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Abdominal wall muscle ultrasound assessment and level of experience in Pilates - an exploratory study

Evaluación de ultrasonido del músculo de la pared abdominal y nivel de experiencia en Pilates – un estudio exploratorio

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Abstract. The core refers to a group of muscles that allow optimal force transfer along the body's kinetic chain and is critical for movement. The goal of this quasi-experimental study was to investigate the relationship between the experience level of Pilates participants and abdominal wall thickness. For this, we compared the thickness of four abdominal muscles—transversus abdominis (TrA), internal oblique (IO), external oblique (EO), and rectus abdominis (RA)—as measured before and after 8 weeks of Pilates training in three conditions, namely, relaxation, abdominal hollowing, and plank exercise. Eighteen participants were distributed into three groups with different levels of Pilates practice—experienced (EG; n=6), inexperienced (IG; n=7), and control (CG; n=5) groups. The RA showed a tendency to increase post-intervention in the EG (all conditions: p=0,002, p=0,006, and p=0,002, respectively for relaxation condition, abdominal hollowing and standing plank). Additionally, significant differences were found in relaxation (p=0.003, d=−0.744) and plank (p=0.009, d=−0.630) conditions in the IG. Significant differences were also registered in the EO muscle in the IG (all conditions: p=0.046, p=0.013, and p=0.008, respectively; d=0.464, d=−0.596, and d=−0.637, respectively). IO muscle thickness tended to increase in the CG in all conditions (p=0.044, p=0.006, and p<0.001, respectively) and the EG in relaxation and plank conditions (p=0.009 and p=0.007, respectively). Within groups, the effects of Pilates practice were more significant post-intervention, with the exceptions being under the contraction condition in the deepest muscles (IO: p=0.109, d=0.083; TrA: p=0.194, d=0.062). Our hypothesis was partially confirmed because 8 weeks of Pilates practice have improved significantly the thickness of the RA and EO muscles in the IG.
Keywords: Abdominal Assessment; Pilates; Abdominal Wall ; Level of Experience

Resumen. El núcleo se refiere a un grupo de músculos que permiten una transferencia óptima de fuerza a lo largo de la cadena cinética del cuerpo y es fundamental para el movimiento. El objetivo de este estudio cuasiexperimental fue investigar la relación entre el nivel de experiencia de los participantes de Pilates y el grosor de la pared abdominal. Para esto, comparamos el grosor de cuatro músculos abdominales: transverso abdominal (TrA), oblicuo interno (IO), oblicuo externo (EO) y recto abdominal (RA), medido antes y después de 8 semanas de entrenamiento de Pilates en tres modos, a saber, relajación, vaciado abdominal y ejercicio de plancha. Dieciocho participantes se distribuyeron en tres grupos con diferentes niveles de práctica de Pilates: grupos experimentados (EG; n=6), inexpertos (IG; n=7) y control (CG; n=5). La RA mostró una tendencia a aumentar postintervención en el EG (todos los modos: p=0.002, p=0.006 y p=0.002, respectivamente para el modo relajación, hueco abdominal y plancha de pie). Además, se encontraron diferencias significativas en los modos de relajación (p=0.003, d=−0.744) y plancha (p=0.009, d=−0.630) en el IG. También se registraron diferencias significativas en el músculo EO en el IG (todos los modos: p=0.046, p=0.013 y p=0.008, respectivamente; d=0.464, d=−0.596 y d=−0.637, respectivamente). El grosor del músculo IO tendió a aumentar en el CG en todos los modos (p=0.044, p=0.006 y p<0.001, respectivamente) y en el EG en los modos relajación y plancha (p=0.009 y p=0.007, respectivamente). Dentro de los grupos, los efectos de la práctica de Pilates fueron más significativos post-intervención, con las excepciones bajo el modo de contracción en los músculos más profundos (IO: p=0.109, d=0.083; TrA: p=0.194, d=0.062). Nuestra hipótesis se confirmó parcialmente porque 8 semanas de práctica de Pilates mejoraron significativamente el grosor de los músculos RA y EO en el IG.
Palabras clave: Evaluación Abdominal; Pilates; Pared Abdominal; Nivel de experiencia

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Introduction

The core is essential for human movement owing to its important contribution to the control of a complex human locomotion system, which results from an intricate relationship among bones, fascia, muscles, tendons, and other key factors, such as neural structures (Ebenbichler, 2001; García-Jaén et al., 2023; Reed, 2012). Anatomically, the core comprises the lumbar spine, abdominal muscles, back extensors, quadratus lumborum, latissimus dorsi, psoas, legs, shoulders, and arms (McGill, 2010). Functionally, the muscles that constitute the core primarily serve to reinforce the trunk, and their primary function is to prevent or restrict movement rather than initiate it. This suggests that the core enhances the overall capabilities of the body (McGill, 2010; Zemkova, 2022). The ability of the core muscles to generate and maintain force is known as core strength. Core stability refers to the ability to stabilize the lumbopelvic region, which involves maintaining proper posture and balance in addition to trunk and hip control during movement (Novak et al., 2021; Reed, 2012). Biomechanically, the spine plays a key role in body movement, particularly locomotion. Its distribution throughout the trunk and division into 33 vertebrae underlie its importance in functional and spatial mobility. The core is the center of the main kinetic chains. Accordingly, core strength control, stability, balance, and motion greatly assist the movements of the upper and lower extremities (Kibler, 2006; Myers &

Kibler, 2018).

