

Article

Not peer-reviewed version

Examining the Cross-Education Phenomenon in Lower Limbs: Insights from the Force-Velocity Profile

[Jessica Rial-Vázquez](#), Juan Fariñas, [María Rúa-Alonso](#), [Iván Nine](#), [Manuel Avelino Giráledz-García](#), [Eliseo Iglesias-Soler](#)*

Posted Date: 26 December 2025

doi: 10.20944/preprints202512.2364.v1

Keywords: cross-transfer; set configuration; unilateral training



Preprints.org is a free multidisciplinary platform providing preprint service that is dedicated to making early versions of research outputs permanently available and citable. Preprints posted at Preprints.org appear in Web of Science, Crossref, Google Scholar, Scilit, Europe PMC.

Copyright: This open access article is published under a [Creative Commons CC BY 4.0 license](#), which permit the free download, distribution, and reuse, provided that the author and preprint are cited in any reuse.

Disclaimer/Publisher's Note: The statements, opinions, and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions, or products referred to in the content.

Article

Examining the Cross-Education Phenomenon in Lower Limbs: Insights from the Force-Velocity Profile

Jessica Rial-Vázquez ¹, Juan Fariñas ¹, María Rúa-Alonso ¹, Iván Nine ¹, Manuel Avelino Giráledz-García ¹ and Eliseo Iglesias-Soler ^{1,*}

Performance and Health Group, Faculty of Sports Sciences and Physical Education, Department of Physical Education and Sports, University of A Coruña, 15179 A Coruña, Spain

* Correspondence: eliseo.iglesias.soler@udc.es

Abstract

This study explored whether the cross-education (CE) phenomenon could be examined through the force-velocity (FV) profile. Nineteen participants completed 5-weeks of unilateral knee extension protocols differing in set configuration. Traditional training group (TT) carried out 4 sets of 8 repetitions and 3 min rest between sets, whereas inter-repetition training group (IRT) completed 32 repetitions with 17.4 s rest between repetitions. Intervention was performed with the 10-repetition maximum load on the dominant limb. Individual linear FV profiles (slope: S_{FV} ; theoretical maximum force and velocity: F_0 and V_0 ; and maximum estimated power: P_{max}) were obtained for trained and untrained legs pre-post intervention. The trained limb showed significant increases in post-test for F_0 , P_{max} , and a steeper S_{FV} ($p<0.05$). In the untrained limb, F_0 ($p=0.042$) and P_{max} ($p=0.010$) also improved, whereas no changes were observed in V_0 nor S_{FV} . Set configuration did not modulate the FV adaptations in either trained or untrained limb. Our results showed that the CE effect was not manifested in the force–velocity (F–V) profile of the untrained limb (i.e., no shift in S_{FV} . Our results showed that the CE effect was nor manifested in the FV profile of the untrained limb (i.e., no S_{FV} shift). However, these findings indicate that strength and power transfer can be accomplished with low-fatigue training protocols, which may offer a more tolerable and practical option in clinical and performance settings.

Keywords: cross-transfer; set configuration; unilateral training

1. Introduction

Cross education (CE) consists in the strength transfer from trained to untrained limb after a unilateral strength training period [1,2]. Neural adaptations have been suggested as the most plausible candidates to mediate the CE phenomenon [3–5] because it occurs without muscle hypertrophy [6,7] and without significant muscle activity in the nontrained limb [8]. It occurs with voluntary, stimulated, or imaginary contractions and the magnitude of transfer was estimated around 12% [9]. This phenomenon showed to be useful to restore symmetry in hemiparesis after strokes and during immobilizations caused by limb injuries [10].

Recently, it has been suggested that 2-3 weeks of unilateral resistance training is enough to cause CE [11,12] but experts consensus recommend at least 4 weeks to enable a functionally significant transfer of strength [13]. Current research shows that the combination of fatigue with high intensity loads exhibit greater cross-education than lower intensities [14–16]. For example, when comparing an elbow flexion unilateral protocol of 30 sets of 1 repetition at 10 repetition maximum (10RM) load with another consisting of 5 sets of 6 repetitions at the same 10RM load (both matched for total volume and rest intervals) only the latter protocol, involving repetitions performed near muscular failure, produced cross-education [14]. In this line, Colomer-Póveda et al. [17], observed that training until failure with 25% of 1RM did not cause CE, whereas training with 75% reaching or not muscular failure, resulted in CE in both cases.

