Review Article
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Multifunctional role of the diaphragm: biomechanical analysis and new perspectives

Abstract

This study explores the complex role of the diaphragm, traditionally considered essential in respiratory physiology, expanding understanding of its multifunctionality. Beyond respiratory mechanics, the diaphragm contributes to postural stabilization, lumbar support, and regulation of intra-abdominal pressure (IAP). By analyzing the diaphragm's eccentric contraction, we introduce two innovative concepts: "Diaphragm Antagonist Muscles" (DAM) and "Centration". DAM represents an evolution of the abdominal belt concept, integrating the pelvic floor and lower posterior trunk muscles. This muscular synergy is vital for respiratory dynamics and functions such as posture and integrity of the musculoskeletal, pressure, and postural systems. Centration, proposed as a conscious modulation skill of IAP, activates a neurophysiological interaction between the diaphragm, lower posterior trunk muscles, and the pelvic floor, revealing new implications of the diaphragm in sports, health, and kinesiological contexts.

Keywords: muscular synergy, movement mechanics, neurophysiology, lumbar stabilization, centration

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Introduction

The diaphragm, a musculotendinous structure shaped like a dome, concave inferiorly, is strategically located between the thorax and abdomen. Historically recognized as fundamental in respiratory physiology[1,2] this traditional view has guided biomechanical and physiological research for decades. However, the multifunctionality of the diaphragm has recently become an object of increasing interest and investigation, with various studies demonstrating its central role not only in respiratory mechanics but also in postural stabilization, lumbar support, and regulation of intra-abdominal (IAP) and thoracic pressure.[3–5]

In this context, understanding the dynamic functioning of the diaphragm in interaction with other structures becomes intriguing. While its concentric contraction, essential for inspiration, has long been studied, the importance of its eccentric phase has been recognized in recent years.[6] This cyclical phase, where the diaphragm elongates and stabilizes, plays a crucial role in expiration and in modifying intra-abdominal and thoracic pressures.

During inspiration, the concentric contraction of the diaphragm lowers the phrenic center, increasing the vertical diameter of the thorax. This generates resistance from the vertical structure of the mediastinum, tensioned, and from the mass of abdominal organs compressed into a smaller space. This compressive mass is contained, as reported in the literature, by the so-called "abdominal girdle": the rectus and transverse abdominis muscles, and the small and large oblique muscles, without which the phrenic center would lose the solid support allowing the diaphragm to lift the ribs.[7,8] However, these are not the only muscles involved, as the pelvic floor and lower posterior trunk muscles also play a role.[9]

The concept of "Diaphragm Antagonist Muscles" (MAD) emerges as a synergistic-antagonistic system of the diaphragm that includes the abdominal girdle, pelvic floor, and posterior trunk muscles: on deep, middle, and superficial planes. This is because, according to Pascal's law, the diaphragm exerts pressure on the organs, and this pressure remains unchanged at every point of contact with the abdominal organs, dispersing at 360°.[10] Thus, force generation implies involvement not only of the anterior abdominal muscles (abdominal girdle) but of all anatomical structures.

MAD thus identifies a group of muscles between the thoracic diaphragm and the pelvic wall that, working in tandem with the thoracic diaphragm, ensure the efficiency of the respiratory, pressure, and postural system, having indirect effects on the IAP and musculoskeletal system. From this perspective, the diaphragm alternates in its respiratory cycles of inspiration-expiration, a work of concentric-eccentric contraction, creating a dynamic alternation of increases in thoraco-abdominal pressure. The eccentric contraction characterizes the expiration phase, where the increased tone of the MAD muscles exceeds the contraction of the diaphragm which will elongate under this increased force, assuming an even more domed position.[11]

The authors, therefore, emphasize that the expiration phase is not characterized by a relaxed release of the diaphragm, but by an eccentric contraction that allows the reduction of the anteroposterior and transverse diameter of the thoracic cage.[12] Recent studies in the field of sports science offer relevant perspectives for the training of abdominal belt muscles and the improvement of breathing. For instance, Nelson Kautzner Marques Junior, in his study "Specificity Principle Applied in Volleyball",[13] highlighted how targeted training can effectively influence specific muscle groups, such as those in the abdominal belt, which are crucial in volleyball. Additionally, Marco Machado, in his 2022 work,[14] linked physical activity with cardiovascular health, underscoring the importance of effective respiratory and abdominal functionality for disease prevention.

Recent research in the field of kinesiology has deepened the role of the diaphragm in motor functions and sports activities. Studies like those of Gabar et al.,[15] have highlighted the importance of this interaction, showing how the diaphragm influences core stability and has significant implications for both physical fitness and athletic performance. This relationship is particularly relevant in the context of applied kinesiology, where understanding the synergy between the diaphragm and other muscles can significantly influence training and rehabilitation strategies.

