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BIOMECHANICAL FOUNDATIONS AND BENEFITS OF ACTIVE ORTHOSES IN THE TREATMENT OF IDIOPATHIC SCOLIOSIS

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Abstract. *The aim of this article is to provide a biomechanical analysis of different types of orthoses, with a particular focus on the benefits of an active sensor orthosis. The first part of the article focuses on the biomechanics of passive orthoses, which use constant corrective forces exerted by rigid brace on the patient's body. The principles of such braces, their effect on spinal alignment and the limitations of their static nature are discussed. The second part focuses on active orthoses, which integrate modern technologies, such as sensors, to dynamically adjust the corrective forces to the patient's current state. Current solutions that allow monitoring and adaptation of the brace's performance are discussed, which significantly increases the effectiveness of treatment. The final part of the article focuses on the advantages of active orthoses in scoliosis therapy compared to traditional passive orthoses. The active therapeutic approach allows the brace's action to be dynamically adapted to the patient's current needs, which increases wearing comfort and treatment effectiveness. The use of technology also enables ongoing assessment of therapy progress and better adaptation of corrective forces to the patient's individual anatomical and biomechanical characteristics.*

Keywords: biomechanics, pressure sensors, idiopathic scoliosis, Cheneau brace

BIOMECHANICZNE PODSTAWY I ZALETY AKTYWNYCH ORTEZ W TERAPII SKOLIOZY IDIOPATYCZNEJ

Streszczenie. *Celem tego artykułu jest biomechaniczna analiza różnych typów ortez, ze szczególnym uwzględnieniem korzyści wynikających z zastosowania aktywnej ortezy z czujnikami. Pierwsza część artykułu skupia się na biomechanice ortezy pasywnej, która wykorzystuje stałe siły korekcyjne wywierane przez sztywne elementy gorsetu na ciało pacjenta. Omówiono zasady działania takich gorsetów, ich wpływ na ustawienie kręgosłupa oraz ograniczenia wynikające z ich statycznego charakteru. Druga część dotyczy ortez aktywnych, które integrują nowoczesne technologie, takie jak sensory, umożliwiające dynamiczne dostosowanie sił korekcyjnych do bieżącego stanu pacjenta. Zostały omówione dotychczasowe rozwiązania, które pozwalają na monitorowanie i adaptację działania gorsetu, co znacząco zwiększa efektywność leczenia. Ostatnia część artykułu skupia się na zaletach ortezy aktywnej w terapii skoliozy w porównaniu do tradycyjnych ortez pasywnych. Aktywne podejście terapeutyczne pozwala na dynamiczne dostosowywanie działania gorsetu do bieżących potrzeb pacjenta, co zwiększa komfort noszenia i efektywność leczenia. Wykorzystanie technologii umożliwia także bieżącą ocenę postępów terapii oraz lepsze dostosowanie sił korekcyjnych do indywidualnych cech anatomicznych i biomechanicznych pacjenta.*

Słowa kluczowe: biomechanika, siły nacisku, skolioza idiopatyczna, gorset typu Cheneau

Introduction

Idiopathic scoliosis (IS) is a three-dimensional spinal deformity that primarily affects children and adolescents. One of the fundamental components of conservative treatment is orthotic bracing, aimed at halting the progression of spinal curvature. This article presents a comparison of the biomechanical aspects of traditional braces and the advantages of modern active orthotic systems.

Idiopathic scoliosis, being a complex three-dimensional spinal curvature, necessitates an interdisciplinary therapeutic approach. One of the primary tools in scoliosis management is the orthopaedic brace, most commonly the traditional static Cheneau orthosis [16, 35, 43], which utilizes mechanical forces applied to the patient's body to correct pathological spinal curvatures.

The orthosis achieves spinal deformity correction through the application of multipoint pressure forces on the patient's torso, particularly in the regions of the spine and thorax [20, 36]. The biomechanics of the brace play a critical role in understanding and optimizing the effectiveness of these devices in the treatment of idiopathic scoliosis, making this a key area of focus for improving therapeutic outcomes.

1. Biomechanics of passive orthoses

Analysing the biomechanics of passive orthoses used in the treatment of idiopathic scoliosis, it is essential to begin with a discussion of the spine – a key component of the skeletal system. The human spine consists of 33–34 vertebrae [6], divided into the following regions: cervical (C), thoracic (Th), lumbar (L), sacral (S), and coccygeal (Co). The spine is responsible for maintaining posture, protecting the spinal cord, and enabling trunk mobility.