A model of the interactions among all these elements was proposed by Hoffman and Gabel (2013) based on the Panjabi model of core stabilization, which stresses the interaction between three systems, namely, the active, the passive, and the neural (Majewski-Schrage et al., 2014; Panjabi, 1992; Radziminska & Weber-Rajek, 2017). Hoffman suggested replacing a dualistic classification of muscles as "global/local" (Bergmark, 1989) or "facilitators/inhibitors" (Metcalfe & Lawes, 2013) with a double interactive system, where stability and mobility work in harmony according to the required movement, ultimately determining the quality of movement. The "active" system comprises the spine muscles and tendons, while the "passive" system is related to vertebrae and other spine-associated structures, such as articulating facets, intervertebral discs, spinal ligaments, joint capsules, as well as the passive mechanical properties of the muscles. Finally, the neural system is composed of the forces and movement transducers in ligaments, tendons, and muscles, in addition to neural control centers (Hoffman & Gabel, 2013; Panjabi, 1992). Thus, core strength and core stability seem to be two sides of the same coin. This control and interaction allow for optimal force transfer throughout the body's kinetic chain, which ultimately results in the desired movement of the terminal segment (Kibler, 2006; Zemkova, 2022).

Pilates is a well-known, functional, full-body workout designed by Joseph Hubertus Pilates in the early twentieth century (Irez et al., 2011). Its method has six principle - center, concentration, control, precision, fluidity, and breathing (Tarnas et al., 2023; Wells et al., 2012). Core strength (M Carrasco-Poyatos et al., 2019; Cruz-Ferreira et al., 2011; Yook et al., 2022) and core stability (Lee, 2021; Panhan et al., 2019; Pereira et al., 2022) are among the most studied and recognized effects of Pilates practice. However, many factors such as age, sex, experience level, Pilates exercise type (classic, modern), equipment used (large apparel, small apparel, or mat), and training goal (performance, rehabilitation, well-being) can influence the effect of Pilates training on these variables. Research on the influence of Pilates on core strength and stability has traditionally relied on ultrasound echography (Naruse et al., 2022; Prentice et al., 2021). The obtained data have indicated that Pilates practice is commonly associated with the strengthening of an important muscle set, comprising the transversus abdominis (TrA), internal oblique (IO), external oblique (EO), rectus abdominis (RA), and lumbar multifidus (LM), in different populations and conditions (Bergamin et al., 2015; Morilla, 2022; Shaker & Ashmawy, 2021).

In a study with patients with chronic low back pain (CLBP), Cruz-Díaz et al. (2017) demonstrated that TrA thickness was significantly different after 6 and 12 weeks of Pilates practice compared with before using either apparel or mat Pilates. In another study involving patients with this condition, the same influence was observed not only in the TrA, but also in the IO, EO, RA, and LM muscles (Batibay et al., 2021). Meanwhile, in primiparous women, Pilates practice improved the inter-recti distance, waist circumference, and abdominal muscle endurance, factors that contributed to the recovery from or prevention of diastasis recti (Lee et al., 2023). Tsartsapakis, Gerou, et al. (2023) compared the effects of five different Pilates exercises on TrA thickness and found that the biggest changes in TrA size occurred when participants performed the Dead Bug exercise. In another study with CrossFit practitioners, the same authors found that the hollowing maneuver increased TrA, IO, and LM thickness to a greater extent than abdominal bracing (Tsartsapakis, Pantazi, et al., 2023). In a study involving 29 healthy women, Siqueira (2015) identified significant differences in RA thickness after 10 sessions of Pilates exercise. Moreover, some authors (Critchley et al., 2011; Tejada-Medina & Díaz Caro, 2021), found that Pilates exercises produced greater TrA activity or more strength in Pilates practice.

Pilates instructors also had greater TrA thickness than regular resistance exercise instructors during four stabilization exercises—abdominal drawing-in maneuver, bridging, roll-up, and one-leg raise. Similarly, IO showed greater thickness among Pilates and resistance instructors than in sedentary controls (Moon et al., 2015). Finally, long-term Pilates practice resulted in a reduction in RA thickness automatic activation during the active straight leg raise test (Gala-Alarcón et al., 2018). Barbosa et al. (2018) used surface electromyography to study the activation of deep abdominal (TrA and IO) and spine stabilizer (longissimus dorsi) in experienced and inexperienced participants. During the drawing-in maneuver, experienced participants presented greater activation of both muscles than the inexperienced ones, pointing to an association between the level of Pilates experience and muscle activation.

However, no study, known to the authors, has reported on the association between abdominal wall muscle thickness and the level of experience in Pilates. Our research question aims to investigate this association. Our goal is to examine how a Pilates intervention program affects the abdominal wall thickness in participants with varying levels of Pilates experience. We hypothesize that inexperienced participants will have significantly higher values of TrA and IO, EO, and RA thickness after the intervention compared to before. Additionally, we expect to find smaller differences between the groups regarding conditions and muscles at the pre-intervention assessment than at post-intervention.

Materials and Methods

Design

This was a case-control study comparing the effects of an 8-week Pilates intervention program on the thickness of abdominal muscles (TrA, IO, EO, and RA). The study involved two Pilates-based skills, namely, standing plank and the side crisscross (Figures 1 and 2). The research was conducted following the Declaration of Helsinki guidelines (2013) and was approved by the Ethics Committee of the

Faculty of Sport and Physical Education at the University of Coimbra (approval number: CE/FCDEF-UC/00042022). The study protocol and design have been previously published (Pereira, 2024).

Participants

A convenience sample of 18 participants was distributed into three groups according to the level of Pilates experienced (EG; n=6), inexperienced (IG; n=7), and control (CG; n=5) groups. The sample size and power were calculated using G*Power software (version 3.1.9.6; University of Kiel, Germany). The study required a two-tailed test with an alpha level of 0.05, power of 90%, and an effect size (*d*) of 2,57, which was taken into consideration during the study design (Barbosa et al., 2018; Yentur et al., 2021).

