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Resistance training intervention performed with different muscle action durations influences the maximal dynamic strength without promoting joint-angle specific strength gains

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ABSTRACT

The present study investigated the effect of 10-week matched (range of motion, volume, intensity, rest, and repetition duration) training protocols with varying muscle action duration (MAD) on maximal voluntary isometric contraction (MVIC) test at eight different knee angles and one-repetition maximum (1RM) test after in seated knee extensor machine. Forty women were allocated into one control and three training groups with varying MAD: 5C1E (5s concentric action [CON] and 1s eccentric action [ECC]), 3C3E (3s CON and 3s ECC), and 1C5E (1s CON and 5s ECC). All training groups (5C1E, 3C3E, and 1C5E) showed a greater relative response in 1RM performance than the control group (0.1 ± 3.5%, $p \leq 0.05$). The 1C5E group presented greater relative increases in the 1RM performance (22.1 ± 11.6%) compared to 5C1E (13.6 ± 9.2%; $p \leq 0.05$) and 3C3E (14.1 ± 5.5%, $p \leq 0.05$) groups. The training groups increased the MVIC performance more than the control group ($p \leq 0.05$), although there were no significant differences between the training groups. This study demonstrated that isoinertial resistance training protocols with shorter CON MAD showed greater maximum dynamic strength performance response than matched training protocols with other MAD configurations. However, the configuration of MAD did not induce angle-specificity to increase the maximum isometric strength.

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KEYWORDS
Torque; resistance exercise; time concentric/eccentric muscle action; dynamic maximum strength; isometric maximum strength

1. Introduction

Studies using isometric training report that gains in maximum isometric strength occurred at the trained angle and at adjacent angles, known as angle-specificity. (Noorkoiv et al., 2014; Thepaut-Mathieu et al., 1988) However, in isoinertial dynamic training, Rhea et al. (2016) report that the angle but also the magnitude of the load could influence one repetition maximum (1RM) test performance. The results of this same study (Rhea et al., 2016) showed that maximum dynamic strength increases were specific to the joint angles that were adequately stimulated (i.e., overloaded), not just joint angles contained in the range of motion (ROM) selected for training. Higher load values led to higher mean torque values in strength training exercises. (Dalleau et al., 2010) Therefore, if the magnitude of the load determines the strength adaptations, it becomes relevant to investigate the effects of variables capable of altering instantaneous torque throughout the ROM in training protocols, such as the repetition duration, which may result from varying configurations on muscle actions durations (MAD). (Tanimoto & Ishii, 2006)

Similar loads (%1RM) cause different instantaneous torques throughout the ROM in matched training protocols with different MAD. (Tanimoto & Ishii, 2006) Training protocols with shorter MAD generate greater torque at the initial angles of the concentric (CON) and the final angles of the eccentric (ECC) muscle actions (e.g., knee extension) compared with similar protocols but with longer MAD. (Bentley et al., 2010; Tanimoto & Ishii, 2006) Additionally, close to the CON and the ECC final angles, training protocols with longer MAD generate greater torque than protocols with short MAD. (Bentley et al., 2010; Tanimoto & Ishii, 2006) Given that 1RM test performance (e.g., knee extension machine) is limited by a "sticking region" at the beginning of the movement (i.e., CON muscle action), (Folland et al., 2005) it is possible to expect that protocols with shorter MAD could be more effective for maximum dynamic strength increases due to high torque generated at the initial angles of the CON muscle action.

To date, only one longitudinal study compared training protocols with the same repetition duration but varying MAD. (Gillies et al., 2006) The results of this study demonstrated a similar increase in strength (1RM) between groups after a 9-weeks training protocol. However, this study (Gillies et al., 2006) did not equate load (i.e., % 1RM) and volume (number of repetitions in each session) between training protocols. Considering the importance of these variables on the strength gains, (Lasevicius et al., 2018) further investigation to elucidate the effect of MAD on 1RM test performance appears to be necessary.