CE is commonly explored by specific tests such as maximum voluntary isometric contraction, 1RM load, peak torque, pennation angle or muscle thickness [7] because they can identify significant changes in strength manifestation. However, to the best of our knowledge, no studies have explored more comprehensive strength evaluations. Establishing the force–velocity relationship (FV) allows for the determination of different indicators of muscle function and provide a more integrative mechanical representation of the individual capabilities. In this sense, the recording of the FV individual profiles may provide information summarized by theoretical maximal force (F_0), velocity (V_0), the maximal power output ($P_{\max}$) and the slope of the linear regression (S_{FV}). The literature suggests that the individual FV profiles are sensitive to change after few weeks of resistance training, and training protocols have the potential to impact different regions of that relationship [18]. In this sense, the manipulation of the resistance training parameters is key to producing changes in a specific part of the FV spectrum. Particularly, the set configuration parameter, defined as the number of repetitions performed in each set with regard to the maximum feasible [19] was suggested to modulate the FV adaptations after middle-term interventions [20]. Training programs incorporating short set configurations, commonly named cluster sets [21], performed far from muscular failure have demonstrated particular efficacy in shifting the FV relationship toward a velocity-oriented profile in lower limbs (i.e., flatter slopes) [20]. Cluster set protocols have been associated with minimal intra-set velocity loss, no significant elevations in blood lactate concentration, and a low rate of perceived exertion, factors that collectively enable individuals to sustain exercise performance without experiencing high levels of fatigue [22,23]. Given that CE is primarily driven by neural adaptations, it can be hypothesized that more fatiguing long set configurations may be especially effective in eliciting adaptations in the nontrained limb, compared to shorter, cluster set configurations. However, to the best of our knowledge, no study has examined the entire FV spectrum to determine whether different set configurations elicit specific adaptations in the high-velocity or high-force region of the untrained limb.

Knowing that the manifestation of CE varies according to the manipulation of set configuration [14], this study aims to determine the extent to which CE is reflected in the FV profile. In this context, the main aim of this study was to explore the FV profile changes of both trained and untrained limbs following unilateral knee extension programs differing in set configuration.

2. Materials and Methods

2.1. Experimental Design

A randomized trial was conducted in order to address the purposes of the study. **Figure 1** shows the experimental design and the resistance training protocols conducted during intervention. Two preliminary sessions were provided to familiarize participants with the testing procedures. A dynamic progressive loading protocol was then executed for unilateral knee extension of the dominant and non-dominant leg, progressing until 1RM was determined. Moreover, a 10RM test was also conducted only with the dominant limb. Then participants were randomly assigned into 2 groups: Traditional training group (TT; $n=11$) or inter-repetition rest training group (IRT; $n=8$).

The experimental groups completed ten sessions of unilateral knee extension exercises using the dominant limb at 10RM load. Training was performed twice a week, with a 48-hour recovery period between sessions. After training intervention, the dynamic progressive loading test was repeated with trained and untrained legs.

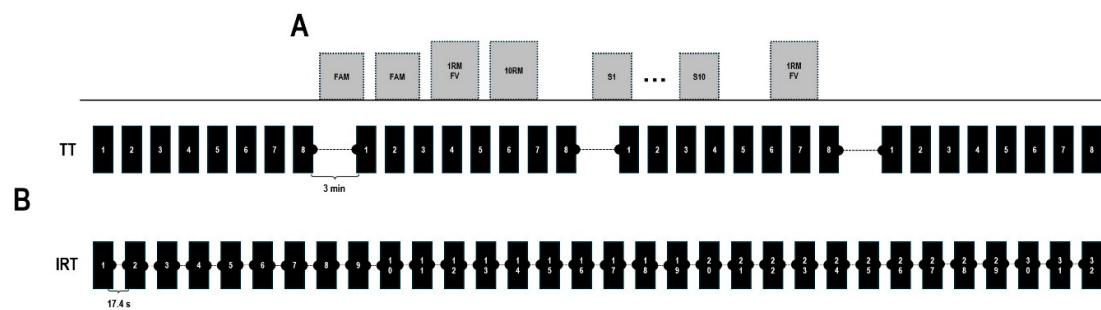


Figure 1. Study design (A) and resistance training protocols (B). FAM: familiarization session; 1RM-FV: dynamic progressive loading test until one repetition maximum to obtain the force-velocity profile of each subject; 10RM: ten repetition maximum test; S1: resistance training session number one; S10: resistance training session number ten; TT: traditional training group; IRT: inter-repetition rest training group.

2.2. Participants

Nineteen sport science students (4 women and 15 men) with at least three months of experience in resistance training completed this study. Descriptive data of the participants regarding their group allocation are shown in **Table 1**. An informed consent was read and signed by participants. The study was approved by the University of A Coruna (Spain) Ethics and conducted according with Declaration of Helsinki.

Table 1. Participants characteristics.

Parameter	TT	IRT
Age (years)	23 ± 3	22 ± 2
Sex	2 females / 9 males	2 females / 6 males
Heigh (cm)	172 ± 7	174 ± 8
Weight (kg)	73 ± 9	74 ± 11
BMI (kg·m-2)	25 ± 2	24 ± 2
Laterality	2 left-footed / 12 right-footed	1 left-footed / 9 right-footed

TT: traditional training group; IRT: inter-repetitions training group.

2.3. Procedures

2.3.1. Familiarization Sessions

Two familiarization sessions with at least 48h of rest between them were conducted in order to standardize knee extension machine positions for each participant, familiarize them with exercise technique and determine their dominant leg. At the beginning of the first session, body mass and height was assessed using a digital scale (Omron BF-508, Omron Healthcare Co., Kyoto, Japan) and a stadiometer (Seca 202, Seca Ltd., Hamburg, Germany). Body mass index was calculated as kilograms divided by height in meters squared (kg/m2).

Then sessions continued with a standardized warm-up of 5 min of cycling on a cycle ergometer (Monark 828E, Monark Exercise AB, Vansbro, Sweeden) at 60-80 rpm. During each session participants were asked to complete a set with their 50% perceived maximum load and two sets to approximate the 10RM load. The final set was completed until muscular failure to familiarize participants with maximal effort. Rest time between sets was 2 min. Familiarization was conducted with both limbs.