The spine is a complex biomechanical structure with multiple degrees of freedom, providing both stability and mobility. Each spinal region has unique anatomical and functional characteristics. The individual vertebrae are interconnected by facet joints, ligaments, and intervertebral discs, which function as shock absorbers. Each spinal segment possesses six degrees of freedom: three translational (anterior–posterior, superior–inferior, and medial–lateral displacements) and three rotational (rotation around the vertical, transverse, and sagittal axes) [6]. Spinal movements occur in three anatomical planes:

1. sagittal plane – flexion and extension,
2. frontal plane – lateral bending,
3. transverse plane – axial rotation.

The flexibility of intervertebral discs and joints allows for smooth and coordinated spinal motion. Under normal physiological conditions, mechanical loads are evenly distributed along the spine, supported by its natural curvatures. In the presence of pathology – such as scoliosis – this balance is disrupted, leading to asymmetric loading and lateral curvature of the spine.

Each vertebra has twelve degrees of freedom, encompassing both translational and rotational movements along and around the three principal axes, as illustrated in Fig. 1. The movement of spinal vertebrae involves dynamic changes in the angles between their respective axes. An orthopaedic brace operates by restricting the degrees of freedom of the spine. Through precise fitting, the brace limits vertebral motion along specific axes and within particular planes. As a result, it constrains the range of movement in directions such as flexion, extension, rotation, and lateral bending. The purpose of this action is to stabilize the spine, minimize uncontrolled motion, and support the maintenance of proper posture. In scoliosis treatment, a rigid orthosis is one of the key therapeutic tools. Its biomechanics are based on principles of corrective forces acting on the spine. By providing external support and stabilization, the orthosis alters the distribution of forces on the vertebrae, promoting realignment of the spinal column and preventing further progression of the curvature.

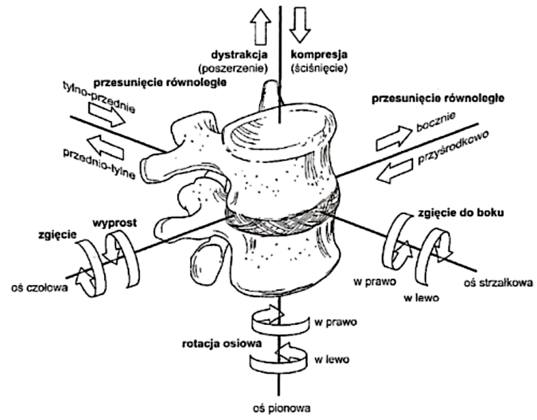

Fig. 1. Degrees of freedom of the spine using a lumbar vertebra as an example [22]

Adolescent idiopathic scoliosis (AIS) is a progressive three-dimensional spinal deformity of unknown aetiology [8]. According to the guidelines of the Scoliosis Research Society (SRS), AIS is defined as a lateral spinal curvature with a Cobb angle of at least 10 degrees, measured on a standing radiograph. The condition is characterized by increasing spinal and trunk deformity during periods of rapid growth, resulting from displacements in all three anatomical planes and structural changes in vertebrae. Scoliosis typically begins with elongation and misalignment of the vertebral column, leading to a loss of physiological thoracic kyphosis, vertebral rotation, and lateral deviation of the spinal axis. Persistent, unilateral loading of the growth plate disrupts normal bone development, and asymmetry in vertebral and disc structure intensifies uneven loading. This process leads to a "vicious cycle" mechanism described by Stokes [38], consistent with the Hueter-Volkmann law [18, 42], which states that excessive mechanical loading inhibits growth, while reduced loading accelerates it. Brace therapy aims to mechanically reduce pressure at the apex of the curvature, supporting vertebral regeneration by decreasing asymmetric loading and interrupting the progression of the vicious cycle [20].