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Another important aspect that should be considered is the muscle capacity to produce maximum strength across joint angles. (Lanza et al., 2017) Athletes of varying sports present distinct performances of maximum strength when tested at different joint angles. (Ullrich & Brueggemann, 2008) However, performance on the 1RM test does not represent the maximum strength in all angles because the force requirement is submaximal outside the joint angles of the “sticking region”. (Brown & Weir, 2001) An alternative is the use of maximal voluntary isometric contraction (MVIC) tests at varying joint angles. (Alegre et al., 2014; Folland et al., 2005; Ullrich & Brueggemann, 2008) Thus, considering that there is an angle-specificity in maximum isometric strength performance (Noorkoiv et al., 2014; Thepaut-Mathieu et al., 1988) and that MAD influences the instantaneous torque along with the ROM. (Tanimoto & Ishii, 2006) Therefore, it is possible to hypothesise that larger MVIC gains would occur at initial angles of the ROM for faster training protocols. In contrast, larger MVIC improvements at the end of the ROM would be observed for slower training protocols.

Based on our previous arguments, the present study aimed to investigate the effect of matched (ROM, volume, intensity, rest, and repetition duration) training protocols with different MAD on the dynamic maximum strength (measured by 1RM test performance) and isometric response at varying joint angles after a training period.

2. Material and methods

2.1. Subjects

Forty untrained women, aged between 18 and 35 years (mean ± SD: age = 22.1 ± 3.4 y; body mass = 59.4 ± 7.8 kg; height = 162.1 ± 5.4 cm) were randomly assigned and stratified by 1RM performance into three experimental groups and a control group. Volunteers performed knee extension training protocols for 10 weeks (3 weekly sessions separated by 48 to 72 hours). The sample size was calculated by the software G. Power (version 3.1.7). An effect size value of 0.45 was obtained through the relative change in performance in the MVIC test at the 90° angle (the angle that showed the least relative difference in comparing two experimental groups) using data from Folland et al. (2005) Participants were informed about the study objectives, procedures, and risks and freely signed an informed consent form. The local ethics committee approved this study, which complied with the Declaration of Helsinki.

2.2. Procedures

2.2.1. Tests

Initially, height and body mass measurements were performed. The participants were positioned on the machine to maintain the flexion of the hip at an angle of 110º. The lateral epicondyle of the femur was aligned with the machine rotation axis, and the distal support of the machine was placed approximately 3 cm above the medial malleolus. These positions were recorded for future replication during the subsequent tests and training sessions. All test sessions were performed at the same time of the day for each participant.

After positioning the participant on the machine, the MIVC and 1RM tests were performed on a seated knee extension machine adapted with a load cell and potentiometer. Machines with similar adaptations have been reported in the literature (Dalleau et al., 2010; Folland et al., 2005) and enable recording torque and knee angles. These tests were performed in the first (familiarisation), second (pre-test), and last (post-test) experimental sessions. The MVIC test consisted of two trials at each angle of 30º, 40º, 50º, 60º, 70º, 80º, and 90º of knee flexion (0º = full knee extension), 3 s duration, and a two-minute rest between angles and trials. Testing order at each angle was randomised between the participants, and the order was maintained during the post-test session. (Noorkoiv et al., 2014) The highest peak torque value registered between two trials at each angle was used for analysis. During the MVIC test, participants received verbal encouragement from the evaluators and were instructed to apply maximum force against the fixed lever of the knee extensor machine. The two MVIC values at each angle were used for reliability calculation, in which the intraclass correlation coefficient values ranging from 0.95 to 0.96, relative standard error of measurement values ranging from 6.6% to 5.6%, and the mean coefficient of variation values at pre- and post-test sessions were 3.6 ± 3.3% and 3.1 ± 2.8%, respectively.