Written informed consent was obtained from all the subjects involved in the study. The participants were selected from nearby Pilates studios between February 1st and February 28th, 2023. The EG comprised participants practicing Pilates for over 6 months, with more than 1 hour of practice per week (Barbosa et al., 2018). The IG was composed of subjects who had not practiced Pilates for at least 3 months before the intervention (María Carrasco-Poyatos et al., 2019). The CG, in addition to not having practiced any form of Pilates for at least 3 months before the intervention, also did not practice any form of Pilates during the study. The participants were allowed to maintain their physical activity routines or create new routines, excluding body and mind activities such as yoga, body balance, and Tai-chi, among others. The exclusion criteria were pregnancy and medical contraindications to physical exercise.

Intervention

During the 8 weeks between assessments, the EG continued their normal Pilates activity, which included at least one 60-minute session per week in their usual facilities. Additionally, they added two new Pilates-based skills, namely, the standing plank and the side crisscross (Barbosa et al., 2018). For the Standing Plank: The practitioner should maintain a 60-degree plank position with support from a backrest bar at shoulder height. Then, should elevate both heels, moving the platform backward and forward while keeping the plank position (Figure 1). For the Side Criss Cross: The practitioner should place one arm on a backrest bar above hip height and slowly transition into a lateral plank position. The foot in front should be opposite to the arm that is supported on the backrest bar. The exercise involves crossing both feet while maintaining the lateral plank and crossing the arm according to the opposite foot (Figure 2).

After the first assessment, the IG started a weekly program in one of the Pilates studios participating in this study. This group had a standardized session, which lasted for an average of 55 minutes (Table 1). They performed two laps around the circuit, performing 8 to 10 repetitions at each station according to their level of capacity, performing the standing plank in the first lap and the side crisscross in the second.

All instructors involved in this study had Polestar certification and received 4 hours of specific training to teach and supervise these two new skills. Both exercises were performed on a sliding machine called a "Standing Machine", which allows exercises in various positions, adding some instability in the longitudinal axis, particularly in orthostasis. A patent for the Standing Machine is currently pending with the National Institute of Industrial Property under the number 118908.

Figure 1. Standing plank

Figure 2. Side crisscross

Table 1.
Pilates routine in the inexperienced group

2025, Retos, 62, 54-67

Weeks 1–4	Weeks 5 and 6	Weeks 7 and 8
Standing Leg Pump (Chair)	Standing Leg Pump (Chair)	Standing Leg Pump (Chair)
Front and Oblique Reverse Abdominals (Reformer)	Front and Oblique Reverse Abdominals (Reformer)	Front and Oblique Reverse Abdominals (Reformer) with an added yellow spring
		Bridging (Mat)
Footwork (Reformer)	Footwork (Reformer)	Footwork (Reformer)
Side Sit Up (Ladder Barrel)	Side Sit Up (Ladder Barrel)	Side Sit Up (Ladder Barrel)
Adapted Leg Pull Front (Mat)	Adapted Leg Pull Front (Mat)	Adapted Leg Pull Front (Mat)
Rolldown Series (Cadillac) with small yellow springs	Rolldown Series (Cadillac) with small yellow springs	Rolldown Series (Cadillac) with long yellow springs
Standing Plank (Standing Machine) (two series of eight repetitions in the first lap of the circuit)	Standing Plank (Standing Machine) (two series of eight repetitions in the first lap of the circuit)	Standing Plank (Standing Machine) (two series of eight repetitions in the first lap of the circuit)
Side Criss Cross (Standing Machine) (two series of 8 repetitions in the second lap of the circuit)	Side Criss Cross (Standing Machine) (two series of eight repetitions in the second lap of the circuit)	Side Criss Cross (Standing Machine) (two series of eight repetitions in the second lap of the circuit)

Before the assessments, a video exemplifying the exercises was shown to the participants. The participants could repeat the viewing and ask questions about the execution of the exercises. In the standing plank exercise, the participants had to maintain a smooth slope and then flex and extend their feet for eight cycles. The message shown in the supporting video was: "Grab the backrest strap below your shoulders and lean your body backward. Stretch your back and move your feet back and forth. Only the feet should move, keeping the body elongated. Stretch your back and try to breathe normally."

Outcomes

Abdominal wall muscle ultrasound was used to assess the thicknesses of the RA, IO, EO (Kim, 2013) and TrA muscles (Tahan et al., 2016). The apparatus was a portable ultrasound Acuson P500® with a transducer (Siemens Healthcare GmbH, Erlangen, Germany) operated by a blinded researcher with over 10 years of experience. The data were collected during rest (relaxation) and while performing the AH (contraction), as well as during a standing plank, with the arms holding the backrest, after eight repetitions.

The anatomical assessment markers for each muscle are presented in Table 2.

Table 2.
Markers of anatomical assessment for each muscle

RA	Measurements on the right side only
OE	Probe: Transversal
IO	Zone: 10 cm to the right of the umbilical scar at the midpoint between the iliac crest and the last rib
TrA	Measurements on the right side only Probe: Horizontal Zone: At the level of the navel and 2 cm to the right of the mid-axillary line

Legend: RA, rectus abdominis; EO, external oblique; IO, internal oblique; TrA, transversus abdominis.

Measurements were all taken on the right side of the participants' trunks (Madokoro et al., 2020) (Figure 3).