Historical background

The understanding of the diaphragm's dynamism and its physiological role has undergone profound transformations over the centuries. Since ancient times, the respiratory function of the human body has been a subject of interest for philosophers and doctors. Hippocrates emphasized the importance of breathing for human life and health.[16] During the Renaissance, Leonardo da Vinci emerged as a key figure in anatomical and physiological research, highlighting the complexity of the diaphragm.[17,18] His studies laid the groundwork for biomechanical research on diaphragmatic function.

In the 20th century, the expansion of research on the diaphragm was significantly stimulated by new imaging tools and experimental techniques. Haldane's discovery about partial gas pressure highlighted the diaphragm's critical importance in regulating these pressures, underscoring its essential role beyond respiratory function.[19] With the evolution of medical science in the 21st century, research by Smith & Johnson and Brown deepened the understanding of the diaphragm's various modes of contraction and their effects on posture and the spine.[20,21] These studies emphasized the importance of examining the diaphragm not only as a "support/engine" of the respiratory system but as a multifunctional element.

Eccentric contration and IAP

The diaphragm is characterized not only by concentric contraction during inspiration and eccentric contraction during expiration but also by a relationship of complex and dynamic contractions of the abdominal muscles (DAM) and accessory muscles.[22] This muscular synergy generates an increase or decrease in the volumes of the thoracic and/or abdominal cavity with a consequent change in pressure. During inhalation, intra-thoracic pressure decreases and becomes negative not only relative to the external environment but also in relation to the abdominal cavity. Conversely, during exhalation, the pressure polarities between the cavities reverse.[23] As highlighted by Levine et al., this aspect becomes particularly salient during events that cause an increase in intra-abdominal pressure, such as coughing, sneezing, or exercise in acceleration, during which the diaphragm actively resists opposing forces.[24] The relationship between the contraction of the diaphragm and its accessory muscles ensures the correct level of pressure in humans.[25]

Given the vital importance of breathing, the authors emphasize the importance of analyzing this function as a complex system in continuous multifunctional interaction with other systems that, although ancillary to achieving the primary goal, actively contribute to its functioning and exert effects on both the thoracic and abdominal cavities simultaneously.[22] Their coordinated eccentric-concentric contraction ensures the functionality of pressure in the abdominal and thoracic cavities as well as the correct respiratory rhythms.[26]

Among the accessory muscles described in the literature, we find the external and internal intercostal muscles that play a crucial role in the expansion and contraction of the thoracic cavity and, consequently, in intra-thoracic pressure.[27] During inhalation, the external intercostal muscles contract, lifting the ribs and expanding the thoracic cavity. The internal intercostal muscles participate in exhalation, lowering the ribs and reducing thoracic volume.[28] Simultaneously, the scalene and sternocleidomastoid muscles contribute to raising the first two ribs during deep inhalation, facilitating air intake.[29]

Other important muscles in the multifunctional framework are the pelvic floor muscles, such as the levator ani muscle, essential for stabilizing the lower abdomen and regulating IAP during changes in thoraco-abdominal pressure.[30] The pelvic floor is indeed a complex network of muscles and connective tissues that support the pelvic and abdominal organs by resisting the pressure exerted by their weight and compression vectors.[31] The diaphragm and pelvic floor, although anatomically distant, are closely related and also work in contractile duet during many body functions. During inhalation, while the diaphragm works in concentric contraction, the pelvic floor contracts and lowers slightly. During exhalation, the diaphragm works eccentrically, and the pelvic floor contracts concentrically.[32] This coordination ensures a balance of intra-abdominal and intra-thoracic pressures, essential for functions such as urinary continence and lumbopelvic stability. Dysfunction in one of these muscles can affect the other, emphasizing their mutual dependence.[33,34]

The infero-posterior back muscles, related to the full extension of the spine, such as the erector spinae and quadratus lumborum, are essential not only for postural support but also for stabilizing the spine during breathing and correct posture (Table 1).[35]

Table 1 Accessory muscles in breathing

Muscles involved in breathing	Contribution to IAP	Contribution to thoracic pressure
Transversus abdominis	✔	
Obliques (internal and external)	✔	
Quadratus lumborum	✔	
Iliopsoas	✔	
Multifidus	✔	
Pelvic floor muscles (e.g., levator ani, coccygeus)	✔	
Rectus abdominis	✔	
Intercostal muscles (internal and external)		✔
Scalene muscles (anterior, middle, posterior)		✔
Sternocleidomastoid		✔
Neck muscles (various)		✔
Serratus posterior muscles (superior and inferior)		✔
Diaphragm muscle	✔	✔
Anterior serratus muscles		✔
Pectoralis minor		✔
Subclavius muscles		✔
Iliocostal muscles (lumbar, thoracic, cervical)		✔
Longissimus muscles (thoracic, cervical)		✔
Spinal muscles		✔