After a 10-min rest break after the MVIC tests, the 1RM test was performed. The 1RM test was performed within a maximum of 6 trials, with 3-min rest periods provided between trials. The weight was gradually increased, and when the participant could not achieve 30º of knee extension during the CON muscle action, the prior successful load lifted was recorded, representing the 1RM test result. (Diniz et al., 2014; Lacerda et al., 2019, 2020)

2.2.2. Training sessions

The experimental groups performed different isoinertial training protocols for 10 weeks (3 times a week with 48 to 72 hours of recovery between sessions). Resistance training protocols consisted of 3 to 5 sets (3 sets during weeks 1–2; 4 sets during weeks 3–4; 5 sets during weeks 5–10) of 6 repetitions with 50% of the 1RM test, 3-min rests between sets and 6 s repetition duration. Experimental groups were differentiated by MAD: 5s CON and 1s ECC (Group 5C1E); 3s CON and 3s ECC (Group 3C3E); and 1s CON and 5s ECC (Group 1C5E). The data provided by the potentiometer allowed the participants to have online access to the MAD and ROM data of each muscle action on a laptop screen during all training sessions and tests. In addition, a metronome was used to help participants maintain pre-established MAD. Mean and standard deviation of the duration of ECC and CON muscle action, considering all 30 training sessions, were as follows: Group 5C1E = 4.85 ± 0.26s e 1.13 ± 0.19s; Group 3C3E = 2.86 ± 0.22s e 3.12 ± 0.24s and Group 1C5E = 1.10 ± 0.14s e 4.88 ± 0.26s. The 1RM tests were re-assessed before the first weekly training session at every two weeks and the beginning of the third week. These procedures aimed to maintain the relative intensity (50% 1RM) within the proposed training protocols settings throughout 10 weeks of training. A 10-min rest period separated the 1RM test and the start of the training session.

In all 30 training sessions, signals (potentiometer and load cell) were synchronised and converted into digital signals by an A/D board (BIOVISION, Germany) with 14 bits and an input range of −5 to +5 volts. Dasylab software (DASYLAB 11.0, Ireland) was used, for the acquisition and treatment of all signals, with a sampling frequency of 2000 Hz. To assess the torque–angle relationship between the different protocols, the torque generated during each set (for each repetition) throughout the training sessions was calculated at every 10º of knee joint displacement from 100º to 30º in each muscle action and were normalised to the 1RM value.

2.2.3. Statistical analyses

The normality and the homogeneity of the variances were confirmed by Shapiro-Wilk and Levene tests, respectively. All dependent variables were transformed into relative responses [(post-test – pre-test)/pre-test * 100]. One-Way ANOVA was performed to compare the relative increase of the 1RM test between the groups. The mixed ANOVA (between subjects' effects = group; within subjects' effects = angle) was used to compare the variation in performance on MVIC tests at varying angles between and within groups. The torque–angle relationship from all 30 training sessions data was calculated by a three-way ANOVA (group x muscular action x angle). The Scott-Knott's post hoc test was used, (Scott et al., 1974) and the effect size was estimated using eta squared (η^2). (Fritz et al., 2012) All statistical procedures were performed in the statistical packages SISVAR, and SPSS 15.0 and the level of significance was set at $p \leq 0.05$.

3. Results

The One-Way ANOVA indicated a significant difference between the groups in the relative increase of the 1RM test ($F_{3.36} = 12.92$; $p < 0.001$; $\eta^2 = 0.52$). More specifically, all experimental groups presented higher relative increases in the 1RM than control, and group 1C5E was greater than groups 5C1E and 3C3E (Figure 1) (Table 1).

Results of relative change in MVIC showed only significant effects for group ($F_{3,\ 36} = 4.78$; $p = 0.007$; $\eta^2 = 0.121$) and angle ($F_{6,\ 216} = 4.81$; $p < 0.001$; $\eta^2 = 0.063$). Post hoc analysis indicated that the experimental groups presented greater MVIC increases than the control group, and that relative change was greater in 50°, 60° and 70° than in the other angles ($p < 0.05$) (Figure 2) (Table 2).