2.3.2. Knee extension Exercise

The exercise was performed unilaterally in a knee extension machine (Technogym, Gambettola, Italy) with 90 degrees on hip and knee flexion. Lever arm and backrest were fixed at the same position for all testing and intervention sessions. Participants were fixed with straps by the hip and chest in order to isolate the knee extensors muscles. Arms were folded in the chest. The range of motion was from 80° (knee flexed) to 0° (full extension).

2.3.3. 1RM Test

1RM load was measured using a progressive load protocol based in velocity loss [14,20] which has shown a high reliability [24]. Before completing 5 min of cycling at 60-80 rpm and 5 min of joint mobility, participants completed 10 controlled repetitions of unilateral leg extension with a preferred light load. Then the test started with three repetitions with 20kg as fast as participants could. The greatest mean propulsive velocity (MPV) of those three repetitions was set as maximum reference velocity. Sets of three repetitions were repeated (with 1 min of rest between them) until participants losses a 25% of the maximum reference velocity. Load increments ranged 10-15kg. After this, participants performed 2 repetitions in each set with increments of 5-10kg until losing 50% of the reference velocity. Then, they completed sets of one repetition with 3 min-rest with increments of 2.5-5kg until 1RM was obtained defined as the load at which participants were able to perform only one repetition. A linear velocity transducer (T-Force System, Ergotech Consulting, Murcia, Spain) was used in all sessions to obtain MPV, mean propulsive force (MPF), and mean propulsive power (MPP). This procedure was performed with both legs (i.e., dominant and non-dominant), being leg testing order randomized in pre-test and replicated in post-test. This procedure was performed before and after the 10 weeks protocol. For each participant, the FV relationship was calculated for both legs using MPV and MPF values recorded during this progressive loading test.

2.3.4. 10RM Test

Participants were tested in the load with they could perform 10 repetitions but not 11. Following a warm-up consisting of 5 min of cycling at 60–80 rpm and 5 min of joint mobility exercises, participants completed a set with a load corresponding with 50% of 1RM as specific warm-up. After 5-6 min of rest, they repeated the exercise with 70% 1RM. If the participants completed 11 repetitions, the load was increased in 2.5–5 kg, whereas if they could not complete 10 repetitions, the load was decreased until the 10RM was obtained. Muscular failure was identified when the participant was unable to overcome the load or when the full range of movement of the exercise was not completed. All the tests were recorded in 3 ± 1 attempts. This procedure was performed with dominant leg, and the obtained load was used in the intervention sessions.

2.3.5. Training Protocols

Participants were assigned to TT or IRT groups following a randomized block design. Participants completed 10 unilateral strength training sessions of knee extensors of the dominant limb twice per week with at least 48 hours of rest between each session. TT group carried out 4 sets of 8 repetitions with 10RM load and three min of rest between each set whereas IRT group completed 32 repetitions with 10RM load and 17.4 s of rest between them (See **Figure 1**).

2.4. Data Analysis

From each progressive loading 1RM test (pre-post intervention for dominant and non-dominant legs) the individual FV relationship was obtained considering MPV and MPF. In cases where multiple repetitions were recorded for a given load, the repetition exhibiting the highest MPV was retained for analysis. Linear models were commonly used to fit the FV relationship of resistance exercises due to their good reliability and goodness of fit [24]. Moreover, previous studies involving unilateral knee

extension exercises have employed and recommended the use of linear models to fit FV data [25,26]. Accordingly, our data was analyzed using linear approaches.

Firstly, the goodness of fit of the lineal model to adjust FV data was presented through the coefficient of determination (R^2) and the standard error of estimation (SEE). After obtaining the individual linear regression, the following parameters were obtained: the theoretical maximum force achieved at null velocity (F_0), the theoretical maximum velocity when force is zero (V_0), the slope of the linear regression ($S_{FV} = - (V_0/F_0)$) and the theoretical maximum power ($P_{max} = (F_0 \times V_0)/4$).

2.5. Statistical Analysis

Descriptive values are reported as mean $\pm$ SD. For R^2 , medians and range were reported. To check the normal distribution of variables Shapiro-Wilk’s test was used.

Changes in FV profile parameters (F_0 , V_0 , S_{FV} , and P_{max}) were analyzed by 2×2 ANOVA with group (TT and IRT) and time (pre-test and post-test) as factors regarding trained and untrained legs. When a significant interaction was detected, post-hoc tests were carried out with Bonferroni’s adjustment. The effect size for each factor of ANOVA was reported using the partial eta squared (η^2).

Statistical analysis was performed with SPSS 20 (IBM, Armonk, NY, USA) and graphical results were presented using Graphpad Prism v5.01 for Windows (Graphpad Software, San Diego, CA, USA). The level of statistical significance was set at 0.05.