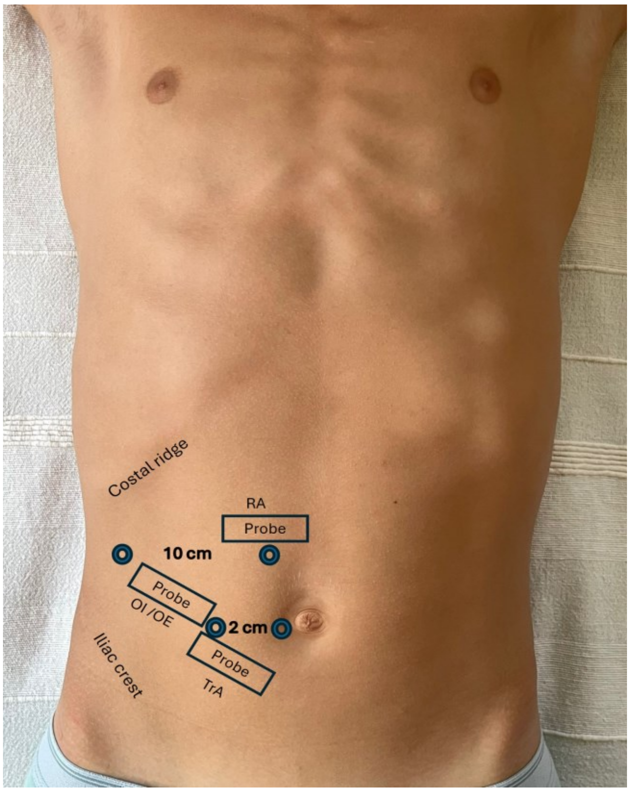


Figure 3. Right side of the participants' trunk

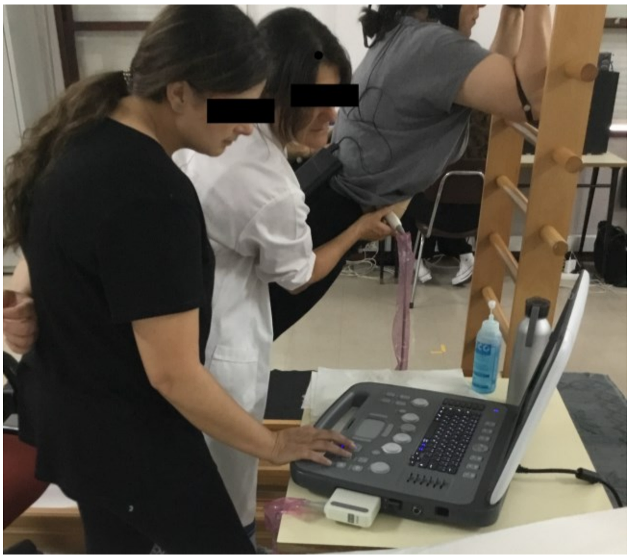


Figure 4. Measures in Plank Position

In relaxation and contraction modes, participants were in hook-lying position with their feet on the table and hips flexed 45° and knees 90°, with their arms extended along their torso. Images of the EO, IO, and TrA muscles were obtained with the transducer positioned vertically to the participant's trunk, 10 centimeters to the left of the navel, at the midpoint between the iliac crest and the last rib. For the RA muscle, the transducer was positioned horizontally right above the navel. The position and angle of the transducer were adjusted until a clear image of the borders of the abdominal muscles was obtained, enabling the measurement of the muscle thickness in a horizontal direction (Madokoro et al., 2020). To avoid the influence of breathing, the participants were instructed to inhale and hold their breath during the measurement collection immediately after exhaling (Teyhen, 2005). Data were collected in millimeters on the right side of the body by identifying muscle boundaries in three repeated measurements (Siqueira, 2015).

The procedure of positioning the transducer as well as image quality optimization was performed by the blinded examiner while another operator confirmed the registration/recording process (Teyhen, 2005).

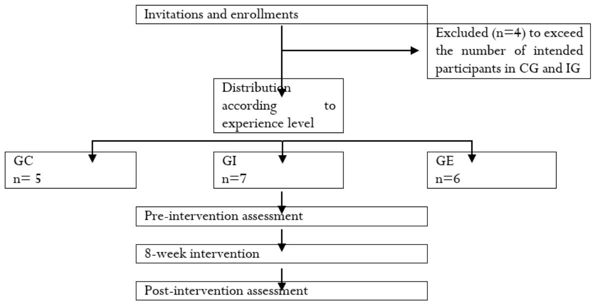
2.5. Statistical Methods

Paired-sample T-tests were used to compare muscle thickness between assessments, after checking the assumptions of normality and homogeneity (Pallant, 2020). In both cases, Cohen *d* (*d*) effect size (ES) was estimated and interpreted using the following criteria: ES < 0.2, no effect; 0.2 ≤ ES < 0.5, small effect; 0.5 ≤ ES < 0.8, large effect; and ES ≥ 0.8, very large effect.

The influence of the level of experience on all dependent variables was assessed through univariance analysis (ANOVA) after checking normality and homogeneity assumptions (Pallant, 2020). Tukey's post-hoc test was performed for multiple comparisons of means within groups (Tabachnick, 2021). The estimation of the effect size, $\eta 2$ (the proportion of the variance in the dependent variables that can be explained by the independent variables), was also presented (Pallant, 2020). The ES was presented as $\eta 2$ for one-way ANOVA and interpreted using the following criteria: no effect, ES < 0.04; minimum effect, 0.04 ≤ ES < 0.25; moderate effect, 0.25 ≤ ES < 0.64; and strong effect, ES ≥ 0.64).45 Additionally, the power (π) of the univariance analysis test was presented. Data analysis was conducted using IBM SPSS (IBM SPSS Statistics for Mac, version 28.0. Armonk, NY, USA); *p*-values < 0.05 were considered statistically significant.

Results

All the participants had an attendance rate of 100%, i.e., they undertook eight Pilates sessions. The participant flow chart is illustrated in Figure 5.



Comparisons of the RA thickness pre- and post-intervention are presented in Table 3. The RA showed a tendency to increase after the intervention. There were two exceptions in the C in relaxation condition (x=9.54±1.82 vs. x=9.11±1.97) and during the plank exercise (x=10.10±1.23 vs. x=8.91±2.81), where the thickness baseline decreased. Significant differences were found for the IG measures in relaxation condition (*p*=0.003; *d*=−0.744) and during the plank exercise (*p*=0.009; *d*=0.630).

For the EG, the three measures obtained revealed significant differences between pre- and post-intervention (*p*=0.002, *d*=0.883; *p*=0.006, *d*=0.731; and *p*=0.002, *d*=0.847, for relaxation condition, abdominal hollowing and standing plank)(Table 3).