The Cheneau orthopaedic brace corrects the three-dimensional deformity of the spine by applying multipoint pressure forces to the torso. In the frontal plane, it shifts the spine and thoracic cage along the body's axis; in the transverse plane, it operates as a three-point force system; and in the sagittal plane, it supports the restoration of physiological curvatures, particularly thoracic kyphosis. Special relief areas within the brace allow for displacement of anatomical structures in response to these forces [31]. The Cheneau brace is indicated for progressive idiopathic scoliosis with a Cobb angle exceeding 25°. Treatment effectiveness depends on proper patient qualification, accurate brace fabrication, and adherence to clinical recommendations [30]. Pressure measurement aids in monitoring the brace's fit, while analysis of radiographic correction outcomes facilitates therapy optimization by determining the maximum effective corrective force needed to shift the spine in the desired direction [40].

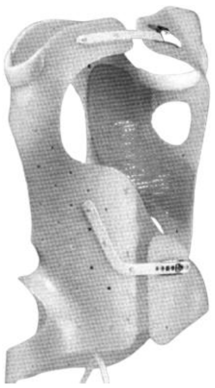

Fig. 2. The CTM brace [32]

All corrective orthoses bearing the Cheneau name originate from the Cheneau–Toulouse–Münster (CTM) brace, developed in 1979 by Dr. Jacques Cheneau from France and Professor Matthias from Münster, Germany. The CTM brace (shown in Fig. 2) was fabricated from polyethylene, featured an anterior opening, and was secured using two metal rods. By applying targeted mechanical pressure at specific points, it corrected spinal curvature morphology and inhibited the progression of scoliosis [32].

Since its creation, numerous variants of the orthosis have been developed to enhance corrective effectiveness. One such variant is the Rigo Cheneau brace [43], designed by Dr. Manuel Rigo from Barcelona, a student of Dr. Cheneau. This is a dynamic brace featuring specifically designed voids that allow for tissue migration, patient growth, and unrestricted breathing. Similar to the CTM model, it is made of polymeric material and fastened using two adjustable straps to regulate compression.

Fig. 3. The WCR brace during treatment [43]

In 2012, the WCR (Wood–Cheneau–Rigo) brace was introduced (shown in Fig. 3), designed to accommodate various types of spinal curvatures. This orthosis is handcrafted and individually tailored to the patient's specific spinal curvature pattern, spinal flexibility, and skeletal maturity. It applies torsional forces and operates according to the principle of a three-point pressure system, enabling correction of spinal deformities in all three anatomical planes. The corrective mechanism involves applying pressure at the apex of the curvature and at two counter-pressure points on the opposite side [33]. This approach is referred to as the three-point pressure system (Fig. 4). More advanced braces, such as Cheneau-type orthosis, incorporate multiple such systems in a three-dimensional spatial arrangement, adapting them to the specific characteristics of the spinal deformity [16, 35].

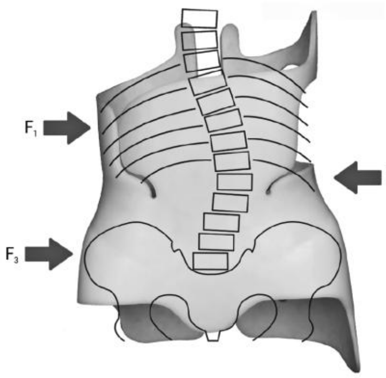

Fig. 4. Schematic of the three-point pressure system. F_1, F_2 – forces acting on the thoracic cage; F_3 – force acting on the pelvis [16]

Three-dimensional spinal curvature correction is based on the integration of several biomechanical mechanisms [34]:

- a three-point pressure system in the frontal plane, which aligns the curvature and restores spine balance,
- a derotational force couple in the transverse plane,
- proper sagittal plane alignment of the spine.

In scoliosis, lateral curvature causes compression of soft tissues on the concave side and expansion on the convex side. The three-point force system corrects the lateral deviation by decompressing the concave region and reducing tension on the convex side, thereby facilitating vertebral derotation. This system consists of one primary corrective force and two counterforces acting from lateral to medial. Derotational pads, positioned obliquely, generate rotational forces in the transverse plane. The effectiveness of system depends on the placement and orientation of pads [34].

The force couple system comprises two opposing forces acting across a broad section of the torso. This configuration concentrates the greatest pressure on the most rotated vertebra, enabling localized derotation and contributing to the correction of pathological thoracic lordosis [34].