3. Results

Regarding pretest, the medians of R^2 for trained and untrained legs were 0.972 (Range: 0.865 to 0.993) and 0.972 (Range: 0.926 to 0.992) respectively. The SEE values were 25.98 ± 11.84 N for trained and 28.14 ± 13.39 N for untrained leg. Considering post-test, R^2 for trained and untrained legs were 0.966 (Range: 0.927 to 0.986) and 0.960 (Range: 0.919 to 0.991). The SEE values in post-test were 36.44 ± 12.48 N for trained and 30.65 ± 15.58 N for untrained legs. **Table 2** shows pre-post values (mean $\pm$ standard deviations) and ANOVA results. Overall, significant increases in post-test were observed in both trained and untrained leg regarding F_0 and P_{max} whereas only S_{FV} was improved after intervention in the trained leg ($p=0.001$; $\eta^2=0.495$). **Figure 2** represents the mean force-velocity relationships before and after intervention in both groups (i.e., TT and IRT) and both legs (i.e., trained and untrained)

Table 2. Pre-post intervention values (mean $\pm$ standard deviations) and ANOVA results in both groups (i.e., TT and IRT) and both legs (i.e., trained and untrained).

			ANOVA				
			p-value and (η^2)				
	Parameters	Group	Pre-test	Post-test	TIME	GROUP	T x G
TRAINED LEG	S_{FV} (Ns/m)	IRT	-711.80 $\pm$ 178.17	-853.96 $\pm$ 256.93	0.001	0.545	0.939
		TT	-658.91 $\pm$ 153.88	-795.78 $\pm$ 230.99	(0.495)	(0.022)	(0.000)
	F_0 (N)	IRT	827.20 $\pm$ 240.50	977.81 $\pm$ 296.86	<0.001	0.614	0.931
		TT	770.59 $\pm$ 212.12	916.34 $\pm$ 269.52	(0.628)	(0.015)	(0.000)
	V_0 (m/s)	IRT	1.15 $\pm$ 0.10	1.14 $\pm$ 0.09	0.637	0.859	0.936
		TT	1.16 $\pm$ 0.15	1.15 $\pm$ 0.09	(0.013)	(0.002)	(0.000)
	P_{max} (W)	IRT	241.73 $\pm$ 82.65	281.03 $\pm$ 88.06	<0.001	0.700	0.853
		TT	228.46 $\pm$ 78.01	264.92 $\pm$ 82.21	(0.597)	(0.009)	(0.002)
UNTRAINED LEG	S_{FV} (Ns/m)	IRT	-735.12 $\pm$ 69.30	-727.79 $\pm$ 76.36	0.254	0.650	0.174
		TT	-735.48 $\pm$ 59.10	-815.60 $\pm$ 65.12	(0.076)	(0.012)	(0.076)

F_0 (N)	IRT	841.47 ± 253.41	855.82 ± 260.52	0.042	0.979	0.129
	TT	810.20 ± 226.79	889.26 ± 250.98	(0.221)	(0.000)	(0.130)
V_0 (m/s)	IRT	1.14 ± 0.10	1.18 ± 0.12	0.624	0.213	0.263
	TT	1.10 ± 0.14	1.09 ± 0.11	(0.014)	(0.090)	(0.073)
P_{max} (W)	IRT	242.06 ± 81.44	253.49 ± 82.26	0.010	0.741	0.512
	TT	226.28 ± 78.23	244.64 ± 77.81	(0.328)	(0.007)	(0.026)

S_{FV}: slope of the linear Force-velocity regression; F₀: force axis intercept; V₀: velocity axis intercept; P_{max}: maximum estimated power; IRT: inter-repetition group; TT: traditional training group; TxG= time x group interaction.

