηp2 = 0.27), and the Muscle factor displayed a statistically significant but medium effect ($p = 0.037$, ηp2 = 0.06) (Table 1). While the factor Muscle and Contraction did not have significant effects, and the effect was small ($p = 0.726$, ηp2 = 0.04). Regarding the differences between muscle groups, the results showed that there were no significant differences between muscle groups ($p > 0.05$). Finally, the study examined the effects of different exercise interventions on muscle performance. The results showed that there were significant differences between ECC Before and ECC After ($p < 0.001$), as well as between CON Before and CON After ($p = 0.025$).

The results of parameter Tc showed that the factor of Contraction had a significant and large effect on muscle performance ($p < 0.001$, ηp2 = 0.17), while the factor of Muscle and the interaction between Muscle and Contraction did not have significant effects, and the effect was small (Muscle: $p = 0.051$, ηp2 = 0.05; Muscle × Contraction: $p = 0.884$, ηp2 = 0.03) (Table 2). Regarding the differences between muscle groups, the results showed that there were no significant differences between muscles. Finally, the study examined the effects of different exercise interventions on muscle performance. The results showed that there were significant differences between ECC Before and ECC After ($p < 0.001$), but there were no significant differences between CON Before and CON After ($p = 0.708$).

The results of parameter Dm showed that the factor of Muscle had a significant and medium effect on muscle performance ($F = 4.554$, $p = 0.004$, ηp2 = 0.09), while the factor of Contraction and the interaction between Muscle and Contraction did not have significant effects, and the effect was small (Contraction: $F = 2.565$, $p = 0.057$, ηp2 = 0.05; Muscle × Contraction: $F = 0.221$, $p = 0.991$, ηp2 = 0.01) (Table 3). Regarding the differences between muscle groups, no significant differences between any other muscle groups ($p > 0.05$). Finally, the study examined the effects of different exercise interventions on muscle performance. The results showed that there was no significant differences between results.

The results show that both types of training led to changes in the

**Table 1**
Results of the Td parameter analyses.

| Factors | Test statistics | | Effect size |
|---|---|---|---|
| | f | p | $\eta_p^2$ |
| Muscle | 2.911 | 0.037 | 0.06 |
| Contraction | 17.607 | < 0.001 | 0.27 |
| Muscle × Contraction | 0.68 | 0.726 | 0.04 |
| **Group** | | | |
| **Group 1** | **Group 2** | | **p** |
| LEFT BF - Biceps Femoris | RIGHT BF - Biceps Femoris | | 0.991 |
| LEFT ST - Semitendinosus | RIGHT ST – Semitendinosus | | 0.162 |
| ECC Before | ECC After | | < 0.001 |
| CON Before | CON After | | 0.025 |

**Table 2**
Results of the Tc parameter analyses.

| Factors | Test statistics | | Effect size |
|---|---|---|---|
| | f | p | $\eta_p^2$ |
| Muscle | 2.65 | 0.051 | 0.05 |
| Contraction | 9.574 | < 0.001 | 0.17 |
| Muscle × Contraction | 0.484 | 0.884 | 0.03 |
| **Group** | | | |
| **Group 1** | **Group 2** | | **p** |
| LEFT BF - Biceps Femoris | RIGHT BF - Biceps Femoris | | 1 |
| LEFT ST - Semitendinosus | RIGHT ST - Semitendinosus | | 0.707 |
| ECC Before | ECC After | | < 0.001 |
| CON Before | CON After | | 0.708 |

**Table 3**
Results of the Dm parameter analyses.

| Factors | Test statistics | | Effect size |
|---|---|---|---|
| | f | p | $\eta_p^2$ |
| Muscle | 4.554 | 0.004 | 0.09 |
| Contraction | 2.565 | 0.057 | 0.05 |
| Muscle × Contraction | 0.221 | 0.991 | 0.01 |
| **Group** | | | |
| **Group 1** | **Group 2** | | **p** |
| LEFT BF - Biceps Femoris | RIGHT BF - Biceps Femoris | | 0.503 |
| LEFT ST - Semitendinosus | RIGHT ST - Semitendinosus | | 0.58 |
| ECC Before | ECC After | | 0.495 |
| CON Before | CON After | | 0.953 |

neural and muscular profile of the hamstring muscles, as evidenced by the shorter Td, Tc, various results in Dm, and increase Vrd after the training interventions. However, the type of contraction during training significantly differentiated the results (Table 4).