A three-way ANOVA indicated a significant interaction (group x angle x muscle action) for the torque–angle relationship ($F_{12,\ 454} = 190.9$; $p < 0.001$; $\eta^2 = 0.59$). Post hoc identified that CON muscle actions on groups 5C1E and 3C3E are significantly different from group 1C5E at all the angular intervals ($p < 0.05$). Also, ECC muscle actions on groups 1C5E and 3C3E are significantly different from group 5C1E at all the angular intervals ($p < 0.05$). Groups 5C1E and 1C5E presented with an opposite torque–angle relationship in both muscle actions, and the greatest values of instantaneous torque can be seen between the 90°-80° and 40°-30° intervals (Group 5C1E: CON 30°-50°> 50°-60°>60°-70°> 70°-80°> 80°-100°; ECC 30°-50°<50°-60°<60°-70°, 90°-100°<70°-90°; Group 1C5E: CON 30°-40°<40°-50°<50°-60°<60°-70°<70°-80°<80°-90°<90°-100°; ECC 30–50° >50°-60°>60°-70°>70°-80°>80°-100°). Group 3C3E presented in both muscular actions a progressive increase in the instantaneous torque as the knee-joint angle becomes smaller (Group 3C3E: CON 30°-50°> 50°-60°> 60°-70°>70°-80°> 80°-90°>90°-100°, ECC 30°-50°>50°-60°>60°-70°>70°-80°> 80°-100°), Figure 3.

4. Discussion

The present study supports that training in varying MAD influences the maximum dynamic strength performance; however, it did not promote angle-specific strength responses. The training groups presented with significant increases in 1RM test

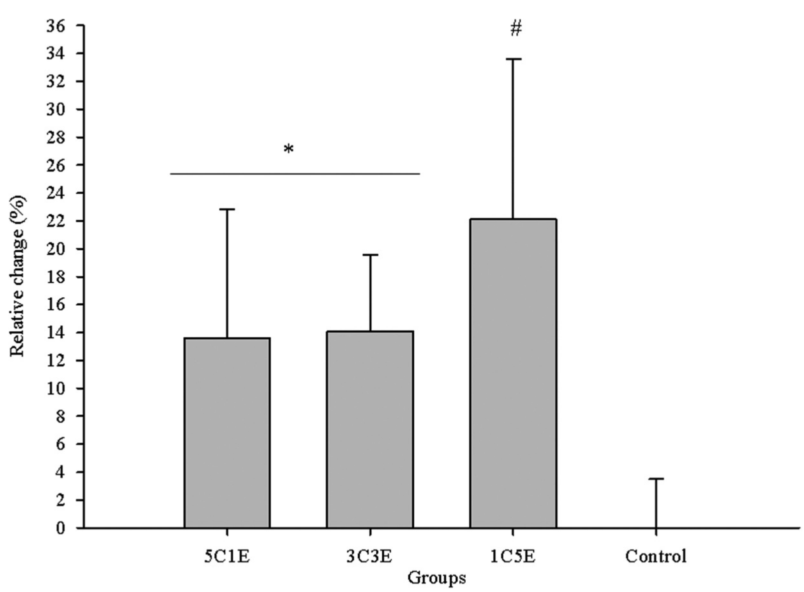

Figure 1. Relative change in the performance of the 1RM test and inferential analysis. 5C1E – 5s concentric action and 1s eccentric action; 3C3E – 3s concentric action and 3s eccentric action; 1C5E – 1s concentric action and 5s eccentric action. * – Groups 5C1E and 3C3E are greater than control group ($p < 0.05$). # – Group 1C5E is greater than other groups ($p < 0.05$).

Table 1. Pre- and post-test (kg) and the change (%) in the 1RM test in response to 10 weeks of resistance training. 5C1E – 5s concentric action and 1s eccentric action; 3C3E – 3s concentric action and 3s eccentric action; 1C5E – 1s concentric action and 5s eccentric action.

Group	1RM Pre-test (kg) Mean ± SD	1RM Post-test (kg) Mean ± SD	Change (%) Mean ± SD
5C1E	36.3 ± 8.5	40.8 ± 7.7	13.6 ± 9.2
3C3E	32.7 ± 6.9	37.3 ± 7.5	14.1 ± 5.5
1C5E	34.1 ± 7.2	41.0 ± 6.1	22.1 ± 11.5
Control	39.2 ± 6.9	39.1 ± 7.1	00.0 ± 3.5

performance compared to the control group. Also, the 1C5E group demonstrated a greater relative response in the 1RM test than the 5C1E and 3C3E groups (see Figure 1). These differences in the 1RM increases between groups are reinforced by the large effect size value (η^2 = 0.52). Fritz et al. (2012) The present results contradict the findings of Gillies et al. (2006) who observed a similar increase in the 1RM test in the training groups with the same repetition duration but different MAD. However, in contrast to the present study, which standardised the same relative intensity (50% 1RM) for all groups, Gillies et al. (2006) established the intensity of 6–8RM for all groups. As the MAD influences the maximum number of repetitions for the same relative intensity, (Goto et al., 2009) it is possible that in the study by Gillies et al. (2006) the groups have trained with different relative intensities. Considering that load alterations may influence maximal strength performance, (Fonseca et al., 2014) perhaps the methodological difference on the intensity prescription between the present study and Gillies et al. (2006) justify the contradictory results between the studies.

