Marked Effects of Pilates on the Abdominal Muscles: A Longitudinal Magnetic Resonance Imaging Study

CECILIA DORADO[1], JOSE A.L. CALBET[1], ANA LOPEZ-GORDILLO[1], SANTIAGO ALAYON[2], and JOAQUIN SANCHIS-MOYSI[1]

[1]Physical Education Department, University of Las Palmas de Gran Canaria, Las Palmas de Gran Canaria, SPAIN; and [2]Diagnostic Imaging Department, Hospital San Roque Maspalomas, Grupo San Roque, Maspalomas, SPAIN

ABSTRACT

DORADO, C., J. A.L. CALBET, A. LOPEZ-GORDILLO, S. ALAYON, and J. SANCHIS-MOYSI. Marked Effects of Pilates on the Abdominal Muscles: A Longitudinal Magnetic Resonance Imaging Study. *Med. Sci. Sports Exerc.*, Vol. 44, No. 8, pp. 1589–1594, 2012. **Purpose**: The study's purpose was to analyze the effects of Pilates on the volume of the rectus abdominis (RA), obliques, and transversus abdominis, with the last two considered conjointly (OT). **Methods**: The volume of OT and RA were determined using magnetic resonance imaging in nine nonactive healthy women, before and after 36 wk of a standardized Pilates training program (Modern Pilates). **Results**: The volume of the dominant OT was increased by 8% ($P < 0.05$) with training, whereas the nondominant OT volume remained unchanged (+2%, $P = 0.58$). The total volume of RA increased by 21% after Pilates ($P < 0.05$) because of a similar increase of dominant and nondominant RA volume (21% and 20%, respectively, $P < 0.05$). Before Pilates, the volume of the OT was 8% greater in the nondominant compared with the dominant side ($P < 0.01$). This asymmetry was compensated by Pilates training (2%, $P = 0.43$). No side-to-side asymmetries in RA muscle volumes were observed either before (2%, $P = 0.51$) or after (1%, $P = 0.81$) Pilates. **Conclusions**: The present study reveals the existence of asymmetries in the muscles of the abdominal wall in nonactive healthy women. Pilates practice twice a week for 9 months elicits hypertrophy of the abdominal wall muscles, particularly of the RA, and eliminates preexisting asymmetries of the OT. Modern Pilates can be recommended as an effective method to reinforce the muscles of the abdominal wall and to compensate preexisting asymmetric developments. **Key Words:** PILATES, ABDOMINAL WALL, MUSCLE HYPERTROPHY, ASYMMETRY, LOW BACK

Pilates is a training method aiming at the symmetric strengthening of the muscles of the abdominal wall and spine, on the basis of muscle actions performed at low speeds with a high isometric component. Pilates has become a fast-growing popular trend in rehabilitation and fitness programs (10), although scientific evidence on the specific effects of Pilates is scarce. Abdominal muscles are critical for sport performance because of their role in the transfer of moment between the upper and lower extremities (3,12). The muscles of the abdominal wall function as an operational stability system protecting the spine from injury (6,24,42). Weakened abdominal wall (22,25) and abdominal muscle asymmetries have been associated with low back pain (5,21). Pilates training has been demonstrated to enhance abdominal muscle strength (14), and there is some evidence supporting its effectiveness in the management of low back pain (35). A potential mechanism by which Pilates could improve muscle strength is by inducing hypertrophy of the main abdominal muscles, but this has not been assessed yet.

The Pilates method was developed in the early part of the 20th century. Since Freidman and Eisen (17) structured, for the first time, a teacher training course, the Pilates method has become increasingly popular (29,30). Nowadays, there are several variations of the Pilates method, some designed for use in rehabilitation and others for general fitness (10). A common aim of Modern Pilates is the strengthening of the abdominal muscles to stabilize and support the lower back (8). In fact, Pilates training programs have been associated with improvements in abdominal strength and spine posture (14), static balance (40), and abdominal endurance (28), reducing the risk of low back pain (35). Given the close relationship between rectus abdominis (RA) muscle cross-sectional area (CSA) and strength (16,18), we hypothesized that if Pilates really improves abdominal muscle strength, it should also elicit some degree of muscle hypertrophy. We have recently observed natural asymmetries in the abdominal wall muscles of healthy individuals who are sedentary and athletes

Address for correspondence: Prof. Cecilia Dorado, Departamento de Educación Física, Campus Universitario de Tafira, 35017 Las Palmas de Gran Canaria, Canary Island, Spain; E-mail: cdorado@def.ulpgc.es.
Submitted for publication September 2011.
Accepted for publication February 2012.

