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Does running performance affect the thoracic diameter expansion among different running intensities?

Gonzalo Garrido-López [a], Javier Rueda [a], Alejandro F. San Juan [a], Markus Bastir [b], Benoit Beyer [c], Enrique Navarro [a,*]

[a] *Sport Biomechanics Laboratory, Department of Health and Human Performance, Faculty of Physical Activity and Sports Sciences INEF, Universidad Politécnica de Madrid, Madrid, Spain*
[b] *Paleobiology Department, Museo Nacional de Ciencias Naturales, CSIC, Madrid, Spain*
[c] *Laboratory for Functional Anatomy, Faculty of Motor Sciences, Université libre de Bruxelles, Bruxelles, Belgium*

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ABSTRACT

Traditionally, breathing expansion has been considered solely as a physiological process, neglecting the biomechanical aspects. This expansion does not appear to occur uniformly across the upper and lower levels of the ribcage. Moreover, running performance seems to be a determining factor for the thoracic wall movements. This study aims to analyse how mediolateral and anteroposterior thoracic diameters vary at different levels (upper, middle, and lower) in athletes with different running performance levels at various running intensities. Twenty-two healthy athletes were recorded using optoelectronic plethysmography while performing an incremental running test. Three recordings were taken from each subject at different running intensities, and three running performance groups were created by the final velocity obtained in the incremental test. An increase in the thoracic expansion of anteroposterior and mediolateral diameters at all levels was observed while the exercise intensity rose. However, a mirrored pattern was found while the intensity rose: the upper anteroposterior and lower mediolateral diameters appear to expand more during the initial phase of the effort, whereas the upper mediolateral and lower anteroposterior diameters expand more during the final phase of the effort. No significant differences were found between running performance groups at the same exercise intensity, although the mirrored pattern was slightly seen when analysing each group separately. Bigger differences among running performance groups are needed to glimpse thoracic kinematics variances. Further research on thoracic kinematics is required to understand better respiratory disorders, fitness assessments, and respiratory diseases.

1. Introduction

Traditionally, breathing has been considered solely as a physiological process, neglecting the biomechanical aspects (Aliverti et al., 2022). The thorax expands and compresses during breathing due to the movement of the ribs with the vertebrae and the sternum (Fig. 1) (Kapandji, 1973).

Conventionally, gas analysers and spirometry have been used to assess respiratory variables. Still, these techniques lack analysing kinematics (Chynkiamis et al., 2021; Houssein et al., 2021; Stubbe et al., 2022a). For such kinematic evaluations, the most used systems are motion capture ones, which are non-invasive and permit capturing the position of reflective markers (Aliverti et al., 2001). The use of these techniques to analyse respiratory patterns began in 1994, with a study that used 4 cameras, and 32 reflective markers placed on the thorax (Ferrigno et al., 1994). Although thoracic kinematics were initially studied with magnetometers in 1967 and plethysmography in 1991 (Lumb and Nunn, 1991; Mead et al., 1967), and from then this technique has evolved into optoelectronic plethysmography (OEP) (Massaroni et al., 2017b).

OEP has demonstrated great concordance with spirometry results and has been validated for analysing respiratory kinematics (Feitosa et al., 2019; Houssein et al., 2021; Sarro et al., 2018; Stubbe et al., 2022a). Proper data collection relies on marker placement, with models ranging from 5 to 89 markers. Recently, 5–32 markers models have been shown to facilitate data collection, producing results very similar to

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* Corresponding author.
E-mail addresses: gonzalo.garrido.lopez@upm.es (G. Garrido-López), javier.ruedao@upm.es (J. Rueda), alejandro.sanjuan@upm.es (A.F. San Juan), mbastir@mncn.csic.es (M. Bastir), bbeyer@ulb.be (B. Beyer), enrique.navarro@upm.es (E. Navarro).

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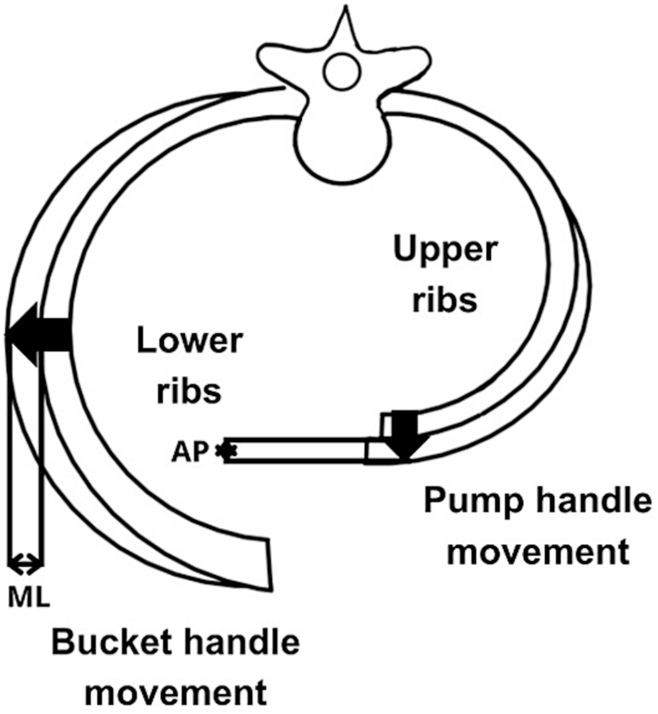

Fig. 1. Graphical description of the movements of the different ribs (AP: anteroposterior diameter, ML: mediolateral diameter).
Adapted from Kapandji, 1973.

spirometry (Martins et al., 2021; Massaroni et al., 2018, 2017a; Rodrigues et al., 2019; Shamantseva et al., 2023; Stubbe et al., 2022b), concluding that reduced marker models are sufficient to obtain biomechanical variables (Kaneko and Horie, 2012; Stubbe et al., 2022a). Various studies have used OEP to analyse breathing in different positions, compare deep and relaxed breathing, and measure variables during exercise (Cavassini et al., 2022; Massaroni et al., 2017b; Nicolò et al., 2020a; Zhao et al., 2022).