One explanation for the greater performance of group 1C5E in the 1RM test may be related to the torque–angle relationship. The results obtained in the torque–angle relationship are consistent with those that used different MAD reported in the literature. (Bentley et al., 2010; Tanimoto & Ishii, 2006) In the 5C1E and 1C5E groups, high torque values were found at stretched positions (i.e., near the end of the ECC and the beginning of the CON, respectively; see Figure 3). Unlike group 3C3E, where the greatest torque values were found at

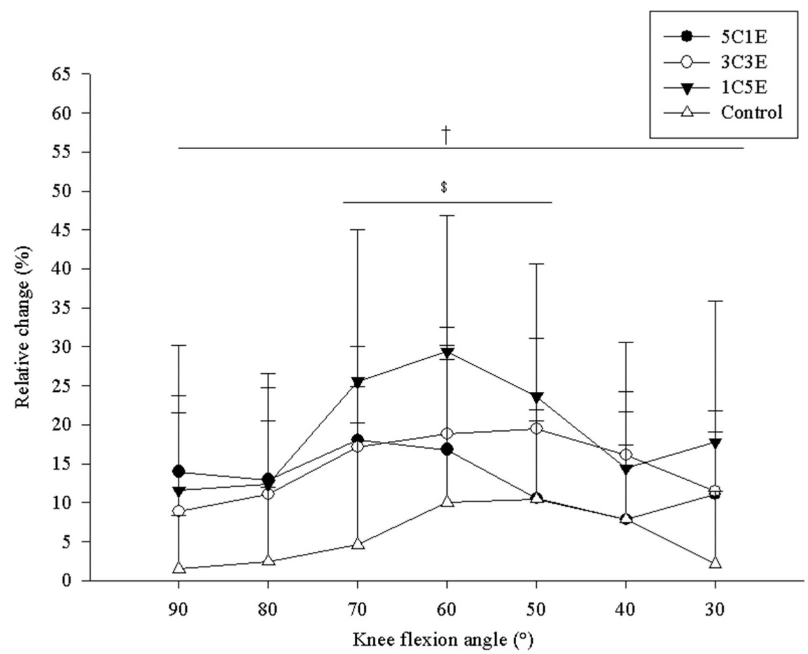

Figure 2. Relative change in the performance of MVIC tests at different angles and inferential analysis. 5C1E – 5s concentric action and 1s eccentric action; 3C3E – 3s concentric action and 3s eccentric action; 1C5E – 1s concentric action and 5s eccentric action. † – Experimental groups were greater than the control group ($p < 0.05$). $ – 50°, 60°, and 70° were greater than other angles ($p < 0.05$).

Table 2. Pre-test (kg), post-test (kg), and change (%) in the MVIC test at different angles in response to 10 weeks of resistance training. 5C1E – 5s concentric action and 1s eccentric action; 3C3E – 3s concentric action and 3s eccentric action; 1C5E – 1s concentric action and 5s eccentric action.