Supplemental digital content is available for this article. Direct URL citations appear in the printed text and are provided in the HTML and PDF versions of this article on the journal's Web site (www.acsm-msse.org).

0195-9131/12/4408-1589/0
MEDICINE & SCIENCE IN SPORTS & EXERCISE®

DOI: 10.1249/MSS.0b013e31824fb6ae

(26,39). In healthy women, a 4% greater RA thickness (assessed with ultrasounds) has been reported for the dominant compared with the nondominant middle portion (18). Given the symmetric nature of Pilates exercises, we also hypothesized that Pilates may serve to reduce or eliminate preexisting asymmetries in the muscles of the abdominal wall.

Therefore, the main aim of this study was to determine the effects of a standardized 36-wk Pilates training program on the volume of RA and obliques and transversus abdominis (OT) in nonactive healthy women using magnetic resonance imaging (MRI).

METHODS

Subjects and study design. It was estimated that to show a significant increase of at least 6% in RA muscle volume, a sample size of at least 10 women would be required ($\alpha = 0.05$, power = 0.80) (26,38,39). Twelve healthy premenopausal women agreed to participate in the study. To be included, participants were required to be sedentary, i.e., not have practiced any kind of regular exercise during the precedent 5 yr with no previous experience with Pilates. Additional requisites were not to be pregnant and not to be affected by chronic diseases, musculoskeletal conditions, low back pain, or bone fractures. None of the participants have had cesarean sections. Three women were nulliparous, two had one child, three had two children, and one had three children. Three women had an abdominal surgery before 10 yr old (one had an appendectomy and two had a surgery to correct umbilical hernias). The abdominal structure of these three women was similar to that observed in the rest of the group. All subjects were informed about the potential benefits and risks of the study and gave a written consent to participate. Participants were also informed about the possibility to be excluded from the study if they missed more than one training session every 4 wk. Between the 12th and 16th weeks, three subjects were excluded from the study for this reason. Table 1 shows the main characteristics of the participants completing the study ($n = 9$). This investigation was approved by the ethical committee of the University of Las Palmas de Gran Canaria.

Participants took part in a 36-wk standardized Modern Studio Pilates training program, twice weekly, for 55 min each training session. All sessions were conducted in groups of four or less participants who always trained together, at the same time of the day with the same Pilates instructor.

TABLE 1. Physical characteristics of nonactive women and total length of RA and OT, from the pubic symphysis to the discal space between L1 and L2 (mean ± SD), before and after Pilates training.

Variables	Before Pilates	After Pilates	*P*
Age (yr)	35.7 ± 5.4	36.4 ± 5.4	<0.001
Height (cm)	164.1 ± 5.6	164.3 ± 5.5	0.19
Body mass (kg)	66.7 ± 7.5	66.5 ± 7.8	0.54
BMI (kg·m^{-2})	24.8 ± 2.6	24.7 ± 2.7	0.36
Total body fat (%)	34.6 ± 2.1	36.7 ± 4.0	0.22
RA length (cm)	19.5 ± 3.1	19.5 ± 2.9	0.98
OT length (cm)	17.1 ± 4.3	17.1 ± 4.3	0.50

BMI: body mass index (weight (Kg)/(Height (m))^2

Two different Pilates instructors (certified by the Pilates Method Alliance) were involved in the training program, and they followed the same structured protocol (Table 2). The training program included standardized Studio Pilates exercises as described elsewhere (1) and showed in Supplementary Digital Content 1 to 4 http://links.lww.com/MSS/A160; http://links.lww.com/MSS/A161; http://links.lww.com/MSS/A162; and http://links.lww.com/MSS/A164; The exercises were executed on a mat and also using a Pilates machine called a "reformer" (Balanced Body Reformer Equipment; Balanced Body®, Sacramento, CA). Footwork exercises using the reformer were performed with two red springs and one green spring. The other reformer exercises were performed with two red springs.