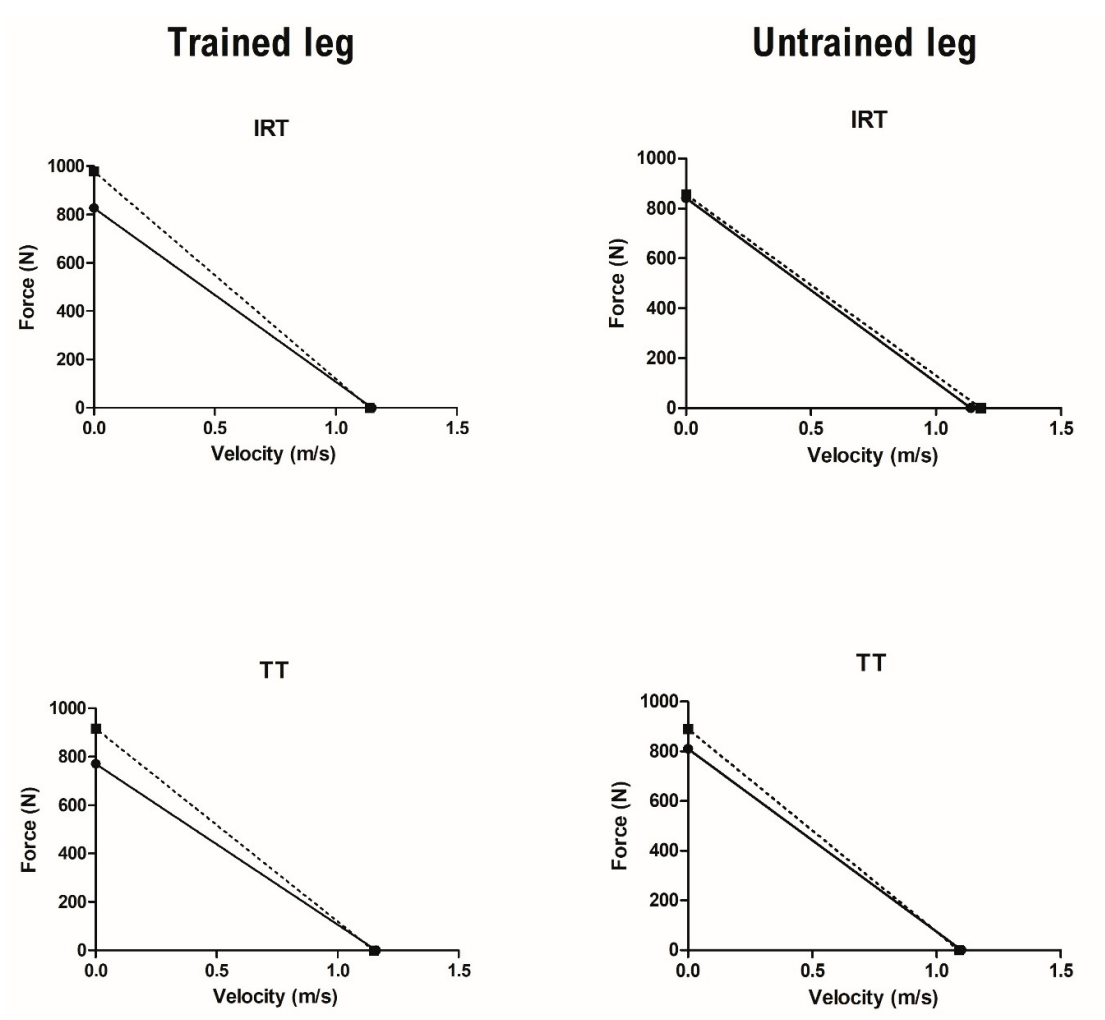


Figure 2. Mean force-velocity relationships of inter-repetition (IRT) and traditional (TT) groups before (solid line) and after training interventions (dashed line).

4. Discussion

The main findings were: i) significant improvements in F₀, P_{max} and steeper slopes (S_{FV}) were observed in the trained limb, showing a change towards a force-oriented profile ii) Increases in F₀ and P_{max}, but not in V₀ or S_{FV} were detected in the untrained leg, suggesting that CE phenomenon was not refected in the FV profile iii) Set configuration did not modulate the changes in the FV parameters in either the trained nor untrained legs.

The linear regression models exhibited an excellent goodness of fit ($R^2 > 0.870$) when analyzing force and velocity data for both trained and untrained limbs. These findings reinforce the suitability of this regression approach for modeling FV relationships in unilateral exercises [25,26].

4.1. Trained Leg

After intervention, the FV profile regarding trained leg shifted toward a force-oriented profile (i.e., steeper slopes). The increase in F_0 , together with the absence of changes in V_0 , indicates that the enhancement in $P_{\max}$ was primarily driven by substantial adaptations in the high-force region. This change was consistent in both training groups, so set configuration did not modulate the changes in the FV profile. This aligns with the findings of a previous study [27], in which two unilateral knee extension resistance training protocols were conducted separately to each leg (inter-repetition vs. traditional set configuration). Despite the higher training velocities observed during the inter-repetition rest protocol, both approaches led to similar improvements in the FV mechanical profile, specifically toward greater force-generating capabilities. On the other hand, our results contrast with other studies that showed different neuromuscular adaptations when resistance training protocols differing in set configuration were performed [20]. Short set configurations produced improvements in the high-velocity region of the FV profile, attributable to their capacity to preserve neuromuscular performance during training (i.e., minimal intra-set losses in velocity and power) even when performed with high load intensities [20]. Specifically, that study reported a shift toward a more velocity-oriented profile only after short-set configurations in the lower-limb exercise (i.e., half squat), whereas this adaptation was absent in the upper-limb exercise (i.e., bench press).

In this sense, the velocity-specificity principle of resistance training indicates that strength gains are greatest at or near the velocity of training [28]. Based on that, previous studies have shown that adaptations in the high-velocity region of the FV relationship were primarily produced after explosive training with medium-light loads, whereas heavy-load training preferentially enhances the high-force region [29]. In our study, load intensity was equated between protocols (i.e., 10RM load). This load a priori should stimulate the medium to high-force region of the FV profile, especially in the traditional training group, where the final repetitions of each set were performed near to muscular failure. In this sense, it was not surprising that TT group shifted towards a more force-oriented profile. A similar outcome was observed following the IRT protocol, where only minimal velocity losses are presumed to have occurred. The adaptations observed may be explained by the proper execution of the IRT intervention, which did not benefit from the stretch-shortening cycle. Each repetition required initiating the movement from rest and overcoming inertia to generate contraction (i.e., concentric pattern).

4.2. Untrained Leg

To the best of our knowledge this is the first study that explored if CE could be examined through the FV profile. Although the FV relationship can be described using different parameters depending on the regression model applied to the FV data, the slope remains the primary parameter accounting for individual FV profile shifts [30]. Our results showed significant improvements in F_0 and $P_{\max}$ in the untrained leg but no changes in S_{FV} were observed. In this sense, no CE was detected in the FV profile.