		Test angles						
Group		90°	80°	70°	60°	50°	40°	30°
5C1E	Pre (Nm)	182.0 ± 61.7	198.8 ± 47.8	204.6 ± 46.2	211.3 ± 49.3	201.7 ± 46.0	180.1 ± 49.0	162.6 ± 36,3
	Post (Nm)	202.1 ± 56.1	222.3 ± 53.4	239.5 ± 48.9	244.6 ± 51.8	219.8 ± 39.3	190.3 ± 35.8	179.5 ± 37.2
	Change (%)	14.0 ± 16.2	13.0 ± 13.6	18.1 ± 12.0	16.8 ± 13.3	10.6 ± 11.4	7.9 ± 13.8	11.1 ± 10.7
3C3E	Pre (Nm)	162.3 ± 38.2	179.2 ± 40.9	194.0 ± 37.5	198.0 ± 42.2	186.0 ± 35.6	161.7 ± 30.0	150.8 ± 31.5
	Post (Nm)	174.7 ± 38.6	196.8 ± 38.0	225.9 ± 37.5	231.7 ± 37.5	219.9 ± 30.6	186.8 ± 31.2	166.9 ± 30.4
	Change (%)	8.9 ± 12.6	11.1 ± 9.4	17.1 ± 7.8	18.8 ± 13.7	19.5 ± 11.6	16.1 ± 8.2	11.5 ± 7.7
1C5E	Pre (Nm)	173.6 ± 31.8	188.3 ± 31.0	197.0 ± 32.8	191.9 ± 29.8	175.8 ± 31.9	161.8 ± 35.1	146.7 ± 29.5
	Post (Nm)	192.6 ± 33.1	210.4 ± 33.4	244.1 ± 40.0	246.9 ± 45.1	214.6 ± 30.2	182.5 ± 31.7	169.6 ± 26.7
	Change (%)	11.6 ± 12.2	12.4 ± 12.3	25.6 ± 19.5	29.4 ± 17.5	23.6 ± 16.9	14.4 ± 16.2	17.8 ± 18.0
Control	Pre (Nm)	182.3 ± 33.8	188.9 ± 29.5	207.7 ± 25.9	206.7 ± 29.3	182.4 ± 27.2	172.8 ± 33.8	162.8 ± 19.4
	Post (Nm)	185.4 ± 37.9	192.4 ± 27.0	215.3 ± 27.6	223.7 ± 24.8	199.9 ± 24.2	184.3 ± 27.4	165.9 ± 21.1
	Change (%)	1.5 ± 6.9	2.5 ± 9.6	4.6 ± 15,7	10.1 ± 18.4	10.5 ± 10.1	7.9 ± 9.5	2.2 ± 9.3

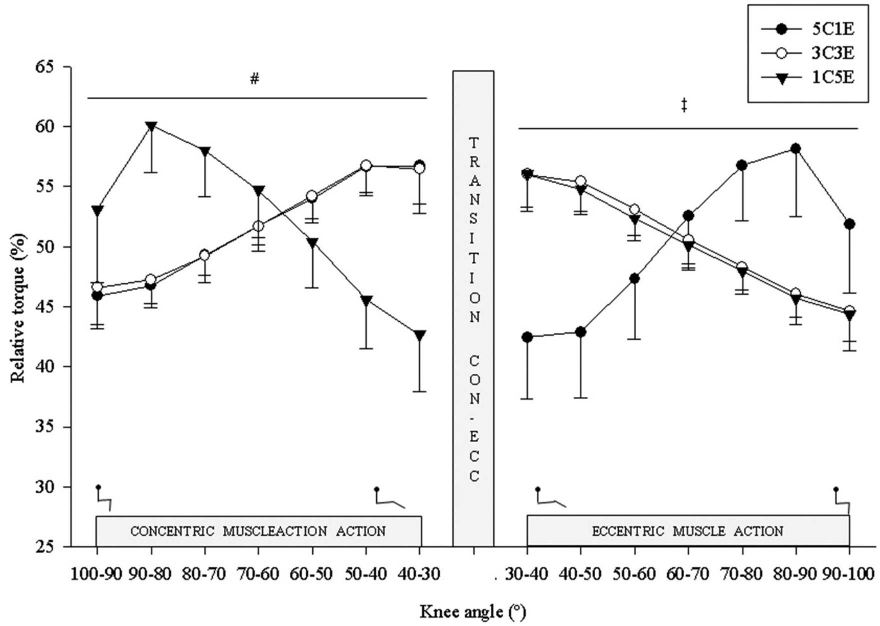

Figure 3. Descriptive and inferential analysis of torque–angle relationship in concentric and eccentric muscle action of training groups. 5C1E – 5s concentric action and 1s eccentric action; 3C3E – 3s concentric action and 3s eccentric action; 1C5E – 1s concentric action and 5s eccentric action. # – Groups 5C1E and 3C3E are significantly different from group 1C5E at all the angular intervals ($p < 0.05$). ‡ – Groups 1C5E and 3C3E are significantly different from group 5C1E at all the angular intervals.