Moreover, it is crucial to analyse breathing considering the trunk both as a whole and, dividing it into different compartments to obtain more detailed information (Aliverti et al., 2022, 2001; Zannin et al., 2019). Some studies analyse the thoracic ribcage and abdomen separately, while others divide the thorax into various parts (Aliverti et al., 2022; Zannin et al., 2019).

Further, not all individuals exhibit the same mechanical breathing pattern. Breathing differences are found among sex, age, and illness (Cavassini et al., 2022; Mendes et al., 2020; Shaghayeghfard et al., 2024). Healthy subjects show an anteroposterior thoracic expansion that is 1.8 times more pronounced, with respiratory capacity values being 1.6 times greater than patients with pulmonary pathology (Luu et al., 2021). Physical fitness seems to be the most determining factor (Bellemare et al., 2003; Binazzi et al., 2006; Romei et al., 2010; Vogiatzis et al., 2005). In healthy individuals, a much greater increase in anteroposterior diameter compared to mediolateral is observed, particularly in athletes, who exhibit significantly greater control over their respiratory muscles than the general population (Kapandji, 1973; Martins et al., 2021). Some authors have demonstrated that different exercise programs increase breathing volume and expansion, concluding that breathing can be trained, and physical fitness levels can be assessed through thoracic kinematics (Ahmed et al., 2024; Campos et al., 2019; Rodrigues et al., 2019; Wada et al., 2016). However, there is insufficient information about respiratory mechanics and the changes in thorax motion patterns among subjects with different endurance capacities (Lopes et al., 2024).

During high-intensity exercise, the thorax tends to start to expand by the lower ribcage, followed by the abdominal one, the clavicles section, and finally by the middle and upper ribs sections (Smyth et al., 2022). Various authors have demonstrated that the abdominal section and the lower thoracic section contribute more in cyclists and swimmers than in other athletes, showing the influence of posture and the type of exercise performed (Lopes et al., 2024; Mendes et al., 2020; Sarro et al., 2018; Shaghayeghfard et al., 2024; Sonpeayung et al., 2018; Takashima et al., 2017).

Depending on the specificity of the sport, the mechanical breathing pattern is altered to increase breathing efficiency (Campos et al., 2019; Rodrigues et al., 2019; Silvatti et al., 2012). In exercise with lower intensity, such as walking, the ribcage distortion is minimal, while during training it is minimized because of the muscles' coordination (Sanna et al., 1999). For all these reasons, it is essential to develop a measurement tool to evaluate health or fitness based on the thoracic ROM (Massaroni et al., 2017b; Sarro et al., 2018; Smyth et al., 2020; Stubbe et al., 2022a). Respiratory volume and thoracic kinematics are considered key factors in assessing the proper function of the respiratory system (Ando et al., 2011; Meric et al., 2016).

The present study aims to analyse thoracic expansion in both the anteroposterior and mediolateral diameters in different thoracic levels and running intensities, comparing these differences across running performance groups.

The hypothesis establishes that greater expansion will be found in the anteroposterior diameter at higher thoracic levels in all running intensities. In the middle thoracic region, it is expected that both the anteroposterior and mediolateral diameters will expand similarly and will grow with increasing intensity, while in the lower thoracic region, the mediolateral diameter will expand more than the anteroposterior diameter at all running intensities, although both diameters will increase when exercise intensity rises. Additionally, it is hypothesised that subjects with better running performance will expand their thoraxes more in the inferior part near the abdominal muscles, followed by the superior part, and ending in the middle one.

2. Material and Methods

2.1. Data Acquisition technique

This methodology was previously used and detailed (Garrido-López et al., 2024). An optoelectronic system (VICON®, (Oxford Metrics Ltd., Oxford, UK)) comprising six video cameras (120 Hz) was used for determining the 3D position of a set of 13 reflective markers (Fig. 2 and Table 1). Following VICON® System guidelines, the cameras were calibrated, obtaining less than 1 % error, and reliability on the determination of the position of the reflective markers of each camera of less than ± 2 mm. The 3D data of the markers was treated using Woltring's method (mean square error of 4 mm^2). A custom-made code on VICON® software using a programming language was used for determining the variables.

2.2. Mechanical variables

The analysed variables were two thoracic diameters at different thoracic levels. The variables were the result of the following operations:

- Anteroposterior diameter:
  - o Upper (ATD1): Distance between markers T1 and CLAV.
  - o Middle (ATD2): Distance between marker T5 and the midpoint between CLAV, STRN, TOAC5L, and TOAC5R.
  - o Lower (ATD3): Distance between marker T7 and the midpoint between TOAUCR and TOAUCL.
- Mediolateral diameter:
  - o Upper (MTD1): Distance between markers LCO1 and RCO1.
  - o Middle (MTD2): Distance between the midpoint between markers TOLR and RCO1, and the midpoint between TOLL and LCO1.
  - o Lower (MTD3): Distance between markers TOLL and TOLR.