Table 3.
Comparison of RA thickness before and after Pilates intervention

Group	Condition	RA_{pre}		RA_{post}		t	df	p	d	95% CI		Classification
		x	±SD	x	±SD					inf	sup	
CG	Relaxation	9,54	1.82	9.11	1.97	1.25	14	.231	.323	-.305	1.16	
	Contraction	9.35	2.04	9.66	1.52	-.68	14	.505	-.177	-1.28	.662	
	Plank	10.10	1.23	8.91	2.81	1.45	14	.168	.375	-.567	2.95	
IG	Relaxation	10.85	2.63	11.88	3.05	-3.40	20	.003	-.744	-1.66	-.400	Strong
	Contraction	12.58	3.44	12.79	4.16	-.586	20	.565	-.128	-.977	.548	
	Plank	10.33	1.70	12.41	3.21	-2.88	20	.009	-.630	-3.58	-.575	Moderate
EG	Relaxation	9.80	2.27	11.08	2.64	-3.74	17	.002	-.883	-2.00	-.560	Strong
	Contraction	9.90	2.69	11.00	2.52	-3.10	17	.006	-.731	-1.84	-.351	Strong
	Plank	10.28	2.23	11.97	3.00	-3.59	17	.002	-.847	-2.68	-.696	Strong

Legend: x: mean; ±SD: standard deviation; t: T-Test; df: degrees of freedom; p: level of significance (>0,05); d: Cohen d; CI: confidence intervals; inf: inferior; sup: superior

The results for EO muscle thickness are presented in Table 4. A tendency for greater thickness was observed in the post-intervention compared with the pre-intervention assessment. Again, there were two exceptions, namely, in relaxation condition in the IG and EG (*x*=5.43±2.14 *vs*. *x*=4.41±0.43 and *x*=4.75±1.46 *vs*. *x*=4.60±1.23, respectively for relaxation condition, abdominal hollowing and standing plank). EO thickness increased under the contraction condition (*p*=0.025, *d*=0.648) in the CG, with a strong effect size (p=0.025, d=−0.648). Significant differences were also found for the IG under all conditions (p=0.046, d=0.464; p=0.013, d=−0.596; and p=0.008, d=−0.637, respectively for relaxation condition, abdominal hollowing and standing plank.

Table 4.
Comparison of OE thickness before and after Pilates intervention

Group	Condition	EO_{pre}		EO_{post}		t	df	p	d	95% CI		Classification
		x	±SD	x	±SD					inf	sup	
CG	Relaxation	4.60	1.44	5.41	1.68	-1.86	14	.083	-.483	-1.72	.118	
	Contraction	5.61	1.88	6.60	1.60	-2.50	14	.025	-.648	-1.82	-.142	Strong
	Plank	5.67	1.85	6.75	1.66	-2.05	14	.060	-.529	-2.19	.049	
IG	Relaxation	5.43	2.14	4.41	.43	2.12	20	.046	.464	.018	2.00	Moderate
	Contraction	5.14	.73	5.91	.84	-2.73	20	.013	-.596	-1.35	-.181	Moderate
	Plank	6.98	2.14	8.54	1.76	-2.91	20	.008	-.637	-2.68	-.446	Moderate
EG	Relaxation	4.75	1.46	4.60	1.23	.589	17	.564	.139	-.387	.687	
	Contraction	4.52	1.03	4.92	1.57	-1.21	17	.242	-.286	-1.09	.295	
	Plank	5.58	.86	5.66	.85	-.371	17	.715	-.087	-.486	.341	

Legend: x: mean; ±SD: standard deviation; t: T-Test; df: degrees of freedom; p: level of significance (>0,05); d: Cohen d; CI: confidence intervals; inf: inferior; sup: superior

Table 5 depicts pre- and post-intervention measures related to the IO muscle. The results obtained show the same tendency as for the RA and EO muscles, with greater thickness values recorded in the post-intervention assessment.

Two exceptions to this tendency were detected, namely, the IO muscle was thicker before the intervention under contraction condition in the IG (x=9.80±3.16 *vs.* x=9.44±2.94) and under the relaxation condition in the EG (x=6.77±1.82 *vs.* x=6.08±2.08). In the CG, IO thickness was significantly increased in all conditions (p=0.044, d=−0.570; p=0.006, d=−0.832; and p<0.001, d=1.104, respectively for relaxation condition, abdominal hollowing and standing plank); additionally, in the EG, significant differences in IO thickness were recorded during relaxation and the plank exercise (p=0.009, d=0.693 and p=0.007, d=−0.724, respectively).

Table 5.
Comparison of IO thickness before and after Pilates intervention

Group	Condition	IO_{pre}		IO_{post}		t	df	p	d	95% CI		Classification
		x	±SD	x	±SD					inf	Sup	
CG	Relaxation	5.73	1.62	7.19	2.54	-2.20	14	.044	-.570	-2.86	-.041	Moderate
	Contraction	6.05	1.56	8.50	3.34	-3.22	14	.006	-.832	-4.09	-.821	Strong
	Plank	5.56	1.79	7.49	2.21	-4.27	14	<.001	-1.10	-2.89	-.960	Strong
IG	Relaxation	6.94	3.14	8.12	2.25	-1.64	20	.117	-.358	-2.67	.320	
	Contraction	9.80	3.16	9.44	2.94	.441	20	.664	.096	-1.31	2.01	
	Plank	9.18	.82	9.87	1.94	-1.82	20	.083	-.398	-1.45	.097	
EG	Relaxation	6.77	1.82	6.08	2.08	2.94	17	.009	.693	.194	1.18	Strong
	Contraction	6.91	1.69	7.47	2.26	-.974	17	.344	-.229	-1.75	.646	
	Plank	6.02	1.47	6.96	1.92	-3.07	17	.007	-.724	-1.58	-.293	Strong

Legend: x: mean; ±SD: standard deviation; t: T-Test; df: degrees of freedom; p: level of significance (>0,05); d: Cohen d; CI: confidence intervals; inf: inferior; sup: superior

The results for the TrA muscle are shown in Table 6. The TrA was thicker pre-intervention than post-intervention under contraction condition for both the IG and EG (x=5.30 *vs.* x=5.24 and x=5.45 *vs.* x=5.07, respectively). Significant differences in TrA thickness were found in the CG in contraction condition (p=0.019, d=−0.683). The EG displayed significant differences in TrA thickness during plank exercise (p=0.024, d=0.584).