Physical activity apart from Pilates was assessed using the Minnesota Leisure Time Physical Activity Questionnaire (13). The total moderate and vigorous energy expenditure was not significantly changed during the intervention (68.6 ± 48.3 and 57.5 ± 35.7 METs·h^{-1}·wk^{-1}, $P = 0.38$), before and after Pilates training, respectively.

MRI was used to determine the muscle CSA and muscle volumes of the left and right RA and OT before and after training. All participants were right-handed. In this article, the dominant side of the OT and RA corresponds to the same side of the dominant arm and vice versa.

Body composition analysis. The total percentage of body fat was measured using dual-energy x-ray absorptiometry (QDR-1500, software version 7.10; Hologic Corp., Waltham, MA). Dual-energy x-ray absorptiometry equipment was calibrated using a lumbar spine phantom and following the Hologic guidelines. Subjects were scanned in supine position, and the scans were performed in high resolution as previously reported (34). The coefficient of variation for the assessment of whole-body fat mass with repositioning was below 3.1% (4).

MRI. A 1.5-T MRI scanner (Philips Achieva 1.5-T system; Philips Healthcare, Best, The Netherlands) was used to acquire 8-mm axial contiguous slices from the trunk, abdomen, and pelvis, with a 25% interslice separation. Sagittal, coronal, and transverse localizers of the body were obtained to determine precisely the anatomic sites for image acquisition. Transverse MRI images at rest (a breath hold at expiration) oriented to be perpendicular to the anterior abdominal wall were obtained. Axial gradient-echo T1-weighted MR images were used with a repetition time of 132 ms and an echo time of 4.2 ms, a flip angle of 80° with a 42-cm^2 field view, and a matrix of 256 × 256 pixels (in-plane spatial resolution = 1.64 mm × 1.64 mm). The body phase array coil was used for image acquisition. The total acquisition time was about 20 s, which was within the breath hold tolerance of all subjects.

The acquired MRI images were transferred to a computer for digital reconstruction to determine the CSA. The volume for OT and RA was calculated from the L1–L2 intervertebral disc to the S5. All calculations were carried out by the same investigator, who was blinded to arm dominance, using a specially designed image analysis software (SliceOmatic 4.3; TomoVision, Inc., Montreal, Canada), as described

TABLE 2. Protocol for the Pilates program.

Stage 1 (Weeks 1–12)			Stage 2 (Weeks 12–24)			Stage 3 (Weeks 24–36)		
Exercise	**Reps**	**Time (min)**	**Exercise**	**Reps**	**Time (min)**	**Exercise**	**Reps**	**Time (min)**
Before Pilates								
Pilates breathing	3–4		Same exercises and repetitions as in stage 1			Same exercises and repetitions as in stage 1		
Head flexion								
Scapula movement								
Pelvic tilt								
Leg slide into knee fold								
Femur arcs								
Supine spine twist								
Bridge		10–15			60			5
Side lying leg extension	5–10							
Arrow								
Cat								
Side cat								
C-shape								
Twist								
Mat 1								
Hundred[a]	5–10		Same exercises and repetitions as in stage 1			Same exercises and repetitions as in stage 2		15
Half roll down	3–5							
Single leg stretch	5–10	10–15			10–15			
Double straight leg stretch								
Spine stretch forward	3–5							
			One leg circle	5				
			Rolling like a ball	5–10				
Reformer 1[b]								
Footwork	5–10	20–25	Same exercises and repetitions as in stage 1		30–35	Same exercises and repetitions as in stage 2		30–35
Arm work	4–8							
Hundred	5–10							
Leg circles and frog								
			Stomach massage series	5–10				
			Short box series	4–8				
			Knee stretches series	5–10				
			Elephant	3–6				
			Running	20				
			Pelvic lift	5–10				
Wall								
Arm circles	5–10	5	Same exercises and repetitions as in stage 1		5	Same exercises and repetitions as in stage 1		5
Roll down	2–3							

A full description of the exercises can be found in the Supplementary Digital Content 1 http://links.lww.com/MSS/A160.