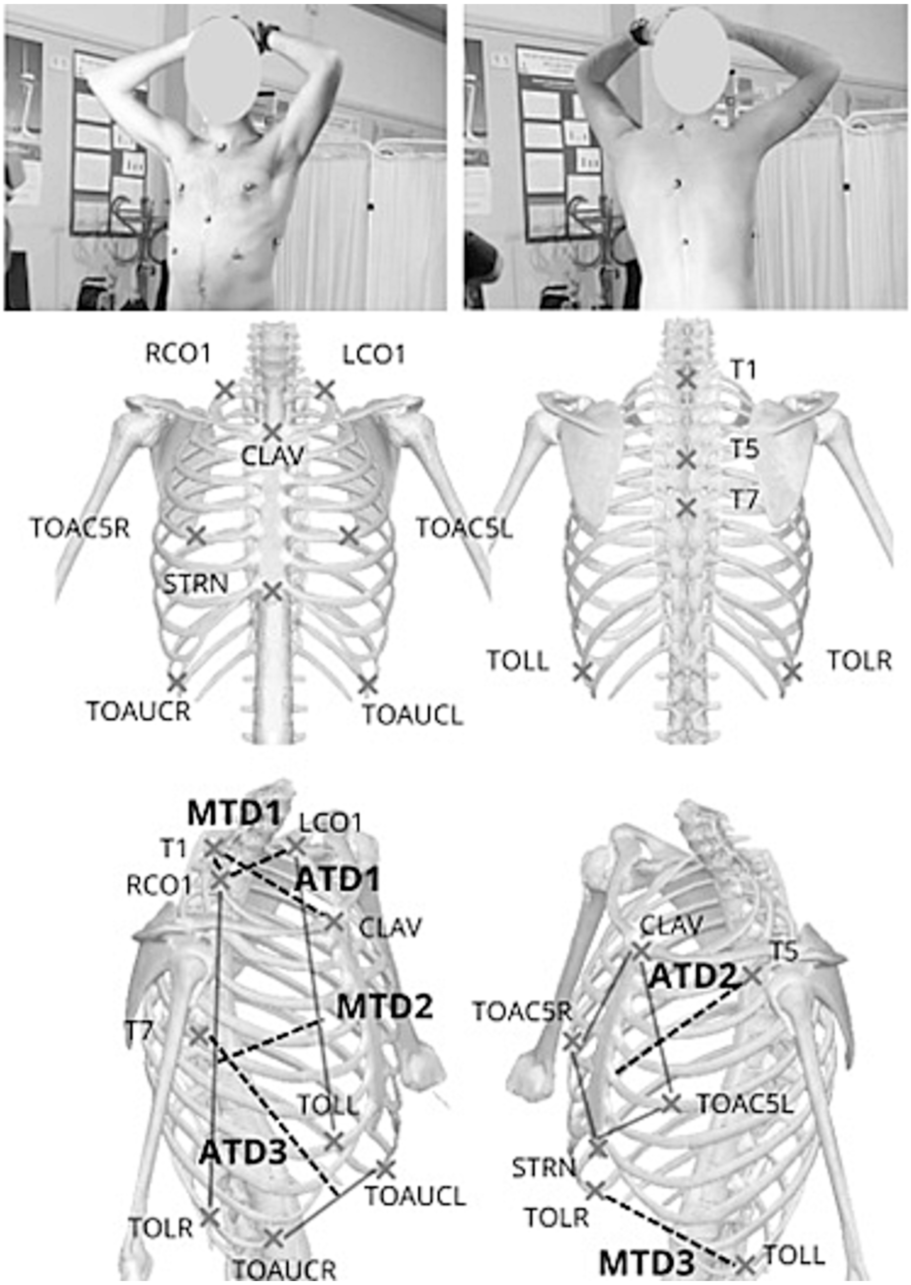

Fig. 2. Markers distribution.

Table 1
Marker model description.

MARKER NAME	MARKER LOCATION
T1	T1 spinal apophysis
T5	T5 spinal apophysis
T7	T7 spinal apophysis
RCO1	Posterior part of the right first rib
LCO1	Posterior part of the left first rib
CLAV	Jugular suprasternal notch
STRN	Xiphoid process
TOAC5R	Mammillary line of the right fifth rib
TOAC5L	Mammillary line of the left fifth rib
TOLR	Lateral part of the right tenth rib
TOLL	Lateral part of the left tenth rib
TOAUCR	Anterior inferior part of the right tenth rib
TOAUCL	Anterior inferior part of the left tenth rib

2.3. Sample

Twenty-two healthy males, amateur athletes (i.e., eight from athletics, eight from soccer, and six from basketball) were analysed

Table 2
Sample description. Footer: RHR: Resting heart rate; HRmax: Maximum heart rate.

Descriptives (N = 22)					
	Age (years)	Weight (Kg)	Height (m)	RHR (bpm)	HRmax (bpm)
Mean	20.9	69.3	1.77	63.9	198
Standard deviation	2.75	6.21	0.0642	7.93	1.84
Minimum	18	57.4	1.65	53	192
Maximum	29	81.0	1.90	86	199

(Table 2). Approval was obtained from the university's ethics committee, and the procedures used adhered to the tenets of the Declaration of Helsinki. All the participants signed an informed consent document. The inclusion criteria were: 1) to have not suffered any injury in the past six months, and 2) to be undertaking regular exercise, including long-distance running (covering at least 20 km per week). The participants could not take part if they fulfilled any exclusion criteria: having suffered respiratory pathologies or other clinical conditions that make it dangerous to perform the test.