Table 6.
Comparison of TrA thickness before and after Pilates intervention

Group	Condition	TrA_{pre}		TrA_{post}		t	df	p	d	95% CI		Classification
		x	±SD	x	±SD					inf	Sup	
CG	Relaxation	3.43	.733	3.63	.636	-.780	14	.448	-.201	-.730	.340	
	Contraction	3.38	.397	4.42	1.54	-2.64	14	.019	-.683	-1.86	-.194	Strong
	Plank	3.70	.636	3.28	.688	1.83	14	.088	.474	-.070	.898	
IG	Relaxation	4.03	.924	4.13	.992	-.465	20	.647	-.101	-.566	.360	
	Contraction	5.30	.909	5.24	1.14	.204	20	.840	.045	-.483	.587	
	Plank	5.03	.784	4.83	1.04	.581	20	.567	.127	-.494	.876	
EG	Relaxation	3.54	.595	4.00	1.10	-1.51	17	.147	-.358	-1.10	.179	
	Contraction	5.45	1.76	5.07	1.45	1.13	17	.271	.268	-.320	1.07	
	Plank	4.26	1.15	3.70	.891	2.47	17	.024	.584	.084	1.05	Moderate

Legend: x: mean; ±SD: standard deviation; t: T-Test; df: degrees of freedom; p: level of significance (>0,05); d: Cohen d; CI: confidence intervals; inf: inferior; sup:

superior

Table 7 compares the results between groups before and after intervention. The main results showed that there were significant differences between groups and contraction condition, with greater differences being found between the CG and the EG, and between the EG and the IG in the pre-intervention assessment. After intervention, these differences increased relative to baseline in both groups. At the end of 8 weeks of Pilates intervention, the IG showed significant differences in the relaxation and plank conditions in RA and all conditions in the OE measurements compared to the baseline value (p=.011, η^2 =.161 and p=.003, η^2 =.202 for RA and p=.041, η^2=.118 and p<.001, η^2=.311 for EO).

Table 7.
Means evaluation within groups in pre- and post-intervention

Muscle	Mode	CG		IG		EG		Z	p	η^2	π	Classification
		x	±SD	x	±SD	x	±SD					
RA	Relaxation	9.54	1.82	10.85	2.63	9.80	2.27	1.67	.197	.062	.337	No Effect
	Contraction	9.35[a]	2.04	12.58[ac]	3.44	9.90[c]	2.69	6.84	.002	.212	.906	Minimum Effect
	Plank	10.10	1.23	10.33	1.70	10.28	2.23	.072	.931	.003	.060	No Effect
EO	Relaxation	4.60	1.44	5.43	2.14	4.75	1.46	1.17	.319	.044	.245	No Effect
	Contraction	5.61	1.88	5.14	.732	4.52	1.03	3.23	.051	.112	.591	No Effect
	Plank	5.67	1.85	6.98[c]	2.14	5.58[c]	.869	3.93	.026	.134	.683	Minimum Effect
IO	Relaxation	5.73	1.62	6.94	3.14	6.77	1.82	1.23	.300	.046	.257	No Effect
	Contraction	6.05[a]	1.56	9.80[ac]	3.16	6.91[c]	1.69	12.9	<.001	.337	.996	Moderate Effect
	Plank	5.56[a]	1.79	9.18[ac]	.827	6.02[c]	1.47	39.2	<.001	.606	1	Moderate Effect
TrA	Relaxation	3.43	.733	4.03	.924	3.54	.595	3.15	.051	.110	.579	No Effect
	Contraction	3.38[ab]	.397	5.30[a]	.909	5.45[b]	1.76	15.1	<.001	.373	.999	Moderate Effect
	Plank	3.70[a]	.636	5.03[ac]	.784	4.26[c]	1.15	10.0	<.001	.282	.980	Moderate Effect

Table 7a Means evaluation within groups in post-intervention

Muscle	Mode	CG		IG		EG		Z	p	η^2	π	Classification
		x	±SD	x	±SD	x	±SD					
RA	Relaxation	9.11[a]	1.97	11.88[a]	3.05	11.08	2.64	4.88	.011	.161	.781	Minimum Effect
	Contraction	9.66[a]	1.52	12.79[a]	4.16	11.00	2.52	4.64	.014	.154	.758	Minimum Effect
	Plank	8.91[ab]	2.81	12.41[a]	3.21	11.97[b]	3.00	6.47	.003	.202	.889	Minimum Effect
EO	Relaxation	5.41[a]	1.68	4.41[a]	.437	4.60	1.23	3.40	.041	.118	.615	Minimum Effect
	Contractions	6.60[b]	1.60	5.91	.841	4.92[b]	1.57	6.53	.003	.204	.892	Minimum Effect
	Plank	6.75[a]	1.66	8.54[ac]	1.76	5.66[c]	.852	18.6	<.001	.423	1	Moderate Effect
IO	Relaxation	7.19	2.54	8.12[c]	2.25	6.08[c]	2.08	3.84	.028	.131	.671	Minimum Effect
	Contraction	8.50	3.34	9.44	2.94	7.47	2.26	2.31	.109	.083	.448	No Effect
	Plank	7.49[a]	2.21	9.87[ac]	1.94	6.96[c]	1.92	11.4	<.001	.311	.991	Moderate Effect
TrA	Relaxation	3.63	.636	4.13	.992	4.00	1.10	1.26	.291	.047	.262	No Effect
	Contraction	4.42	1.54	5.24	1.14	5.07	1.45	1.69	.194	.062	.340	No Effect
	Plank	3.28[a]	.688	4.83[ac]	1.04	3.70[c]	.891	14.6	<.001	.365	.998	Moderate Effect

Legend: Significant differences (p<0.05) between a)Control and Inexperienced; b)Control and Experienced; and c)Experienced and Inexperienced; Z: Z-Test; p: level of significance (>0,05); η^2: Effect Size; π: power test

Table 8 shows the results of Pearson's R correlation test between Body Mass Index (BMI) and muscle (RA, IO, TrA) thickness. No correlation was found between the two variables.