[a] In stage 1, the exercise 'hundred' was performed with neck flexion (3-cm space between the chin and the chest), the dorsal spine in contact with the floor, and knees bent and feet in contact with the floor. In stage 2, hundred was performed as in stage 1 but with the hip and knees bent at 90°. In stage 3, hundred was performed as in stage 1 but with the hip bent at 90° and the knees at 180° (extended).

[b] Reformer exercises were performed with two to three springs.

Time (min): time used to carry out the exercises; reps: repetitions.

elsewhere (31). A threshold was selected for adipose and lean tissues on the basis of the gray-level image pixel histograms to identify and manually trace the muscle boundaries (31).

The total volume (V_{total}) of OT and RA were assessed in each subject (2). The degree of asymmetry was assessed by the calculation of a ratio of the volume of the dominant and nondominant sides [((nondominant − dominant volume)100) / dominant volume]. Muscle length was calculated as the number of slices (S_i) from the proximal reference to the insertion point × the slice thickness + [(S_i − 1) × interslice space]. The degree of hypertrophy was calculated by subtracting the muscle volume before training from the muscle volume at the end of the training program, expressed as a percentage of the pretraining value. To determine the coefficient of variation of the assessment of RA muscle volume, 30 to 40 slices were assessed twice in all subjects, at least 2 wk apart. The examiner was blinded regarding the previous results. The coefficient of variation of RA muscle volume was 1.6%.

Statistical analysis. Results are presented as means ± SD, except for the error bars in the figures, which represent the SEM. Pre- and posttraining comparisons were carried out using the paired Student's t-test adjusted for multiple comparisons using the Bonferroni–Holm method. Significant differences were assumed when $P < 0.05$.

RESULTS

Physical characteristics and total length of RA and OT are summarized in Table 1. No significant differences were observed in height, body mass, body mass index, and percentage of total body fat before and after Pilates. The total length of RA and OT was similar before and after the training program.

APPLIED SCIENCES

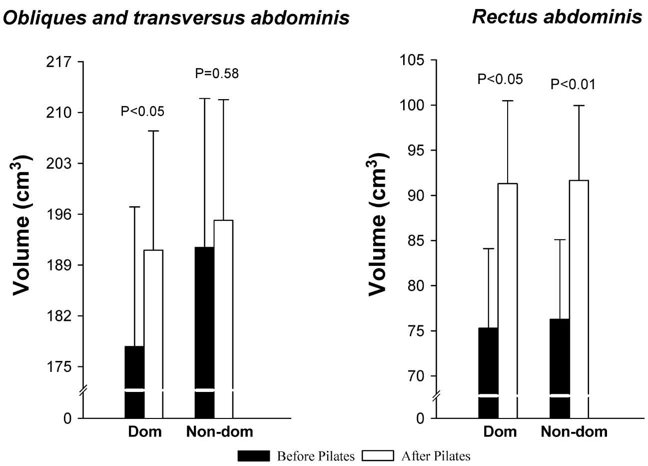

FIGURE 1—Influence of Pilates training on the V_{total} of the abdominal muscles of the dominant and nondominant sides.

Muscle Asymmetries

Before training, the V_{total} of the nondominant OT was 8% greater compared with the dominant side ($P < 0.01$). After Pilates, both sides had similar volumes (side-to-side difference = 2%, $P = 0.43$). The magnitude of asymmetry of RA was similar before and after Pilates (side-to-side difference = 2% and 1%, $P = 0.51$ and $P = 0.81$, respectively).