shortened positions (i.e., the end of the CON and the beginning of the ECC). For dynamic training, strength improvements are specific to joint angles that are sufficiently overloaded, not just joint angles where training occurs. Rhea et al. (2016) Additionally, the 1RM test is influenced by the "sticking region", (Brown & Weir, 2001) located at the beginning of the CON on the seated knee extension machine. (Folland et al., 2005) Also, there is a specificity regarding the muscular action used between the tests and training. (Raue et al., 2005) Thus, in the present study, the 1C5E group presents the greatest instantaneous torque values (overloaded) in the initial angles of the CON, which could be a justification for its superiority over the other training groups in maximum dynamic strength performance.

The training protocols effectively increased the maximum isometric strength in the training groups compared to the control group, with a medium effect size in the ANOVA group factor ($\eta^2 = 0.121$). For all groups, a greater relative increase of the maximum isometric strength was verified in 50° to 70° knee angles compared to the other angles, with a medium effect size for the ANOVA angle factor ($\eta^2 = 0.063$). Thus, the present study results did not show an angle-specificity in the increase of the maximum isometric strength. This may be evidenced by the angles with greater torque values during the training protocol do not present greater relative increases in the maximum isometric strength. In addition, the training was dynamic, and considering the adaptions to training are task-specific, Buckthorpe et al. (2014) this may explain the lack of angle-specificity for the isometric strength measurements.

Angle-specificity has been identified in studies with isometric (Noorkoiv et al., 2014; Thepaut-Mathieu et al., 1988) or dynamic training using reduced ROM. (McMahon et al., 2014) However, this specificity only was found in training performed with angles at a shorter muscle length. (Alegre et al., 2014; Noorkoiv et al., 2014) In longer muscle length, the average increase in strength for a training group would be more homogeneous between the joint angles, presenting a very variable intraindividual response among angles. (Noorkoiv et al., 2014) Therefore, the fact that all training groups in the present study targeted the same ROM (including long and short muscle length positions), and the high individual variability in the relative increases of isometric strength across the angles tested (CV ranging from 68% to 158%), both factors may have contributed to the absence of differences between the training groups and have also impacted in the lack of angle-specificity in the MVIC tests. (Ullrich et al., 2009) Nevertheless, Folland et al. (2005) reinforce that the magnitude of the torque during the dynamic protocol could also influence the angle-specific improvements in isometric strength. Although there are exceptions, (Je et al., 1989; Manning et al., 1990) studies with dynamic training protocol have also found that at 70° of knee extension and adjacent angles, there would be a greater increase in maximum isometric strength than at more extreme angles of the ROM. (Folland et al., 2005; Narici et al., 1996) A hypothesis for the increase in strength in the central angles of the present study would be that there was a more substantial transfer that these angles from training stimuli in extreme angles during dynamic training protocols with complete ROM. (Folland et al., 2005) However, a greater number of studies with isoinertial dynamic training protocols investigating the increase in isometric strength at different angles would be necessary to confirm this hypothesis.

Despite the methodological precautions adopted, some limitations of the present study should be highlighted. Care should be taken in extrapolating the data due to the characteristics of the sample used. In particular, it is recommended that future studies investigate matched isoinertial dynamic resistance training protocols that promote greater differences in the torque–angle relationship to clarify its effect on angle-specificity measured through isometric tests. Finally, it should be noted that the present study uses a single monoarticular exercise, and its information must be interpreted with caution in other training configurations and exercises.

To conclude, this study demonstrated that isoinertial resistance training protocols (matched for ROM, volume, load, repetition duration, and rest) with shorter CON MAD result in greater maximum dynamic strength performance responses and torque at the beginning of the CON than training protocols with other MAD configurations. However, the configuration of MAD did not present angle-specificity for maximum isometric strength.

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Disclosure of potential conflicts of interest

No potential conflict of interest was reported by the authors.

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