2025, Retos, 62, 54-67

Table 8.
Correlation between BMI and abdominal muscles

Muscle	Condition	R	p	95% CI	
				inf	Sup
RA	Relaxation 1	.460	.055	-,009	.763
	Relaxation 2	.184	.465	-.309	.599
	Contraction 1	.149	.556	-.342	.576
	Contraction 2	.131	.604	-.358	.564
	Plank 1	-.026	.919	-.487	.446
	Plank 2	.043	.865	-.432	.500
OE	Relaxation 1	.172	.496	-.321	.591
	Relaxation 2	.147	.561	-.344	.574
	Contraction 1	.435	.072	-.041	.749
	Contraction 2	.081	.748	-.401	.528
	Plank 1	.041	.873	-.434	.498
	Plank 2	.115	.650	-.372	.552
IO	Relaxation 1	.266	.287	-.230	.652
	Relaxation 2	.208	.406	-.286	.615
	Contraction 1	-.025	.921	-.486	.447
	Contraction 2	-.030	.907	-.490	.443
	Plank 1	.075	.768	-.406	.523
	Plank 2	-.213	.396	-.619	.282
TrA	Relaxation 1	.250	.317	-.246	.642
	Relaxation 2	.353	.151	-.136	.704
	Contraction 1	-.112	.659	-.550	.375
	Contraction 2	.174	.489	-.318	.593
	Plank 1	.158	.530	-.333	.582
	Plank 2	-.025	.920	-.487	.447

Legend: #1 refers to pre-intervention assessment; #2 refers to post-intervention assessment; R: R Pearson; p: level of significance (>0.05); CI: confidence intervals; inf: inferior; sup: superior

Discussion

The main goal of this study was to investigate how the level of experience in practicing Pilates can impact the thickness of abdominal muscles; overall, the results showed that abdominal muscle thickness improved with the level of Pilates practice. The study involved an 8-week intervention, during which abdominal muscle measures showed a tendency for change at all levels of experience. All four muscles measured showed significant differences under all conditions. Additionally, the differences between groups were greater post-intervention than pre-intervention, indicative of a change in profiles. In the 8-week Pilates intervention, the IG was more receptive to change, which allowed for greater differentiation relative to the CG, and ultimately brought the group closer to the EG.

RA and EO Muscles

Comparing the pre- with post-intervention results, the RA muscle was the most influenced by Pilates practice. Irrespective of the condition, the IG and the EG had better results after 8 weeks of Pilates training. These results suggest that Pilates practice can effectively improve the size of the RA muscle. The literature is unclear regarding the effect of Pilates on RA thickness. Some studies did not find changes in this variable. For example, Lee et al (Devorski et al., 2024; Lee et al., 2023) identified a significant improvement in abdominal diastasis and abdominal endurance but not RA thickness with Pilates training. Additionally, Devorski et al.(Devorski et al., 2024; Lee et al., 2023) compared the percent-thickness of the RA muscle under plank exercise performed on three different surfaces and found no significant improvements, These results can be explained through the isometric contraction of the RA, where the origin and insertion of the muscle remain static, producing stability. However, our results are in line with the few studies that have pointed to an increase in RA thickness under various conditions of contraction and intervention durations (Dorado et al., 2012; Gala-Alarcón et al., 2018; Moon et al., 2015; Siqueira, 2015). Choi et al. (2021) found greater RA muscle activity under plank with dorsiflexion based on surface electromyography. Overall, the plank exercise position used in our study differs from that of other studies. There were three conditions can justify the spread of results in RA muscle thickness observed in our study: i)almost standing position (functionally at a different angle relative to traditional plank), ii)the movement of the feet, iii) the smooth movement of the pelvis associated with the instability of the platform . These conditions could elicit the natural stabilizing function of the RA, thereby providing some thickening effect resulting from movement. Similarly as Do (2015) that found for the abdominal muscle wall (TrA and IO) when they added the influence of an unstable surface in the exercise, or by Gouridou (2021) who reported that TrA muscle thickness progressively increased in three positions of the Argentinian tango. Moreover, the Volcada position in dancing recruits the thickness of the TrA in a way that is like the plank of our study, despite differences in supporting arms.

Regarding EO muscle thickness, significant differences were detected between pre- and post-intervention in all conditions in the IG. However, the thickness decreased in relaxation condition. In the CG, EO muscle thickness differed significantly between pre- and post-intervention. Giacomini et al.(M. B. Giacomini et al., 2016) registered significant changes in EO measures in resting condition by ultrasound after 8 weeks of Pilates practice. Meanwhile, Vasseljen and Fladmark (2010) found changes in EO muscle thickness in CLBP patients, but only on the left side of EO muscles. These “marginal changes” were obtained after 6 to 8 weeks of specific or general exercises. Conversely, Siqueira et al. (Siqueira, 2015) did not find Pilates-induced changes in this muscle. However, this result could be explained by the fact that the participants were assessed only in the relaxed condition. Similarly, Gala-Alarcón (Gala-Alarcón et al., 2018) did not detect significant changes in EO thickness after 1 year of Pilates practice, and the same conclusion was reached by Gibbons and

Bird (Gibbons & Bird, 2019) when studying three graded isometric exercises on three different surfaces (Pilates table, foam roller, and Oov).