2.4. Experimental design

The running test was incremental on a treadmill device (Telju JT4100- Litin-035, Toledo, Spain). The test started at 7 km/h with a 1 % slope, and the velocity was increased 0.5 km/h every 30 s. The subject's HRmax was estimated and monitored with a pulsometer (Polar Ceinture *H*10+, Polar Electro OY, Kempele, Finland). The VICON® captures were taken when reaching 45 %, 70 %, and 85 % of the heart rate reserve (HRR) (difference between the maximum and resting heart rate) (20 s for each capture). The test ended when the subjects reached maximum exhaustion.

2.5. Statistical variables Definition

The VO_2max is the most used performance marker for cardiovascular capacity, and it is highly related to the final velocity reached in an incremental running test (Lanferdini et al., 2020). The final velocity reached in the incremental test of each participant was used to divide participants into groups with different running performances. Physical fitness appears to be a key determinant of breathing patterns, as individuals with higher fitness levels, particularly athletes, often exhibit superior coordination of respiratory muscles (Bellemare et al., 2003; Binazzi et al., 2006; Romei et al., 2010; Vogiatzis et al., 2005; Kapandji, 1973; Martins et al., 2021). Moreover, breathing kinematics analysis has been proposed as a viable method to assess physical fitness (Ahmed et al., 2024; Campos et al., 2019; Rodrigues et al., 2019; Wada et al., 2016). Therefore, the use of the final velocity obtained in the incremental test as a performance marker not only reflects running capacity but may also provide insights into underlying respiratory adaptations related to fitness level.

Three groups were created based on the percentiles of the final velocity obtained: group 1 (less than 14.3 km/h), group 2 (between 14.3 and 15.7 km/h), and group 3 (more than 15.7 km/h). To evaluate the thoracic diameters from each capture, 10 intervals of 1 s were analysed. For each interval and diameter, the 95 and 5 percentiles and the distance between them were calculated. This data was normalised using the percentile 5 of each diameter for each subject across all intervals, calculating the increased percentage (IP) results. The mean IP was calculated across the 10 intervals for each running intensity and diameter. This data treatment was used in another investigation (Garrido-López et al., 2024).

2.6. Statistical analysis

A two-way ANOVA was conducted for each diameter (running performance factor with three levels: group 1, 2, and 3; and running intensity with three levels: 45 %, 70 %, and 85 % HRR). Jamovi (version 2.2.5) and IBM-SPSS (version 29.0.2.0) were used. GPower (version 3.1) was used to estimate the minimum desirable sample of 24 subjects, establishing a statistical power of 0.9 and an effect size (f) of 0.35. Only the differences reaching above the effect size established were considered. Levene's test and Greenhouse-Geisser corrections were performed. The normality test (Shapiro-Wilk) showed a homogeneous distribution of the data ($p > 0.05$), except for the ATD1_45% variable. Parametric statistical tests were used. The effect size for the main effects was assessed using Generalised Eta Squared (η^2G), with threshold values for small, medium, and large effects being 0.01, 0.06, and 0.14, respectively (Cohen, 1992). The Bonferroni post hoc test was used for analysing differences among groups. The significance level was established at $p > 0.05$.

3. Results

A significant effect of exercise intensity in both the anteroposterior and mediolateral IP in all three trunk levels was found (Tables 3 and 4).

The IP of the anteroposterior diameter was significant at the upper ($F2.30 = 11.13$, $p < 0.001$, $\eta^2G = 0.071$), middle ($F2.32 = 62.628$, $p < 0.001$, $\eta^2G = 0.475$), and lower level ($F2.16 = 16.618$, $p < 0.001$, $\eta^2G = 0.445$). The thoracic expansion significantly increased from 45 % to 85 % HRR across all three thoracic levels: by 1.61 % ($p = 0.005$) in the upper, 2.82 % ($p < 0.001$) in the middle, and 2.7 % ($p = 0.003$) in the lower section. Increases were also observed from 45 % to 70 % HRR at the upper (0.93 %, $p = 0.005$) and middle levels (0.93 %, $p = 0.009$), as well as from 70 % to 85 % HRR in the lower section (2.29 %, $p = 0.012$), with large effect sizes.

The IP of the mediolateral diameter showed statistically significant

Table 3
IP results of the anteroposterior thorax diameter (ATD) among different exercise intensities divided by running performance groups.