Centering can be understood both as a neurophysiological activator and as a modulator, directly influencing the position and functionality of the diaphragm and the pelvic floor.[36] Given the extensive network of neural interconnections, Centering can orchestrate synergistic coordination, ensuring concerted pressure action during various activities, including the respiratory process. Anatomically, the pelvic floor, comprising muscles such as the pubococcygeus, puborectalis, and iliococcygeus, is responsible for supporting the pelvic organs. It plays a crucial role in urinary and fecal continence, functions directly related to intra-abdominal pressure (IAP).[37,38] These pressure dynamics can be influenced by both automatic mechanisms and voluntary interventions.

The interaction between Centering, the functionality of the diaphragm, and the pelvic floor becomes particularly evident in the practice of Centering. When voluntarily modulating IAP, the pelvic floor is indirectly activated, stimulating a reaction in the diaphragm and reflexively in the abdominal wall muscles (DAM).[39] Consequently, a circuit of synergistic and modulated contractions is established, ensuring a functional balance of pressure, proportionate to the intensity of the required action. Numerous studies have highlighted the complexity of the neurophysiological relationship between the diaphragm and pelvic floor, demonstrating how stimulation or dysfunction of one of these muscles can directly influence the other.[40,41] Marieb & Hoehn emphasize the depth of this synergy. While the diaphragm is innervated by the phrenic nerve, the pelvic floor receives signals from the branches of the sacral plexus, allowing subtle coordination between the two, especially in situations that require modulation of IAP, such as coughing or lifting weights. Standring further emphasized the importance of this connection in maintaining adequate IAP during physical activities. In the sports context, the concept of Centering, used to stabilize the trunk overcoming inertia challenges, also intersects with the multifunctionality of respiratory physiology.[42,43]

The dynamics between the diaphragm and pelvic floor, enriched by a multitude of neurophysiological and not just mechanical interactions, offer promising insights for future research and applications in rehabilitation and physical therapy.[44,45] Centering emerges as a crucial concept in modern biomechanics and neurophysiology, emphasizing the deep coordination between the diaphragm and pelvic floor. This interaction, documented by studies like that of Kolar et al., shows how proper synergy between these two elements can enhance lumbopelvic stabilization, bringing benefits in injury prevention and improving athletic performance.

Ultimately, Centering is modulated by the autonomic nervous system (ANS), which, through its sympathetic and parasympathetic components, governs a series of involuntary bodily functions. In this context of interaction, the ANS can regulate the function of both the diaphragm and the pelvic floor, ensuring the adjustment of internal pressures, with potential benefits in terms of disorder prevention. During physical activity, this synergy ensures optimal stabilization, protecting internal organs.[46] Moreover, effective Centering can play a key role in preventing conditions like urinary incontinence, hernias, and other disorders related to the diaphragm or pelvic floor. The relevance of this neurophysiological coordination is further highlighted in clinical and rehabilitative practice, where targeted strategies can strengthen and optimize the function of both muscles.[47,48]

Muscular synergy and neurophysiology

The muscular synergy described between the diaphragm and DAM, although appearing purely mechanical, has profound neurophysiological roots. The coordination between the diaphragm and DAM is orchestrated by complex neural circuits ensuring this synergistic response. In the context of mammals, the diaphragm is primarily innervated by the phrenic nerve, originating from the cervical spinal cord between C3-C5, crucial for ensuring rhythmic contraction of the diaphragm during breathing.[49] The DAM and intercostal muscles possess different innervation networks, with DAM receiving input from the sacral plexus and the intercostal muscles from the intercostal nerves.[50] Studies like those of Hodges & Richardson and Sapsford & Richardson have shown that there is reciprocal functionality between the diaphragm and these muscles, particularly during activities such as orthostatic posture, lower limb movement, and sitting. These connections imply that dysfunctions or stimulations in one can potentially influence the other, underscoring the complexity and importance of their neurophysiological synergy.

Recent research in the field of kinesiology has explored in depth the relationship between the diaphragm, pelvic floor, and athletic performance. Studies like that of Franklin et al., have highlighted the importance of this interaction, showing how the diaphragm influences core stability and has significant implications for both physical fitness and athletic performance. This relationship is particularly relevant in the context of applied kinesiology, where the complexity of the synergy between the diaphragm and other muscles can significantly influence training and rehabilitation strategies. Another significant study in this field was conducted by Critchley and Coutts, examining the neural control of diaphragmatic function. Their findings highlight the importance of understanding the neural control of the diaphragm, not only for breathing but also for its interaction with other muscles and body systems. This study provides valuable insights into the implications of diaphragmatic function for clinical practice, especially in the context of physical rehabilitation and muscle wellness.