The overall magnitude of CE is estimated to be around 12% of the baseline force value for concentric contractions [31]. The recommendation exercise pattern to maximize the strength gains in the contralateral limb includes isometric (>80% of maximum voluntary isometric contraction), eccentric or eccentric-concentric actions (>80% 1RM) [32]. Overall, F_0 in the trained leg increased by 148.18 N ($\eta^2 = 0.628$), corresponding to an 18.5% improvement. In the untrained leg, F_0 increased by 47.3 N ($\eta^2 = 0.221$), representing a 5.7% change. However, this improvement was not sufficient to modify the FV profile or produce alterations in the slope of the untrained leg. That improvement in F_0 contributed to also enhancing $P_{\max}$ in the untrained leg in a similar magnitude (i.e., 16.1% improvement in the trained leg vs. 6.4% increase in untrained leg). As previously noted, the exercise

pattern in the trained limb was exclusively concentric, which may have limited the magnitude of strength transfer. It remains unclear whether an eccentric-concentric pattern performed at higher load intensities through a longer training program [17,32] could induce a greater improvement in F_0 , sufficient to change the slope of the FV relationship and therefore shift the individual profile.

The improvements observed in the high-force region reinforce the utility of maximum voluntary isometric contractions to explore CE phenomenon. Moreover, the increments observed in P_{max} suggest that power-oriented tests may represent a valuable additional tool to investigate CE. Although muscular power has not traditionally been one of the most extensively investigated variables in the context of cross-education, some studies have nonetheless examined this parameter and provide empirical support for the power gains observed in the untrained limb in the present study. For example, a study assessing knee extensors and flexors during isokinetic testing at 240°/s and 60°/s reported that power adaptations were transferred from the trained to the untrained limb, with greater gains observed in the knee extensors than in the flexors [33]. Another study examined the effects of eccentric-overload isoinertial resistance training leg protocols on the adaptations of power measured at 40-80% 1RM and unilateral vertical jump height. Authors found significant increases in the untrained limb for unilateral vertical jump height (6.0–32.9%) and muscle power (6.8–17.5%) [34]. They also suggest that lower percentages of eccentric overload were associated with greater increases in muscle power. An increase in muscle power in non-trained limbs may be particularly relevant in other population groups, such as older adults. Many fundamental daily activities (e.g., walking, rising from a chair) rely on the capacity to generate force rapidly, and therefore power adaptations have the potential to enhance mobility-related outcomes in the elderly. In this sense, CE has clear clinical relevance for frail populations, as fractures caused by falls or the sequelae of cerebrovascular accidents often result in unilateral immobilization or substantial functional deficits. On the other side, given that muscular power is a key determinant of training performance, CE may help maintain, or even enhance, this parameter when an injury or immobilization affects one limb. Such preservation of power in the affected side could potentially facilitate an earlier return to sport participation and daily functional activities compared with traditional rehabilitation protocols [32].

This study is not without limitations. First, the intervention comprised only 10 training sessions, which may have constrained the magnitude of strength adaptations observed in the non-trained limb. Second, the IRT group performed exclusively concentric contractions, a factor that could have attenuated the strength transfer, given that eccentric training has been shown to elicit greater CE responses. Lastly, we did not include a control group of comparison.

From a practical standpoint, our results indicate that the FV profiles (primarily characterized by the slope of the linear regression) did not change in the untrained limb following a 10-session unilateral resistance-training program performed at the 10RM load. This may suggest that the FV profile was not sufficiently sensitive to detect potential adaptations, or that the training parameters and intervention duration were not sufficiently demanding to induce measurable shifts in this profile. Nevertheless, increases in the theoretical maximal force (F_0) and maximum estimated power (P_{max}) were observed in the untrained limb, regardless of set configuration. These findings suggest that strength and power transfer can be achieved through training protocols performed far from muscular failure (i.e., short sets). Given that similar outcomes were obtained regardless of proximity to failure, implementing low-fatigue, low-perceived-exertion protocols may be advantageous for participants, as they could be better tolerated by populations such as older adults or individuals undergoing rehabilitation following limb injury.

Author Contributions: Conceptualization, J.F., M.A.G.-G., and E.I.-S.; methodology, J.F., I.N., and E.I.-S.; formal analysis, J.R.-V.; investigation, J.F. and M.R.-A.; writing—original draft preparation, J.R.-V.; writing—review and editing, M.R.-A. and E.I.-S.; visualization, J.R.-V. and I.N.; supervision, M.A.G.-G. and E.I.-S.; project administration, E.I.-S. All authors have read and agreed to the published version of the manuscript.

Funding: M.R.A. received financial support from the Xunta de Galicia (Consellería de Cultura, Educación, Formación Profesional y Universidades) through the Xunta de Galicia Postdoctoral Fellowships (ED481B-2024-077). I.N. is supported by a predoctoral grant from Spanish Ministry of Science, Innovation and Universities (FPU23/03727).

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of the University of A Coruña.

Informed Consent Statement: Informed consent was obtained from all participants involved in the study.