RUNNING PERFORMANCE GROUP	ATD1	Mean	SE	95 % Confidence Interval	
				Lower	Upper
1*	ATD1_45%	7.87	0.97	5.80	9.93
	ATD1_70%	9.50	0.95	7.49	11.52
	ATD1_85%	9.52	1.22	6.93	12.11
2	ATD1_45%	6.48	0.89	4.59	8.37
	ATD1_70%	7.45	0.86	5.61	9.24
	ATD1_85%	8.22	1.11	5.86	10.59
3	ATD1_45%	5.31	0.82	3.56	7.06
	ATD1_70%	5.91	0.80	4.20	7.61
	ATD1_85%	7.12	1.03	4.93	9.32
TOTAL*¤	ATD1_45%	6.13	0.53	5.09	7.17
	ATD1_70%	7.14	0.62	5.92	8.36
	ATD1_85%	8.15	0.65	6.89	9.42
1#¤	ATD2_45%	4.17	0.71	2.66	5.68
	ATD2_70%	5.43	0.64	4.06	6.78
	ATD2_85%	6.70	0.69	5.24	8.15
2#¤	ATD2_45%	4.65	0.51	3.58	5.72
	ATD2_70%	5.32	0.46	4.25	6.29
	ATD2_85%	7.46	0.49	6.44	8.49
3#¤	ATD2_45%	5.03	0.54	3.89	6.17
	ATD2_70%	5.99	0.49	4.96	7.03
	ATD2_85%	7.97	0.52	6.87	9.07
TOTAL*#¤	ATD2_45%	4.75	0.29	4.18	5.33
	ATD2_70%	5.45	0.31	4.84	6.06
	ATD2_85%	7.49	0.32	6.87	8.11
1¤	ATD3_45%	3.55	0.70	1.93	5.17
	ATD3_70%	4.58	0.73	2.90	6.25
	ATD3_85%	7.15	1.23	4.32	9.98
2¤	ATD3_45%	3.78	0.70	2.16	5.40
	ATD3_70%	4.27	0.73	2.56	5.95
	ATD3_85%	6.63	1.23	3.81	9.46
3	ATD3_45%	4.75	0.54	3.49	6.00
	ATD3_70%	4.96	0.56	3.66	6.25
	ATD3_85%	6.83	0.95	4.64	9.02
TOTAL#¤	ATD3_45%	4.16	0.34	3.50	4.82
	ATD3_70%	4.41	0.46	3.51	5.30
	ATD3_85%	6.63	0.50	5.66	7.60

Key: ATD1/ATD2/ATD3_45%: IP of upper/middle/lower anteroposterior thorax diameter at a running intensity of 45% HRR; ATD1/ATD2/ATD3_70%: IP of upper/middle/lower anteroposterior thorax diameter at a running intensity of 70% HRR; ATD1/ATD2/ATD3_85%: IP of upper/middle/lower anteroposterior thorax diameter at a running intensity of 85% HRR.

* Statistical difference between IP in 45 % HRR and 70 % HRR ($p < 0.05$). # Statistical difference between IP in 70 % HRR and 85 % HRR ($p < 0.05$). ¤ Statistical difference between IP in 45 % HRR and 85 % HRR ($p < 0.05$).

Table 4
IP results of the mediolateral thorax diameter (MTD) among different exercise intensities divided by running performance groups.

RUNNING PERFORMANCE GROUP	MTD1	Mean	SE	95 % Confidence Interval	
				Lower	Upper
1¤	MTD1_45%	4.38	0.77	2.77	6.00
	MTD1_70%	5.61	0.76	4.01	7.21
	MTD1_85%	6.62	1.01	4.51	8.72
2#¤	MTD1_45%	3.56	0.72	2.05	5.07
	MTD1_70%	4.39	0.72	2.89	5.88
	MTD1_85%	6.10	0.94	4.13	8.08
3#¤	MTD1_45%	5.63	0.77	4.01	7.24
	MTD1_70%	5.46	0.76	3.86	7.06
	MTD1_85%	9.46	1.01	7.35	11.57
TOTAL#¤	MTD1_45%	4.48	0.45	3.59	5.37
	MTD1_70%	5.12	0.43	4.28	5.95
	MTD1_85%	7.34	0.63	6.11	8.57
1*	MTD2_45%	1.97	0.20	1.59	2.39
	MTD2_70%	2.83	0.27	2.26	3.40
	MTD2_85%	2.86	0.39	2.03	3.68
2	MTD2_45%	2.03	0.19	1.64	2.42
	MTD2_70%	2.51	0.25	1.98	3.04
	MTD2_85%	2.86	0.37	2.09	3.63
3	MTD2_45%	2.32	0.20	1.90	2.74
	MTD2_70%	2.54	0.27	1.97	3.10
	MTD2_85%	3.12	0.39	2.30	3.94
TOTAL*¤	MTD2_45%	2.10	0.11	1.88	2.32
	MTD2_70%	2.62	0.15	2.33	2.91
	MTD2_85%	2.94	0.21	2.53	3.36
1*¤	MTD3_45%	2.95	0.34	2.25	3.66
	MTD3_70%	4.75	0.42	3.88	5.62
	MTD3_85%	4.97	0.46	4.01	5.94
2*¤	MTD3_45%	3.74	0.32	3.08	4.40
	MTD3_70%	4.92	0.39	4.10	5.73
	MTD3_85%	5.49	0.43	4.59	6.39
3¤	MTD3_45%	3.44	0.34	2.73	4.14
	MTD3_70%	4.31	0.42	3.44	5.18
	MTD3_85%	5.49	0.46	4.53	6.46
TOTAL*¤	MTD3_45%	3.39	0.19	3.01	3.77
	MTD3_70%	4.67	0.23	4.22	5.12
	MTD3_85%	5.33	0.25	4.83	5.82