Muscle Hypertrophy after the Pilates Training Program

OT. The dominant OT had 8% greater muscle volume after Pilates ($P < 0.05$) (Fig. 1), whereas the volume of the nondominant OT was not significantly increased (+2%, $P = 0.58$). Consequently, the degree of side-to-side OT asymmetry showed a trend to be greater before than after Pilates ($P = 0.10$) (Fig. 2).

RA. The V_{total} of RA (both sides analyzed conjointly) increased by 21% after Pilates ($P < 0.05$). Dominant and nondominant RA volume increased by 21% ($P < 0.05$) and 20% ($P < 0.01$), respectively, after Pilates (Fig. 1).

DISCUSSION

This is the first study to clearly demonstrate that Modern Studio Pilates elicits a marked hypertrophy of the muscles of the abdominal wall, more accentuated in the RA than in the OT. Interestingly, Pilates corrected preexisting side-to-side asymmetries in the abdominal muscles of our sedentary women.

RA is considered the main agonist of trunk flexion (33). Our study shows for the first time that nonactive healthy women possess symmetric RA muscles, as previously reported in nonactive men (39). The effect of exercise on RA volume has been studied only in male athletes, who have been compared with sedentary controls (26,39). Thus, this is the first longitudinal study assessing the effects of training on the V_{total} of the main flexor of the trunk. The degree of RA hypertrophy elicited by Pilates in our nonactive healthy women (21%) is comparable to the 26% greater RA volume observed in professional male soccer and tennis players compared with their respective sedentary controls (26). Trunk flexion is a repeated action in Modern Pilates, which is performed concentrically and eccentrically, combined with some strong isometric contractions to maintain the trunk flexed while moving the extremities. In addition, slow and very slow concentric and eccentric trunk flexion movements are also common in Pilates (1). Isometric and eccentric contractions may elicit substantial muscle hypertrophy (9,19). The latter combined with the fact that our participants were nonactive women who had never been involved in any type of regular physical activity may have facilitated this remarkable increase in RA volume (43). It remains to be determined whether RA muscle hypertrophy could have occurred earlier in time (9) and how often Pilates should be practiced to maintain this level of RA hypertrophy.

Pilates includes diagonal or spiral trunk movements that are normally performed at very low speed and mainly with concentric contractions (1,30) and uses symmetric imprint and abdominal drawing-in movements (7,32,37). Despite the latter, the effects of Pilates training on the OT were more accentuated on the dominant side, which had a lower volume at the start of the program than the contralateral side. Importantly, this asymmetric hypertrophy compensated the preexisting side-to-side asymmetry of OT (8% greater volume in the nondominant than in the dominant side). Individual optimal postural alignment (neutral posture) is an important goal of Modern Pilates (30). During Pilates exercises, the relative symmetry of the movements is normally assessed by the instructor, who is placed beside the participant and gives feedback of the quality of movement (32). Studies using electromyography and ultrasound during different Pilates exercises have reported activation ratios around 25% of the maximal voluntary contraction (MVC)

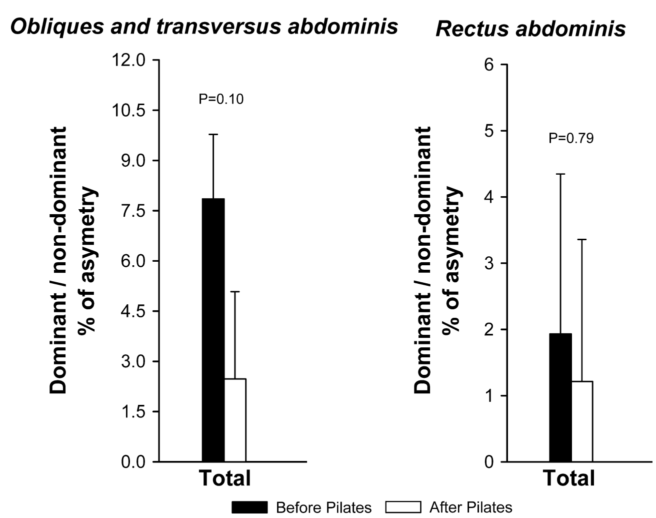

FIGURE 2—Side-to-side asymmetry in muscle volume, before and after Pilates training.

for internal obliques and transversus abdominis muscles (15) and 20%–45% of MVC for external obliques (32,36). It has been suggested that activation levels below 40% of MVC for abdominal muscles may not be enough for muscle strengthening in healthy subjects (41). Although the level of muscle activation was not determined in the current investigation, our results are compatible with levels of activation high enough to elicit muscle hypertrophy.