Data Availability Statement: The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments: We express our gratitude to the participants and the collaborators for their efforts throughout the study.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Beyer, K.S.; Fukuda, D.H.; Boone, C.H.; Wells, A.J.; Townsend, J.R.; Jajtner, A.R.; Gonzalez, A.M.; Fragala, M.S.; Hoffman, J.R.; Stout, J.R. Short-Term Unilateral Resistance Training Results in Cross Education of Strength without Changes in Muscle Size, Activation, or Endocrine Response. *J Strength Cond Res* 2016, 30, 1213–1223, doi:10.1519/JSC.0000000000001219.
2. Farthing, J.P.; Krentz, J.R.; Magnus, C.R. a Strength Training the Free Limb Attenuates Strength Loss during Unilateral Immobilization. *J Appl Physiol* 2009, 106, 830–836, doi:10.1152/japplphysiol.91331.2008.
3. Carroll, T.J.; Herbert, R.D.; Munn, J.; Lee, M.; Gandevia, S.C. Contralateral Effects of Unilateral Strength Training: Evidence and Possible Mechanisms. *J Appl Physiol* 2006, 101, 1514–1522.
4. Lee, M.; Carroll, T.J. Cross Education. *Sports Medicine* 2007, 37, 1–14, doi:10.2165/00007256-200737010-00001.
5. Ruddy, K.L.; Carson, R.G. Neural Pathways Mediating Cross Education of Motor Function. *Front Hum Neurosci* 2013, 7, 397, doi:10.3389/fnhum.2013.00397.
6. Farthing, J.P.; Borowsky, R.; Chilibeck, P.D.; Binsted, G.; Sarty, G.E. Neuro-Physiological Adaptations Associated with Cross-Education of Strength. *Brain Topogr* 2007, 20, 77–88, doi:10.1007/s10548-007-0033-2.
7. Altheyab, A.; Alqurashi, H.; England, T.J.; Phillips, B.E.; Piasecki, M. Cross-education of Lower Limb Muscle Strength Following Resistance Exercise Training in Males and Females: A Systematic Review and Meta-analysis. *Exp Physiol* 2024, doi:10.1113/EP091881.
8. Evetovich, T.K.; Housh, T.J.; Housh, D.J.; Johnson, G.O.; Smith, D.B.; Ebersole, K.T. The Effect of Concentric Isokinetic Strength Training of the Quadriceps Femoris on Electromyography and Muscle Strength in the Trained and Untrained Limb. *J Strength Cond Res* 2001, 15, 439–445.
9. Manca, A.; Dragone, D.; Dvir, Z.; Deriu, F. Cross-Education of Muscular Strength Following Unilateral Resistance Training: A Meta-Analysis. *Eur J Appl Physiol* 2017, 117, 2335–2354, doi:10.1007/s00421-017-3720-z.
10. Farthing, J.P.; Zehr, E.P. Restoring Symmetry. *Exerc Sport Sci Rev* 2014, 42, 70–75, doi:10.1249/JES.0000000000000009.
11. Barss, T.S.; Klarner, T.; Pearcey, G.E.P.; Sun, Y.; Zehr, E.P. Time Course of Interlimb Strength Transfer after Unilateral Handgrip Training. *J Appl Physiol* 2018, 125, 1594–1608, doi:10.1152/japplphysiol.00390.2017.
12. Carr, J.C.; Ye, X.; Stock, M.S.; Bemben, M.G.; DeFreitas, J.M. The Time Course of Cross-Education during Short-Term Isometric Strength Training. *Eur J Appl Physiol* 2019, 119, 1395–1407, doi:10.1007/s00421-019-04130-9.
13. Manca, A.; Hortobágyi, T.; Carroll, T.J.; Enoka, R.M.; Farthing, J.P.; Gandevia, S.C.; Kidgell, D.J.; Taylor, J.L.; Deriu, F. Contralateral Effects of Unilateral Strength and Skill Training: Modified Delphi Consensus to Establish Key Aspects of Cross-Education. *Sports Medicine* 2021, 51, 11–20, doi:10.1007/s40279-020-01377-7.
14. Fariñas, J.; Mayo, X.; Giraldez-García, M.A.; Carballeira, E.; Fernandez-Del-Olmo, M.; Rial-Vazquez, J.; Kingsley, J.D.; Iglesias-Soler, E. Set Configuration in Strength Training Programs Modulates the Cross Education Phenomenon. *J Strength Cond Res* 2019, 1, doi:10.1519/jsc.0000000000003189.