Key: MTD1/MTD2/MTD3_45%: IP of upper/middle/lower mediolateral thorax diameter at a running intensity of 45% HRR; MTD1/MTD2/MTD3_70%: IP of upper/middle/lower mediolateral thorax diameter at a running intensity of 70% HRR; MTD1/MTD2/MTD3_85%: IP of upper/middle/lower mediolateral thorax diameter at a running intensity of 85% HRR.
* Statistical difference between IP in 45 % HRR and 70 % HRR ($p < 0.05$). # Statistical difference between IP in 70 % HRR and 85 % HRR ($p < 0.05$). ¤ Statistical difference between IP in 45 % HRR and 85 % HRR ($p < 0.05$).

differences at the upper (F2.38 = 26.4, $p < 0.001$, $\eta^2G = 0.242$), middle (F2.38 = 11.682, $p < 0.001$, $\eta^2G = 0.218$), and lower level (F2.38 = 36.228, $p < 0.001$, $\eta^2G = 0.390$). An increase of 1.29 % was observed in the lower and 0.52 % in the middle section for thoracic expansion from 45 % to 70 % of HRR ($p < 0.001$ and $p = 0.003$, respectively). Furthermore, increases of 2.86 % in the upper, 0.84 % in the middle, and 1.95 % in the lower section were noted from 45 % to 85 % of HRR ($p < 0.001$, $p = 0.002$, and $p < 0.001$, respectively). Additionally, a significant difference of 2.24 % ($p < 0.001$) was found between 70 % and 85 % of HRR in the upper section, with the effect size being large.

In order to analyse the effect of running performance on the deformations of the thorax, the IP among different exercise intensities of the different running performance groups of both anteroposterior and mediolateral diameters was observed, finding almost no significant differences. However, when we compared the IP among different running intensities group by group some relevant results were found.

Statistically significant differences appeared in every diameter: upper anteroposterior (ATD1) (F2.15 = 1.228, $p = 0.068$, $\eta^2G = 0.301$), middle anteroposterior (ATD2) (F2.16 = 2.236, $p = 0.139$, $\eta^2G = 0.218$), lower anteroposterior (ATD3) (F2.8 = 0.07, $p = 0.993$, $\eta^2G = 0.002$), upper mediolateral (MTD1) (F2.19 = 8.834, $p = 0.002$, $\eta^2G = 0.482$), middle mediolateral (MTD2) (F2.19 = 2.588, $p = 0.101$, $\eta^2G = 0.001$), and lower mediolateral (MTD3) (F2.19 = 2.201, $p = 0.138$, $\eta^2G = 0.188$) (Tables 3 and 4).

Starting with the IP from 45 % to 85 % HRR, significant differences were found in all the groups of MTD1, ATD2, MTD3, and in groups 1 and 2 of ATD3, reaching differences of 2.02 %-3.56 % in group 1, 1.75 %-2.85 % in group 2, and 2.06 %-3.83 % in group 3. From 45 % HRR to 70 % HRR significant differences were found in group 1 in ATD1 (1.64 %, $p = 0.008$) with large effect size, in MTD2 (0.87 %, $p = 0.002$) with small effect size, and in MTD3 (1.8 %, $p < 0.001$) with a large effect size; and in group 2 in MTD3 (1.17 %, $P = 0.005$) with a large effect size. From 70 % HRR to 85 % HRR more differences were found. On ATD2 the IP was significant between group 1 and groups 2 and 3 (1.27 %, $p = 0.004$; 2.14 %, $p < 0.001$; 1.98 %, $p < 0.001$ respectively), and on MTD1 between groups 2 and 3 (1.72 %, $p = 0.006$; 4.00 %, $p < 0.001$ respectively), all of them with large effect size.

4. Discussion

In the present study, the variations in chest expansion at different thoracic sections at different running intensities were assessed, dividing the sample into various running performance groups using OEP. The present analysis included a sample of twenty-two male athletes from various sports disciplines. Previous studies by Mendes et al. (2020) and Shaghayeghfard et al. (2024) have clearly demonstrated sex-based differences in breathing patterns, reporting that females tend to exhibit more thoracic-dominant breathing, characterized by a greater increase in the upper anteroposterior diameter. Future investigations should aim to explore how exercise intensity and running performance influence thoracic expansion patterns specifically in female populations.

Although the sample was divided into three groups based on different running performances using the final velocity obtained from an incremental test, the differences between the groups were not substantial. A physiological VO$_2$ max test should be included in future studies to assess cardiovascular fitness using a more objective measure and to more clearly define groups with greater distinctions between them. This would allow for a more accurate analysis of breathing pattern kinematics across groups with varying cardiovascular capacities. Due to this limitation, most of the results discussed in this section refer to the entire sample as a whole, without division into subgroups.

Our results partially confirm the hypothesis, as the two diameters of the thorax at all three levels increase when exercise intensity rises from 45 % to 85 % of HRR. The bigger expansions occur in the anteroposterior diameter and the upper mediolateral. These results agree with Vogiatzis et al. in 2005, that used OEP during cycling at different intensities, concluding that inspiratory volume increases with rising intensity. Moreover, Kaneko and Horie, (2012) observed that thoracic expansion varies when the breathing pattern is modified, suggesting that a situation involving high-intensity effort may alter the pattern compared to rest.

At the first part of the incremental running test (from 45 % to 70 % of HRR), a significant expansion in the upper and middle anteroposterior diameters occurred, although not in the lower; and in the mediolateral diameter at the middle and lower levels, but not at the upper, exhibiting contrary behaviours. At the final stage of the test (from 70 % to 85 % of HRR), the anteroposterior diameter significantly expanded in the middle and lower sections, while the mediolateral diameter did so only in the upper, demonstrating again inverse conduct (Fig. 3).