Eccentric training produced greater and significant changes in the neural and muscular profile of the hamstring muscles compared to concentric training. The Td, Tc were significantly shorter, the Dm was lower after the ECC training, and Vrd increased in both trainings. The results suggest that eccentric training may be more effective in improving the neural alsond muscular adaptations of the hamstring muscle group compared to concentric training. Specifically, ECC training resulted in a reduction of the parameters: Td by 4.1 ms, Tc by 10.3 ms, Dm by 0.89 mm and increased Vrd by 44 mm·s$^{-1}$, whereas CON training only reduced Td by 1.9 ms and Tc by 2.2 ms, and increased Dm by 0.24 mm and Vrd by 20 mm·s$^{-1}$.

The table shows the results of a study on the effects of an acute bout of resistance training on the contractile properties of the hamstring muscles (Table 5). The data is divided by muscle (left and right biceps femoris and semitendinosus) and contraction type (CON and ECC) and compared before and after the training. The results show that resistance training causes changes in the muscle contractile properties of the hamstring muscles, regardless of the contraction type, as evidenced by the decreased time delay (Td), contraction time (Tc) and increased radial displacement velocity (Vrd). In terms of contraction type, eccentric training resulted in greater and significant changes in the muscle contractile properties of the hamstring muscles than concentric training.

**Table 4**
Comparison of TMG results from two types of concentric (CON) and eccentric (ECC) resistance training.

| Contraction | Td | Tc | Dm | Vrd |
|---|---|---|---|---|
| CON Before | 26.1 ± 2.96 | 37.6 ± 8.77 | 7.55 ± 2.00 | 164 ± 43.5 |
| CON After | 24.2 ± 3.26 | 35.4 ± 9.53 | 7.89 ± 2.11 | 184 ± 48.6 |
| ECC Before | 26.6 ± 2.63 | 39.9 ± 8.91 | 9.20 ± 3.44 | 191 ± 76.11 |
| ECC After | 22.5 ± 2.59 | 29.6 ± 8.96 | 8.31 ± 3.48 | 235 ± 111 |

**Table 5**
Comparison of muscle TMG results in two types of concentric (CON) and eccentric (ECC) resistance training.

| Muscle | Contraction | Td | Tc | Dm | Vrd |
|---|---|---|---|---|---|
| LEFT BF - Biceps Femoris | CON Before | 25.3 ± 2.69 | 34.9 ± 8.77 | 6.81 ± 2.26 | 157 ± 44.6 |
| | CON After | 23.5 ± 2.91 | 32.4 ± 9.59 | 7.24 ± 2.05 | 186 ± 50.6 |
| | ECC Before | 26.5 ± 2.41 | 39.1 ± 11.4 | 9.34 ± 2.58 | 202 ± 64 |
| | ECC After | 21.8 ± 1.93 | 28.9 ± 10.2 | 8.50 ± 3.16 | 250 ± 119 |
| LEFT ST - Semitendinosus | CON Before | 27.2 ± 3.21 | 42.4 ± 5.52 | 8.66 ± 1.4 | 165 ± 42.7 |
| | CON After | 25.1 ± 1.46 | 40.8 ± 7.6 | 8.83 ± 1.96 | 178 ± 42.7 |
| | ECC Before | 27.8 ± 2.88 | 40.8 ± 5.43 | 10.4 ± 4 | 205 ± 76.9 |
| | ECC After | 23.7 ± 2.27 | 30.4 ± 6.42 | 9.49 ± 3.51 | 209 ± 111 |
| RIGHT BF - Biceps Femoris | CON Before | 25.0 ± 2.68 | 34.4 ± 12.1 | 6.35 ± 2.08 | 154 ± 52.1 |
| | CON After | 23.4 ± 4.94 | 31.6 ± 9.96 | 7.19 ± 2.49 | 185 ± 52.7 |
| | ECC Before | 26.8 ± 2.97 | 40.1 ± 12 | 7.88 ± 3.59 | 188 ± 89.2 |
| | ECC After | 22.7 ± 3.23 | 29.0 ± 12 | 6.96 ± 3.42 | 209 ± 113 |
| RIGHT ST - Semitendinosus | CON Before | 26.7 ± 3.04 | 38.7 ± 5.72 | 8.40 ± 1.24 | 179 ± 46.5 |
| | CON After | 24.9 ± 2.88 | 37.1 ± 9.13 | 8.29 ± 1.72 | 189 ± 54.5 |
| | ECC Before | 25.3 ± 1.84 | 39.8 ± 6.26 | 9.18 ± 3.5 | 188 ± 78.7 |
| | ECC After | 21.7 ± 2.6 | 30.2 ± 7.52 | 8.30 ± 3.85 | 225 ± 113 |