Possibly, the lower muscle volume of the dominant compared with the nondominant OT observed in healthy women could explain side-to-side differences in EMG activation during symmetric movements (27). Loss et al. (32) analyzed the activity of external obliques with electromyography in adult healthy women (6 months of experience in Pilates training), during symmetric hip flexion–extension movements with the knees extended and using diverse external mechanical overloads with the Cadillac equipment. The study showed that the muscle activity of the right external oblique varied to account for the different overloads in the extension phase, whereas the left side maintained a similar activity (32). The asymmetric activation of OT could explain the greater hypertrophy of the dominant OT observed in the present study.

It is well documented that abdominal muscles function as an operational stability system to protect the spine from injury (20,24,42). Low back pain is one of the commonest musculoskeletal problems in modern society (11). There is some evidence supporting the effectiveness of Pilates in the management of low back pain (35). The knowledge of the morphological adaptations induced by different training methods is very helpful to design more specific training programs for injury prevention and sports performance. The symmetric hypertrophy of RA induced by Pilates could help to increase intra-abdominal pressure and therefore to prevent low back injuries (24). In contrast, animal (23) and human studies (5,21) have provided evidence that this mechanism of protection is effective when its action is symmetrical between sides.

Limitations. The number of subjects studied, although enough to show a significant effect on the RA volume, might have been too small to show more asymmetries in the muscles of the abdominal wall. Thus, a type II error cannot be ruled out for the change in the level of side-to-side asymmetry after Pilates. Because we used several exercises, it is not possible to ascribe the effect to a specific exercise. Muscle force was not assessed; therefore, we do not know how much force was developed during the training sessions; however, the intensity used in Pilates exercise is small.

In conclusion, the present study reveals the existence of asymmetries in the muscles of the abdominal wall in nonactive healthy women. In addition, we have shown that Modern Pilates twice a week for 9 months elicits hypertrophy of the abdominal wall muscles, particularly of the RA, and eliminates preexisting asymmetries of the OT. Therefore, Modern Pilates can be recommended as an effective method to reinforce the muscles of the abdominal wall and to compensate preexisting asymmetric developments.

This study was supported by a grant from the Real Madrid – Universidad Europea de Madrid Research Chair (2009/04RM).

The authors thank all participants who volunteered in these studies. They also thank Hospital San Roque Maspalomas (Gran Canaria) for allowing them to use their MRI facilities.

None of the authors have any professional relationships with companies or manufacturers who will benefit from the results of the present study. All authors declare that they have no relationships, conditions, or circumstances that present a potential conflict of interest with the present study.

The results of the present study do not constitute endorsement by the American College of Sports Medicine.