The results indicate that the two thoracic diameters at their three levels display a mirrored pattern (Fig. 4). The upper anteroposterior and lower mediolateral diameters reflected a faster change during low to moderate-intensity exercise. This pattern agrees with the one described by Kapandji, in 1973, which concluded that the anteroposterior diameter increases in the upper thorax due to movement of the costotransverse, costovertebral, and costosternal joints, while the

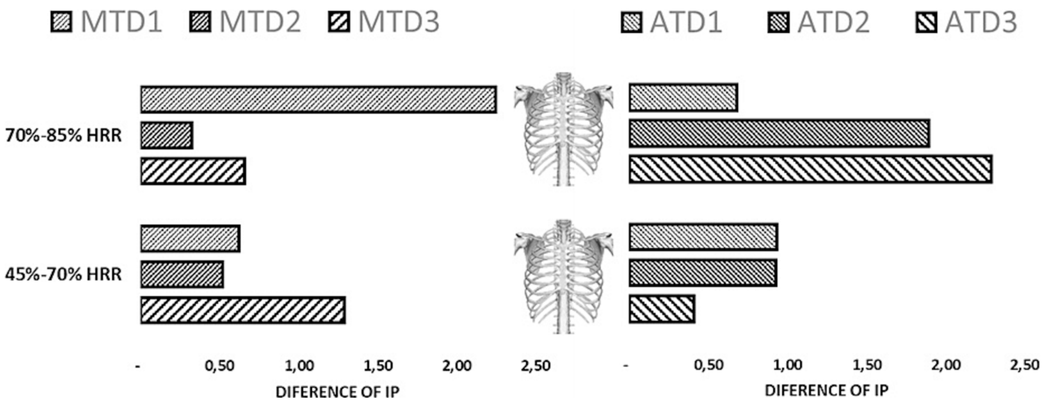

Fig. 3. Difference in diameters IP between running intensities. Graphical description of the mirrored breathing pattern.

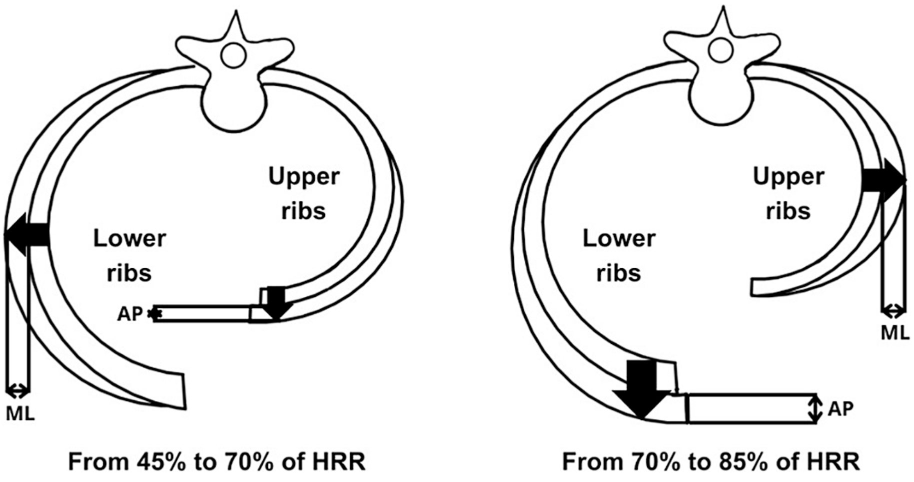

Fig. 4. Graphical description of the thoracic diameter expansion through intensity increase (AP: anteroposterior diameter, ML: mediolateral diameter). Adapted from Kapandji, 1973.

mediolateral diameter increases in the lower thorax through the costotransverse and costovertebral joints.

When intensity increases, the thoracic behaviour appears to reverse (i.e., the lower anteroposterior and upper mediolateral diameters exhibit their greatest expansion), showing a slower response to exercise, and not agreeing with the hypothesis. Despite this, the expansion of the lower anteroposterior diameter when the intensity increases is in line with some studies that have concluded that athletes expand their lower ribs and the abdominal wall during high-intensity exercise (Lopes et al., 2024; Silvatti et al., 2012). This pattern is like the one observed by Smyth et al., in 2022 during high-intensity exercise, starting the expansion by the anteroposterior diameter of the lower ribs and abdomen, and continuing with the upper ones.

Other investigations evaluated these thoracic expansions in length units between maximum inspiration and expiration. Changes of 2.51 to 2.79 cm in the anteroposterior diameter, and from 2.08 to 2.36 cm in the mediolateral diameter were found by Sarro et al. in 2018. When this study’s results are expressed in centimetres, the anteroposterior diameter increases more than the mediolateral diameter at the middle level. Still, it is quite similar to the mediolateral diameter at the upper and lower levels. An increase from the beginning to the end of the test of 0.86 to 1.14 cm in the upper, from 0.99 to 1.53 cm in the middle, and from 0.93 to 1.44 cm in the lower anteroposterior diameter; from 0.80 to 1.28 cm in the upper, from 0.51 to 0.71 cm in the middle, and from 1.02 to 1.59 cm in the lower mediolateral diameter was found.