Spinal balance in the sagittal plane relies on neutral pelvic tilt. The orthosis does not impose retroversion, but rather supports the natural inclination, maintaining the continuity of lumbar lordosis. The brace design allows for selective pressure on the concave side of the lumbar spine, enhancing stability and aiding derotation while avoiding the adverse flattening caused by non-selective anterior abdominal compression [34].

2. Active orthosis – a review of existing solutions

Technological advancements have enabled the development of orthopaedic braces equipped with sensors, actuators, and control electronics. Various constructions and existing scoliosis treatment support systems have been presented [14, 15, 17, 25].

The Cheneau brace corrects spinal curvature through both passive and active pressure. Despite studies on its biomechanics, the precise therapeutic force ranges have not yet been clearly defined. Typically, passive polyethylene braces are used, and their effectiveness depends largely on patient compliance and orthotist expertise. There is a lack of tools for real-time monitoring of pressure and treatment compliance – decisions are primarily based on patient self-reporting and X-ray images. As previously noted, brace therapy without force monitoring is assessed over long-term intervals and requires regular radiographic imaging. Currently, there are no tools enabling clinicians to monitor compliance in real-time. The evaluation of derotation pad forces is typically done during clinical visits when the brace is properly fastened and adjusted. However, most of the treatment takes place outside the clinic, and data indicate that approximately 73% of patients use the brace improperly [44].

Studies have shown that sensors can measure both pressure forces and brace wear time [2, 7, 37]. Systems have been proposed to monitor effective corrective forces from the pads, taking into account skeletal maturity and curve type [4, 27].

Lou et al. developed a measurement system using the SENSYM FS01 sensor, notable for its small size, low energy consumption, and low cost. Data were logged via a microcontroller and transmitted wirelessly within a 30-meter range [3, 27]. They also proposed a system with inflatable air cushions for automatic pressure regulation [23]. In another approach, custom-made TLSO braces were equipped with a low-power data acquisition system that recorded pressure and wear time at 1 reading per minute. The system could store data for up to 4 months. The average compliance rate was $60.0 \pm 4.3\%$ (range 33–82%), and a decrease in pressure was observed along with increased wear time after brace adjustment [25–26, 29]. A system described in [24] measured both pressure and strap tension, allowing for sampling frequencies ranging from 1 Hz to once per day. The device operated for 1 to 14 days on battery power. In testing, 13 sensors were used, recording data every minute over 48 hours. Dehzangi et al. [10] designed a monitoring system that recorded strap force and wear time using pressure sensors, an accelerometer, and a gyroscope. Their algorithm successfully classified patient activity (e.g., walking, running, sitting) with high accuracy.

Studies [3, 11, 12] describe a Boston-type TLSO monitoring system, equipped with Honeywell FSB1500NSB pressure sensors, an accelerometer, and a gyroscope. Data were collected at 40 Hz and transmitted via Bluetooth. Using multimodal modelling and classification, the system precisely assessed brace-to-body contact and patient posture, contributing to the development of a universal pressure distribution model for scoliosis treatment.

In [13], computer graphics and photogrammetry were used to create a 3D model of the patient's back based on images from stereoscopic CCD cameras. This model serves to monitor scoliosis progression and evaluate the need for treatment. Visser et al. [41] proposed a method for automatic design of personalized braces, based on clinical assessment and a 3D model of the torso, obtained using imaging systems and modified in CAD software.

Karol et al. [19] showed that AIS patients who received regular feedback about their brace usage (based on temperature sensor data) wore it for longer durations. A heuristic compliance evaluation method was developed using pressure data segmentation, improving the accuracy of adherence assessment. Bazzarelli et al. [5] introduced a posture assessment system based on electromagnetic technology and an accelerometer, enabling faster and more accurate spinal angle measurements compared to previous methods. Tan et al. [39] developed an automatic scoliosis analysis system using deep learning. Their tool calculates the Cobb angle from radiographs using a nine-layer U-Net convolutional neural network. Lalouani et al. [21] proposed a machine learning algorithm for predicting missing data samples, which helped reduce energy consumption during transmission. Ali et al. [1] presented a finite element method (FEM) analysis of a soft active orthosis, which applied corrective forces using flexible straps controlled by lightweight actuators. The system enabled correction of curvature angles up to 15.96° with pressures ranging from 0 to 8 kPa, comparable to those of rigid braces.