REFERENCES

1. *Anatomy for Pilates*. London (UK): Primal Pictures with Pilates World University™; DVD ROM : ISBN 978-1-907061-13-4. 2008.
2. Bancroft LW, Peterson JJ, Kransdorf MJ, Berquist TH, O'Connor MI. Compartmental anatomy relevant to biopsy planning. *Semin Musculoskelet Radiol*. 2007;11(1):16–27.
3. Borghuis AJ, Lemmink KA, Hof AL. Core muscle response times and postural reactions in soccer players and nonplayers. *Med Sci Sports Exerc*. 2011;43(1):108–14.
4. Calbet JA, Moysi JS, Dorado C, Rodriguez LP. Bone mineral content and density in professional tennis players. *Calcif Tissue Int*. 1998;62(6):491–6.
5. Clark BC, Walkowski S, Conatser RR, Eland DC, Howell JN. Muscle functional magnetic resonance imaging and acute low back pain: a pilot study to characterize lumbar muscle activity asymmetries and examine the effects of osteopathic manipulative treatment. *Osteopath Med Prim Care*. 2009;3:7.
6. Cole MH, Grimshaw PN. Electromyography of the trunk and abdominal muscles in golfers with and without low back pain. *J Sci Med Sport*. 2008;11(2):174–81.
7. Critchley DJ, Pierson Z, Battersby G. Effect of Pilates mat exercises and conventional exercise programmes on transversus abdominis and obliquus internus abdominis activity: pilot randomised trial. *Man Ther*. 2011;16(2):183–9.
8. Culligan PJ, Scherer J, Dyer K, et al. A randomized clinical trial comparing pelvic floor muscle training to a Pilates exercise program for improving pelvic muscle strength. *Int Urogynecol J*. 2010;21(4):401–8.
9. DeFreitas JM, Beck TW, Stock MS, Dillon MA, Kasishke PR 2nd. An examination of the time course of training-induced skeletal muscle hypertrophy. *Eur J Appl Physiol*. 2011;111(11):2785–90.
10. Dunleavy K. Pilates fitness continuum: post-rehabilitation and prevention Pilates fitness programs. *Rehab Manag*. 2010;23(9):10, 12–5.
11. Egle UT, Nickel R. Chronic low back pain as a somatoform pain disorder. *Orthopade*. 2008;37(4):280–4. German.
12. Elliott B. Biomechanics and tennis. *Br J Sports Med*. 2006;40(5):392–6.
13. Elosua R, Garcia M, Aguilar A, Molina L, Covas MI, Marrugat J. Validation of the Minnesota Leisure Time Physical Activity Questionnaire in Spanish Women. Investigators of the MARATDON Group. *Med Sci Sports Exerc*. 2000;32(8):1431–7.
14. Emery K, De Serres SJ, McMillan A, Cote JN. The effects of a Pilates training program on arm–trunk posture and movement. *Clin Biomech (Bristol, Avon)*. 2010;25(2):124–30.