## 4. Discussion

The present study aimed to investigate the effects of an acute bout of resistance training on the contractile properties of the hamstring muscles, specifically focusing on the impact of contraction type (CON vs. ECC) on muscle performance. The results revealed several significant findings, providing valuable insights into the muscular adaptations of the hamstring muscles following different exercise interventions. The study evaluated the muscle contractile properties of the hamstring, through changes in time contraction and displacement of the muscle belly measured by TMG. A muscle with a short contraction time and delay (Tc, Td) indicates high explosiveness, while a muscle with a long contraction time exhibits slowness (Macgregor et al., 2018). A large muscle displacement (Dm) indicates a looser muscle belly, whereas when the muscle has a small displacement, it indicates muscle stiffness (García-Manso et al., 2011).

In the present study Td parameter, representing time delay, decreased in both training types, with ECC showing a twofold greater decrease, indicating similar body reactions to thigh flexion training as observed in gymnasts (Vernetta-Santana et al., 2018). The Contraction factor significantly impacted muscle performance, while the Muscle factor had a medium effect. The Muscle and Contraction interaction did not yield significant effects, suggesting minimal combined influence. No significant variations in muscle performance were observed across different muscle groups, indicating consistent responses to exercise interventions. ECC training had a substantial impact on muscle performance, while CON training had a relatively smaller effect. The Tc parameter decreased in both training types, with a greater change after ECC training, suggesting enhanced muscle performance (Zubac & Šimunič, 2017). The Contraction factor significantly influenced muscle performance, while the Muscle and Muscle × Contraction interaction had minimal effects. No significant differences in muscle performance were found between muscle groups. ECC training resulted in a greater increase in the velocity of radial muscle displacement (Vrd) compared to CON training, increase in this parameter was also seen after high-volume resistance exercise the biceps brachii muscles (García-Manso et al., 2012). This is of significant importance for muscle functionality and movement performance. A higher level of Vrd may indicate faster and more dynamic muscle contractions, which could suggest good muscle force generation and a rapid response to stimuli. The Dm parameter decreased after ECC training and increased after CON training, potentially indicating increased muscle stiffness and reduced parameter values like in plyometric training (Zubac & Šimunič, 2017). The Muscle factor significantly impacted muscle performance, while the Contraction factor and Muscle × Contraction interaction had limited effects. No significant differences in muscle performance were observed between muscle groups. ECC training resulted in faster muscle contraction and a decrease in Dm, suggesting a greater impact on muscle explosiveness compared to CON training. These findings can be linked to studies associating shorter contraction time (Tc) with higher force development rates and the characteristics of strength-trained athletes (Šimuni et al., 2018; Wilson et al., 2019).

The results obtained during the study hold significant importance as they shed light on the contrasting nature of these two types of contractions and their impact on athletes. Specifically, these contractions differ fundamentally in terms of their force generation mechanisms, maximal force production, and energy cost, as indicated by Brazier et al. (2019). It is widely acknowledged that eccentric movements generate greater force compared to isometric and concentric contractions, while also incurring lower metabolic costs. This enables athletes to train with heavier loads, as supported by Brazier et al. (2019) and Hyldahl and Hubal (2014). Moreover, concentric and eccentric contractions exhibit notable distinctions in terms of neural drive, as discussed by Duchateau and Enoka (2016). Additionally, the amplitude of electromyography (EMG) signals tends to be higher during shortening contractions compared to lengthening contractions, as highlighted by Bollinger et al. (2022). Furthermore, due to the increased muscular capacity during lengthening contractions, fewer motor units are recruited, and the discharge rate is lower in comparison to shortening contractions (Duchateau & Enoka, 2016). The prevailing assumption is that eccentric resistance training yields greater effects than concentric resistance training due to the higher mechanical load associated with active lengthening. However, it is worth noting that various studies have reported conflicting findings, with some favoring eccentric training, some favoring concentric training, and others indicating similar effects from both training modes (Hyldahl & Hubal, 2014).