The study in [28] described a brace pressure control system using an air cushion module. If the applied pressure dropped below the required level, the cushions were automatically inflated, improving treatment effectiveness. Similar solution was presented by Chalmers et al. [9], who developed a brace pressure measurement and regulation system using inflatable air pads. Pressure regulation doubled the frequency of maintaining force within the target range (from 31% to 62%). The system included up to four independent, wireless pressure-regulating modules placed at critical brace points. Pressure sensors were used instead of force sensors.

Patent application KR20040103301 describes a night-time scoliosis brace that uses internally adjustable air cushions to maintain optimal corrective positioning. The system provides two-point pressure, relaxation, contraction, and expansion. Patent WO2018220505 presents a rigid plastic torso orthosis for spinal stabilization, including in supine patients. An integrated pneumatic circuit with sensors and a pressure controller allows independent, automatic regulation of each air cushion for precise pressure control.

3. Advantages of active orthoses

The primary challenges in the treatment of idiopathic scoliosis using a brace include the lack of control over wearing time (often too short) and the absence of information regarding the magnitude and location of pressure forces exerted on the body. This leads to ineffective treatment, as the brace is frequently worn incorrectly by the patient. An active brace enables continuous monitoring of the treatment process – the physician can track spinal alignment and measure the pressure forces applied to individual vertebrae, taking into account skeletal maturity and curve type.

Active orthoses allow for dynamic adjustment of pressure, remote monitoring, and personalized therapy, resulting in greater comfort and improved treatment efficacy compared to passive solutions.

The main goal of monitoring and measuring the forces acting on a patient's body during idiopathic scoliosis therapy with a static brace is to develop a decision-making algorithm that would enable the creation of an active brace currently unavailable on the market – one that adapts to the patient’s posture in real time. Existing passive orthoses only provide constant pressure at fixed points. The research described in [40] may enable the development of such a decision-making system, enhancing the effectiveness of idiopathic scoliosis treatment. The proposed solution allows both the monitoring of the therapy status and evaluating the effectiveness and quality of the brace's design and fit, but also actively influencing the treatment process, thus streamlining and accelerating therapy and increasing patient comfort throughout the course of rehabilitation.

Despite their numerous advantages, active orthoses are also associated with several practical limitations. The high cost, resulting from the integration of advanced sensors, electronic modules, and dedicated software, may restrict their availability to patients. In Poland, conventional passive braces are partially reimbursed by the National Health Fund, whereas active orthoses may not be eligible for such reimbursement, thereby requiring patients to cover the full cost. Another challenge concerns technical requirements: the necessity of frequent battery charging or periodic replacement can pose an additional burden for the user. Furthermore, proper training of both patients and medical staff is essential to ensure correct operation and accurate interpretation of data generated by active orthoses. Users must be instructed on device handling, potential maintenance procedures, and appropriate responses to system failures. All these factors may hinder the wider implementation of active orthoses in everyday clinical practice.

4. Conclusion

Contemporary methods of scoliosis correction require a precise biomechanical model that enables control over the forces exerted by a rigid orthosis. Passive braces, such as the Cheneau brace, utilize constant pressure from corrective pads and thermoplastic structures to realign the spinal axis. This brace, commonly used in scoliosis treatment, operates through controlled, typically static pressure applied by derotational pads that act on the spine via the ribs, gradually influencing its curvature.

Traditional methods employed in braces do not allow for dynamic adjustment of these forces based on the changing needs of the patient. The introduction of Internet of Things (IoT) technologies opens new possibilities for monitoring and precise regulation of these parameters.

The application of active orthoses in adolescent idiopathic scoliosis treatment may significantly enhance the effectiveness of therapy, especially in cases with variable deformation dynamics. Active orthoses demonstrate greater therapeutic potential but require further clinical research.

Future clinical research should include trials conducted on larger patient cohorts, comprising at least several dozen individuals, in order to establish a comprehensive knowledge base for decision-support systems in intelligent orthoses. Such systems could enable automatic regulation of corrective forces, for example when the system detects insufficient pressure, the brace would inflate internal air cushions, whereas in the case of excessive pressure, it would reduce the air volume to relieve tissue loading. Studies involving patients with diverse clinical parameters would facilitate the development of flexible therapeutic models, better tailored to the heterogeneous needs of future clinical practice. Equally promising is the integration of active orthoses with mobile applications, which could support therapy monitoring in home-based conditions.

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