APPLIED SCIENCES

15. Endleman I, Critchley DJ. Transversus abdominis and obliquus internus activity during Pilates exercises: measurement with ultrasound scanning. *Arch Phys Med Rehabil*. 2008;89(11):2205–12.
16. Estenne M, Pinet C, De Troyer A. Abdominal muscle strength in patients with tetraplegia. *Am J Respir Crit Care Med*. 2000; 161(3 Pt 1):707–12.
17. Friedman P, Eisen G. *The Pilates Method: Physical and Mental Conditioning*. New York (NY): Wamer Book edition. 1981.191p.
18. Futter CM, Weiler-Mithoff E, Hagen S, et al. Do pre-operative abdominal exercises prevent post-operative donor site complications for women undergoing DIEP flap breast reconstruction? A two-centre, prospective randomised controlled trial. *Br J Plast Surg*. 2003;56(7):674–83.
19. Hather BM, Tesch PA, Buchanan P, Dudley GA. Influence of eccentric actions on skeletal muscle adaptations to resistance training. *Acta Physiol Scand*. 1991;143(2):177–85.
20. Hides J, Fan T, Stanton W, Stanton P, McMahon K, Wilson S. Psoas and quadratus lumborum muscle asymmetry among elite Australian Football League players. *Br J Sports Med*. 44(8):563–7.
21. Hides J, Stanton W, Freke M, Wilson S, McMahon S, Richardson C. MRI study of the size, symmetry and function of the trunk muscles among elite cricketers with and without low back pain. *Br J Sports Med*. 2008;42(10):809–13.
22. Hides JA, Jull GA, Richardson CA. Long-term effects of specific stabilizing exercises for first-episode low back pain. *Spine (Phila Pa 1976)*. 2001;26(11):E243–8.
23. Hodges P, Kaigle Holm A, Holm S, et al. Intervertebral stiffness of the spine is increased by evoked contraction of transversus abdominis and the diaphragm: *in vivo* porcine studies. *Spine (Phila Pa 1976)*. 2003;28(23):2594–601.
24. Hodges PW, Eriksson AE, Shirley D, Gandevia SC. Intra-abdominal pressure increases stiffness of the lumbar spine. *J Biomech*. 2005; 38(9):1873–80.
25. Hodges PW, Richardson CA. Inefficient muscular stabilization of the lumbar spine associated with low back pain. A motor control evaluation of transversus abdominis. *Spine (Phila Pa 1976)*. 1996;21(22):2640–50.
26. Idoate F, Calbet J, Izquierdo M, Sanchis-Moysi J. Soccer attenuates the asymmetry of rectus abdominis muscle observed in non-athletes. *PloS One*. 2011;6(4):e19022.
27. Kanehisa H, Ikegawa S, Fukunaga T. Comparison of muscle cross-sectional area and strength between untrained women and men. *Eur J Appl Physiol Occup Physiol*. 1994;68(2):148–54.
28. Kloubec JA. Pilates for improvement of muscle endurance, flexibility, balance, and posture. *J Strength Cond Res*. 2010;24(3):661–7.
29. Latey P. The Pilates method: history and philosophy. *J Bodyw Mov Ther*. 2001;5(4):275–82.
30. Latey P. Updating the principles of the Pilates method. *J Bodyw Mov Ther*. 2002;6(2):94–101.
31. Lee RC, Wang Z, Heo M, Ross R, Janssen I, Heymsfield SB. Total-body skeletal muscle mass: development and cross-validation of anthropometric prediction models. *Am J Clin Nutr*. 2000;72(3): 796–803.
32. Loss JF, Melo MO, Rosa CH, Santos AB, La Torre M, Silva YO. Electrical activity of external oblique and multifidus muscles during the hip flexion–extension exercise performed in the Cadillac with different adjustments of springs and individual positions. *Rev Bras Fisioter*. 2010;14(6):510–7. English, Portuguese.
33. Norris CM. Abdominal muscle training in sport. *Br J Sports Med*. 1993;27(1):19–27.
34. Perez-Gomez J, Rodriguez GV, Ara I, et al. Role of muscle mass on sprint performance: gender differences? *Eur J Appl Physiol*. 2008;102(6):685–94.
35. Posadzki P, Lizis P, Hagner-Derengowska M. Pilates for low back pain: a systematic review. *Complement Ther Clin Pract*. 2011; 17(2):85–9.
36. Queiroz BC, Cagliari MF, Amorim CF, Sacco IC. Muscle activation during four Pilates core stability exercises in quadruped position. *Arch Phys Med Rehabil*. 2010;91(1):86–92.
37. Rydeard R, Leger A, Smith D. Pilates-based therapeutic exercise: effect on subjects with nonspecific chronic low back pain and functional disability: a randomized controlled trial. *J Orthop Sports Phys Ther*. 2006;36(7):472–84.
38. Sanchis-Moysi J, Idoate F, Izquierdo M, Calbet JA, Dorado C. Iliopsoas and gluteal muscles are asymmetric in tennis players but not in soccer players. *PloS One*. 2011;6(7):e22858.
39. Sanchis-Moysi J, Dorado C, Alayon S, Calbet JAL. Large asymmetric hypertrophy of rectus abdominis muscle in professional tennis players. *PloS One*. 2010;5(12):e15858.
40. Siqueira Rodrigues BG, Ali Cader S, Bento Torres NV, Oliveira EM, Martin Dantas EH. Pilates method in personal autonomy, static balance and quality of life of elderly females. *J Bodyw Mov Ther*. 2010;14(2):195–202.
41. Souza GM, Baker LL, Powers CM. Electromyographic activity of selected trunk muscles during dynamic spine stabilization exercises. *Arch Phys Med Rehabil*. 2001;82(11):1551–7.
42. Tesh KM, Dunn JS, Evans JH. The abdominal muscles and vertebral stability. *Spine (Phila Pa 1976)*. 1987;12(5):501–8.
43. Wernbom M, Augustsson J, Thomee R. The influence of frequency, intensity, volume and mode of strength training on whole muscle cross-sectional area in humans. *Sports Med*. 2007;37(3):225–64.