Further research, such as that of Petrofsky, has underscored the importance of the diaphragm and DAM in respiratory function and postural stability, highlighting the effectiveness of specific training techniques in this area. Finally, studies by Wick and Lewis and Sapsford and Richardson have contributed to a greater understanding of the synergistic relationship between the diaphragm, posture, and core stability, offering important perspectives for functional training and rehabilitation. These studies underscore the need for a holistic approach in kinesiology, where the integration of various techniques and methodologies can lead to optimal outcomes both clinically and athletically.[51]

Clinical applications of centering and DAM

The interaction between the diaphragm, DAM (Diaphragmatic Abdominal Muscles), and the concept of Centering has significant clinical implications, especially in the field of kinesiology. This interaction provides innovative tools for postural rehabilitation, alleviation of lower back pain, and treatment of diastasis recti. Centering, in particular, can be used as an effective rehabilitative approach to refine posture and improve muscular balance.[52] In respiratory rehabilitation, a better understanding of DAM and their synergy with the diaphragm can offer innovative strategies to enhance lung function, especially in patients with disorders such as obstructive bronchopathies. This aspect is particularly relevant in kinesiology, where the integration of respiratory techniques can significantly improve patients' quality of life.

In sports, training focused on the diaphragm and DAM can lead to improved endurance and performance. This is due to more efficient breathing and optimal core stabilization, which includes the anterior and posterior abdominal muscles.[53] It's important to emphasize that this type of training differs significantly from traditional core training. Recent research highlights notable distinctions in performance and benefits derived from core training with or without the use of Centering. It is always important to remember that in activities that require intensive efforts, such as volleyball, there is an increase in blood pressure in the abdominal cavity and a decrease in blood flow to the brain, which can lead to possible onset of headache, asthenia, dizziness, and even damage to blood vessels or the retina. Correct breathing, both in terms of frequency and coordination, must be properly implemented to avoid harm to the body. The athlete and their coach must be well-trained in this preparation for breathing.[54]

Centering, or the alignment and balance of the body, can be effectively connected to breathing through breath awareness. The synergy between centering and diaphragmatic breathing improves lung capacity, promotes deeper breathing, and increases inspiratory volume, enhancing respiratory compliance. This is supported by studies like that of Han and Kim, who found that breathing exercises combined with dynamic upper limb exercises can improve lung function in healthy adults.

Under medical guidance or trained professionals such as physiotherapists or athletic trainers, variations in the pressure of start of inspiration or end of expiration (PEEP) can be achieved.[55] This improvement in breathing is particularly relevant in situations like post cardio-thoracic surgery, the presence of atelectasis, or in cases requiring prolonged and coordinated inspirations/expirations. Patients with limited thoracic expansion due to prolonged bed rest, suffering from obstructive pneumonic bronchopathies, or recovering from severe respiratory infections can benefit from these techniques. Moreover, weight reduction in obese individuals, as indicated by Emirgil and Sobol, improves expiratory vital capacity and functional residual capacity, suggesting that diaphragmatic breathing can be influenced by body composition. Reychler et al., demonstrated that inspiratory muscle training and incentive spirometry improve the strength of respiratory muscles and the mobility of the thoracic wall in older adults.[56]

Pleural effusion drainage, according to Umbrello et al., improves diaphragmatic function in mechanically ventilated patients. Finally, Lee and Choo highlighted that, although combined inspiratory muscle training with diaphragmatic breathing and upper limb exercises does not show significant differences in increasing the amount of air in the lungs compared to diaphragmatic breathing alone, it still improves respiratory function.[57,58] These examples show how centering in synergy with the diaphragm can contribute to improving respiratory health. Various studies support the link between these practices and the improvement of respiratory function. However, it is important to remember that centering alone is not sufficient to prevent or treat moderate/severe respiratory diseases but can be an effective complement to medical therapies. These clinical considerations can provide suggestions for future studies.

Conclusion

The biomechanical interaction between the diaphragm, DAM, and the concept of Centering emerges as an area of significant interest and potential in biomechanics and kinesiology. The diaphragm, long recognized as a primary muscle in respiration, proves to be a key player in postural stabilization, lumbopelvic stabilization, and pressure modulation. In this context, the biomechanical importance of DAM is affirmed as crucial, with Centering acting as a neurophysiological modulator. This can have a significant impact on force distribution and stabilization during physical activity.

Future research in biomechanics and kinesiology is hoped to focus more on these dynamics, analyzing how Centering, in conjunction with the diaphragm and DAM, can support movement mechanics in shaping the correct force distribution in daily and sporting activities. A biomechanical perspective could offer innovative assessment and treatment methodologies, aimed at improving muscular function and athletic performance.

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Conflicts of interest

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