Overall, caution should be exercised regarding the efficiency of thickness measurements in the superficial label of abdominal muscles as a means of assessing muscle activation or force. Brown and McGill (Vera-Garcia et al., 2007) argued that ultrasound may not be valid if used alone as a measure of muscle activation owing to the singular architecture of the abdominal wall. Less significant differences were observed in the deepest muscles as compared to the superficial ones, which aligns with the findings of the authors. Indeed, the RA and EO both showed consistent differences between groups post-intervention.

IO and TrA Muscles

After the intervention, statistically significant differences were observed in all conditions for IO muscle thickness in both the CG and EG, except under the contraction condition in the latter. In the EG, the relaxation condition promoted a decrease in IO thickness after intervention. These results are consistent with previous research in which improvements in IO thickness following Pilates practice and similar workouts over various conditions and time intervals were reported (Gala-Alarcón et al., 2018; M. Giacomini et al., 2016). However, the lack of generalization of these findings to other conditions, groups, or muscles suggests that subject-specific factors may play a significant role in the maneuvers studied. Furthermore, the complexity of neuromuscular structures in the trunk, such as the influence of TrA contraction on thoracolumbar fascia, among others, may lead to large result inconsistencies (Cervera-Cano et al., 2022). Women with patellofemoral pain have been found to exhibit lower thickness in the IO and EO muscles, which is related to self-reported pain (Cholewicki, 1996), while the hip flexor angle has been shown to affect TrA thickness (Vera-Garcia et al., 2007).

Notably, the TrA showed statistically significant differences in thickness after intervention only in the CG. The lack of change in TrA thickness in the IG and EG suggests that task experience may result in efficiency of movement and stabilization, or the instrumental limitation presented above. Hence, the IG and EG registered statistically significant differences in thickness only in superficial muscles (except the EO muscle in the EG). Our data suggest that practicing Pilates can increase the thickness of muscles involved in stabilizing the trunk. Several studies have indicated that relatively less contraction is required for safeguarding and stabilizing the spine. Regarding mechanical function, stability, and strength, a model proposed by Cholewicki (1996) suggests that an increased risk of injury is associated with a combination of instability, vertebral compression, and increased load. In daily activities, pressure on the lumbar spine can be safely supported by 10% to 15% of the maximum co-contraction load of the trunk muscles (Cholewicki, 1996; Vera-Garcia et al., 2007) with no penalties for lumbar pain. Overall, this finding aligns with the submaximal objectives of the Pilates method (Wells et al., 2012). The findings of our study partially confirm our assumptions, as they reveal changes in the expected direction in some, although not all cases. According to Brown and McGill (2010) measuring thickness alone may not be the best approach for detecting the effectiveness of Pilates as the structure and arrangement of fibers can affect the results, which likely explains the variability in the results and the influence of intervention among the groups.

Finally, we did not find a statistically significant relationship between BMI and the thickness of each muscle. This differs from the results of Rostami (2013) who found a significant correlation between body composition and the thickness of the IO and EO muscles. It is important to continue exploring this topic to deepen our understanding of the complex relationship between body composition and muscle contraction.

Pilates practice seems to positively change abdominal wall thickness even in 8-week-long interventions with one 60-minute session per week, which has practical implications for the usefulness of Pilates. These results are in line with other studies (Batibay et al., 2021; Franks et al., 2023; Goz et al., 2023; Mesa, 2023). However, the data of this study points to the tendency of the inexperienced group to become more distant from the control group and closer to the experienced group. This given, an advantage to long-term intervention seems more appropriate, providing increased benefits and accessibility, rather than an increase in the number of sessions per week, which augments the economic cost associated with practicing Pilates.

This study had some limitations that may influence the generalization of our findings. The limited number of participants enrolled may bias the extrapolation of the results. Better body composition analysis should be considered as the BMI does not account for the distribution or percentage of body fat. Also, age correction factors may also be related to muscle thickness. Notably, most Pilates studies involve exercising two to three times per week. The intervention program used in this study did not meet this frequency, especially in the EG and IG, which may have affected the comparison of the results.

Conclusions

Our hypothesis was partially confirmed, with evidence provided by certain groups, conditions, and muscles pointing to a positive influence of Pilates practice on abdominal wall thickness. After 8 weeks of Pilates practice, the thickness of the RA and EO muscles improved significantly in the IG. However, in the deeper muscles (IO and TrA), no significant changes were detected in this group. Our study also showed that the thickness of all the muscles in the EG during the pre-intervention assessment was significantly different from that of the CG and IG, but only in some conditions. The post-intervention measurements differed significantly from the pre-intervention values in all groups, indicating that our hypothesis had been partially verified. Nonetheless, further studies with larger samples and longer Pilates practice periods are required to better understand and interpret the effects of Pilates on the abdominal wall muscles.

Patents

A patent for the Standing Machine is currently pending with the National Institute of Industrial Property under the number 118908.

Supplementary Materials

The following supporting information can be provided by appropriate request to the corresponding author.

Author Contributions

MP and GD conceptualized the study. MP, RM, AA, MAC, and GD developed the methodology. MP, RM, MAC, and VV validated the study. MP, FM, and GD designed data collection. MP, RM, RG, VV, and GD wrote the manuscript. MP, MAC, FM, RG, and GD edited the final version of the manuscript. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

The study was conducted following the Declaration of Helsinki and approved by the Ethics Committee of Faculdade de Ciências do Desporto e Educação Física – Universidade de Coimbra (number CE/FCDEF-UC/00042022) for studies involving humans.

Informed Consent Statement

Informed consent was obtained from all subjects involved in the study.

Data Availability Statement

All original materials used for the study are included in the article and can be made available upon request to the corresponding author

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Conflicts of Interest

The authors declare no conflicts of interest.

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