Romei et al., in 2010 evaluated the thoracic expansion through different posture positions, finding an increase in the three diameters assessed when posture shifted from lying to sitting, resulting in a decrease in the anteroposterior diameter at the abdominal level. The observed changes were between 0.5 and 0.2 cm in the upper anteroposterior, between 0.65 and 0.45 cm in the middle anteroposterior, and between 0.35 and 0.15 cm in the middle mediolateral, maintaining the pattern of this study, where the greatest changes occur in the middle anteroposterior diameter, followed by the upper anteroposterior, and lastly the middle mediolateral (Romei et al., 2010). These results are aligned with another study that noted that when a person is lying down, their anteroposterior and mediolateral thoracic diameters are smaller than when standing, with changes close to 3.3 cm in the upper anteroposterior, 3 cm in the middle anteroposterior, and 3.1 cm in the middle mediolateral diameter (Takashima et al., 2017).

Another study by Yokoyama et al., in 2022 recorded thoracic diameters during maximum inspiration and expiration, finding differences similar to the ones of this investigation: 1.1 cm in the upper mediolateral, 1.5 cm in the upper anteroposterior, 1.1 cm in the lower mediolateral, and 1.2 cm in the lower anteroposterior diameter.

Thoracic expansion increases as exercise demands rise, yet it does not reach the levels of expansion seen during maximum inspiration and expiration. This discrepancy may be explained by the behaviour of the respiratory frequency during high-intensity exercise (Nicolò et al., 2020a,b). It has been shown that respiratory frequency increases with activity intensity, increasing air volume, and oxygen exchange during exercise (Nicolò et al., 2020a,b). When respiratory frequency increases, thoracic movement amplitude also increases, but not at its highest level because the time for inspiration and expiration is reduced, and the residual volume is increased (Kapandji, 1973).

Numerous references have demonstrated that various respiratory diseases diminish thoracic kinematics (Cavassini et al., 2022; Feitosa et al., 2019; Serrano-Villar and Rodríguez-Grande, 2018; Zhang et al., 2017). Unfortunately, most findings in the literature regarding breathing and exercise have reported changes in respiratory volume or other physiological variables that cannot be quantitatively compared with the results of this research. Romei et al., in 2010 highlighted the importance of measuring the thoracic kinematics directly as a biomechanical variable that could provide relevant clinical information regarding the condition of thoracic functionality.

When the sample was divided into 3 running performance groups, no significant differences were found when comparing them at the same running intensity. These results do not agree with other studies that concluded that physical fitness and training might change the mechanical breathing pattern (Campos et al., 2019; Layton et al., 2011; Rodrigues et al., 2019; Silvatti et al., 2012). The absence of differences in the present study could be due to a small difference in performance among groups (average test final velocity 13.0, 14.8, 17.1 km/h, respectively, in groups 1, 2, and 3).

Finally, when the data inside each group was analysed, significant differences were observed, slightly revealing the mirror pattern found when the sample was not sectioned. Inside group 1 significant IP were found in the first part of the incremental test in the upper anteroposterior and the middle and lower mediolateral diameters. While in group 2 only was found on the lower mediolateral diameter. At the end of the running test, groups 2 and 3 showed the same comportment with a significant IP in the middle anteroposterior and the upper mediolateral diameters. However, in group 1 were only found in the middle anteroposterior diameter.

The findings of this study have important implications in both clinical and sports performance contexts. First, the detailed analysis of thoracic expansion across different running intensities enables a more accurate assessment of the mechanical respiratory pattern in athletes, which may serve as a complementary tool to evaluate cardiorespiratory fitness and ventilatory efficiency. This information can be particularly valuable for the design of individualized training programs, including breathing exercises, aimed at optimizing breathing control and thoracic mobility according to the athlete's performance profile. In clinical settings, thoracic kinematic analysis could provide a non-invasive method for monitoring patients with respiratory disorders or for tracking functional improvements during rehabilitation programs. Furthermore, establishing normative patterns of thoracic expansion based on performance levels may help in the early detection of respiratory dysfunctions in athletes or physically active individuals.

The principal limitations of this work are: 1) little differences between running performance groups made it difficult to find alterations of the breathing mechanics; 2) absence of a female sample due to the difficulty of applying this technique, an alternative method should be developed; and 3) the absence of physiological variables to assess the exercise intensity and cardiovascular fitness status.

However, there is no information on the influence of high-intensity running on thoracic diameters using OEP. Therefore, these results could be useful to assess running performance and respiratory dysfunctions. The methodology has a novel and easy approach with applications in sports performance and quality-of-life assessments.

5. Conclusion

In conclusion, when the exercise intensity rises, the pattern of the thoracic expansion has an opposite behaviour between mediolateral and anteroposterior diameters. At the beginning, the thoracic expansion occurs in the upper and middle anteroposterior diameters, while in the middle and lower mediolateral ones. By the end of the exertion, the opposite occurred, the expansion is produced in the middle and lower anteroposterior diameters, while in the upper mediolateral one.

Finally, it is important to emphasize the need for further research on thoracic kinematics for a better understanding of respiratory disorders and as a complementary variable to assess running performance. Future lines of research should focus on larger sample sizes, bigger differences among groups, and different ages and sexes.

CRediT authorship contribution statement

Gonzalo Garrido-López: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Javier Rueda:** Validation, Software, Methodology, Investigation, Data curation, Conceptualization. **Alejandro F. San Juan:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Markus Bastir:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Benoit Beyer:** Writing – review & editing, Supervision. **Enrique Navarro:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

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

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