In the present study, both maximum load training sessions were performed, and it was found that eccentric training led to greater responses in muscle contractile properties. This finding aligns with previous research by Franchi et al. (2014), which also observed greater forces associated with eccentric (ECC) training compared to concentric (CON) training. Additionally, Maeo et al. (2018) demonstrated that eccentric training induces greater muscular changes than concentric training, further supporting our results. It is widely acknowledged that applying a greater external load during the eccentric phase of an exercise can create a potential stimulus of higher intensity. This higher intensity stimulus has been linked to various muscular, morphological, and molecular changes (Franchi & Maffiuletti, 2019). Notably, high-intensity eccentric exercises have been shown to increase strength, neuronal activation, and hypertrophy (Douglas et al., 2017a, 2017b). Consequently, there is significant interest in eccentric training, particularly among athletes and coaching staff involved in strength and power sports (Dolezal et al., 2016). Additionally, both training CON and ECC result in similar muscle hypertrophy, which is achieved through various structural adaptations that may be regulated by different myogenic and molecular responses observed between lengthening and shortening contractions (Franchi et al., 2017). However, this study was able to demonstrate differences in the change of the muscle contractile properties of these different types of training, with eccentric training being indicated as the one in which muscular changes are more pronounced than in concentric training. Therefore, when programming training programs, it is worth paying attention to building efficient muscles through ECC contractions, which seem to bring many benefits.

The overall results of the study demonstrate that both eccentric and concentric training led to changes in the neural and muscular profiles of the hamstring muscles, as evidenced by the observed shorter Td and Tc, varied results in Dm, and increased Vrd following the training interventions. However, the type of contraction employed during the training significantly differentiated the results. Eccentric training induced greater and significant changes in the neural and muscular profiles of the hamstring muscles compared to concentric training. Specifically, eccentric training led to a reduction in Td and Tc, a decrease in Dm, and an increase in Vrd. In contrast, concentric training exhibited a smaller impact on muscle performance, with only slight reductions in Td and Tc, an increase in Dm, and a lesser increase in Vrd. These findings suggest that eccentric training may be more effective than concentric training in improving the muscular adaptations of the hamstring muscle group.

Despite the many practical advantages, this study has some limitations. One of them is the potential lack of generalizability of our results due to differences between sexes in certain muscles regarding contractile properties. Further research will be necessary in the future to better understand and incorporate these differences, allowing for a more comprehensive analysis of the impact of TMG on different gender groups. The limitations of the study could be also the selection of only one muscle group. However, this muscle group was chosen because it is responsible for most injuries in professional sports, causing high costs for entire organizations and the healthcare system. These were preliminary studies conducted only on women, and in the future, it would be worthwhile to expand the study group and conduct studies on groups of professional athletes.

## CRediT authorship contribution statement

**Paweł Pakosz:** Funding acquisition, Project administration, Supervision, Visualization, Writing – review & editing, Writing – original draft, Data curation, Investigation, Formal analysis, Validation, Conceptualization, Methodology. **Mariusz Konieczny:** Supervision, Writing – review & editing, Data curation, Resources, Investigation, Software, Methodology, Conceptualization, Formal analysis. **Przemysław Domaszewski:** Writing – review & editing, Data curation. **Tomasz Dybek:** Writing – review & editing, Data curation, Resources, Formal analysis. **Mariusz Gnoiński:** Software, Methodology. **Elżbieta Skorupska:** Visualization, Writing – review & editing, Writing – original draft, Validation, Conceptualization, Supervision, Project administration, Funding acquisition.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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