15. Colomer-Poveda, D.; Romero-Arenas, S.; Fariñas, J.; Iglesias-Soler, E.; Hortobágyi, T.; Márquez, G. Training Load but Not Fatigue Affects Cross-education of Maximal Voluntary Force. *Scand J Med Sci Sports* 2021, *31*, 313–324, doi:10.1111/sms.13844.
16. Voskuil, C.C.; Andrushko, J.W.; Huddleston, B.S.; Farthing, J.P.; Carr, J.C. Exercise Prescription and Strategies to Promote the Cross-Education of Strength: A Scoping Review. *Applied Physiology, Nutrition, and Metabolism* 2023, *48*, 569–582, doi:10.1139/apnm-2023-0041.
17. Colomer-Poveda, D.; Romero-Arenas, S.; Fariñas, J.; Iglesias-Soler, E.; Hortobágyi, T.; Márquez, G. Training Load but Not Fatigue Affects Cross-education of Maximal Voluntary Force. *Scand J Med Sci Sports* 2021, *31*, 313–324, doi:10.1111/sms.13844.
18. Haff, G.G.; Nimphius, S. Training Principles for Power. *Strength Cond J* 2012, *34*, 2–12, doi:10.1519/SSC.0b013e31826db467.
19. Iglesias-Soler, E.; Mayo, X.; Río-Rodríguez, D.; Carballeira, E.; Fariñas, J.; Fernández-Del-Olmo, M. Inter-Repetition Rest Training and Traditional Set Configuration Produce Similar Strength Gains without Cortical Adaptations. *J Sports Sci* 2016, *34*, 1473–1484, doi:10.1080/02640414.2015.1119299.
20. Rial-Vázquez, J.; Mayo, X.; Tufano, J.J.; Fariñas, J.; Rúa-Alonso, M.; Iglesias-Soler, E. Cluster vs. Traditional Training Programmes: Changes in the Force–Velocity Relationship. *Sports Biomech* 2022, *21*, 85–103, doi:10.1080/14763141.2020.1718197.
21. Tufano, J.J.; Brown, L.E.; Haff, G.G. Theoretical and Practical Aspects of Different Cluster Set Structures. *J Strength Cond Res* 2017, *31*, 848–867, doi:10.1519/JSC.0000000000001581.
22. Jukic, I.; Ramos, A.G.; Helms, E.R.; McGuigan, M.R.; Tufano, J.J. Acute Effects of Cluster and Rest Redistribution Set Structures on Mechanical, Metabolic, and Perceptual Fatigue During and After Resistance Training: A Systematic Review and Meta-Analysis. *Sports Medicine* 2020, doi:10.1007/s40279-020-01344-2.
23. Latella, C.; Teo, W.-P.; Drinkwater, E.J.; Kendall, K.; Haff, G.G. The Acute Neuromuscular Responses to Cluster Set Resistance Training: A Systematic Review and Meta-Analysis. *Sports Medicine* 2019, doi:10.1007/s40279-019-01172-z.
24. Iglesias-Soler, E.; Mayo, X.; Rial-Vázquez, J.; Morín-Jiménez, A.; Aracama, A.; Guerrero-Moreno, J.M.; Jaric, S. Reliability of Force-Velocity Parameters Obtained from Linear and Curvilinear Regressions for the Bench Press and Squat Exercises. *J Sports Sci* 2019, *37*, 2596–2603, doi:10.1080/02640414.2019.1648993.
25. Balsalobre-Fernández, C.; Cardiel-García, M.; Jiménez, S.L. Bilateral and Unilateral Load-Velocity Profiling in a Machine-Based, Single-Joint, Lower Body Exercise. *PLoS One* 2019, *14*, e0222632, doi:10.1371/journal.pone.0222632.
26. Iglesias-Soler, E.; Fariñas, J.; Mayo, X.; Santos, L.; Jaric, S. Comparison of Different Regression Models to Fit the Force–Velocity Relationship of a Knee Extension Exercise. *Sports Biomech* 2019, *18*, 174–189, doi:10.1080/14763141.2018.1442873.
27. Iglesias-Soler, E.; Fernández-del-Olmo, M.; Mayo, X.; Fariñas, J.; Río-Rodríguez, D.; Carballeira, E.; Carnero, E.A.; Standley, R.A.; Giráldez-García, M.A.; Dopico-Calvo, X.; et al. Changes in the Force-Velocity Mechanical Profile After Short Resistance Training Programs Differing in Set Configurations. *J Appl Biomech* 2017, *33*, 144–152, doi:10.1123/jab.2016-0181.
28. Behm, D.G.; Sale, D.G. Velocity Specificity of Resistance Training. *Sports Med* 1993, *15*, 374–388.
29. Cormie, P.; McGuigan, M.R.; Newton, R.U. Adaptations in Athletic Performance after Ballistic Power versus Strength Training. *Med Sci Sports Exerc* 2010, *42*, 1582–1598, doi:10.1249/MSS.0b013e3181d2013a.
30. Samozino, P.; Rejc, E.; Di Prampero, P.E.; Belli, A.; Morin, J.B. Optimal Force-Velocity Profile in Ballistic Movements—Altius: Citius or Fortius? *Med Sci Sports Exerc* 2012, *44*, 313–322, doi:10.1249/MSS.0b013e31822d757a.
31. Manca, A.; Dragone, D.; Dvir, Z.; Deriu, F. Cross-Education of Muscular Strength Following Unilateral Resistance Training: A Meta-Analysis. *Eur J Appl Physiol* 2017, *117*, 2335–2354, doi:10.1007/s00421-017-3720-z.
32. Mirto, M.; Esposito, F.; Iaia, F.M.; Codella, R. Cross-Education of Strength: From Theory to Practice in Contemporary Sports Rehabilitation—A Narrative Review and Clinical Implications. *Sports Med Open* 2025, *11*, 129, doi:10.1186/s40798-025-00931-9.



33. Kannus, P.; Alosa, D.; Cook, L.; Johnson, R.J.; Renström, P.; Pope, M.; Beynnon, B.; Yasuda, K.; Nichols, C.; Kaplan, M. Effect of One-Legged Exercise on the Strength, Power and Endurance of the Contralateral Leg. *Eur J Appl Physiol Occup Physiol* 1992, 64, 117–126, doi:10.1007/BF00717948.
34. Maroto-Izquierdo, S.; Nosaka, K.; Blazeovich, A.J.; González-Gallego, J.; de Paz, J.A. Cross-education Effects of Unilateral Accentuated Eccentric Isoinertial Resistance Training on Lean Mass and Function. *Scand J Med Sci Sports* 2022, 32, 672–684, doi:10.1111/sms.14108.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.