The Biomechanical Principles and Clinical Applications of Orthoses for Adolescent Idiopathic Scoliosis

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Abstract. External lumbar orthoses are widely used in the conservative treatment of spinal deformities, especially adolescent idiopathic scoliosis (AIS). This article reviews the design and construction, biomechanical mechanisms, clinical applications, and the advantages and disadvantages of these orthoses. Based on a synthesis of 14 recent studies, including rigid and flexible orthotic designs, rigid orthoses - particularly the Boston and Cheneau types - have demonstrated reliable effectiveness in preventing the progression of scoliosis, especially in AIS patients with Risser grades of 0-2. This review emphasizes that mechanical design, material properties, and patient compliance significantly influence the efficacy of stents. However, rigid orthoses offer better corrective force, but their discomfort and impact on movement limit compliance. On the contrary, soft and dynamic braces can improve wear resistance but are less effective in structural correction. Emerging smart orthoses integrate CAD/CAM, active adjustment mechanisms (such as TSA), and pressure sensors. Through personalized and adaptive support, they have the potential to bridge this gap. External lumbar orthoses remain the cornerstone of scoliosis rehabilitation. Future development should focus on integrating biomechanical accuracy, personalized modeling, and real-time feedback systems to enhance efficacy and user experience.

Keywords: Lumbar Orthoses; Adolescent Idiopathic Scoliosis; Boston Orthosis; Cheneau Orthosis; CAD/CAM.

1. Introduction

Scoliosis most commonly occurs during adolescence between the ages of 10 and 15, so we call it adolescent idiopathic scoliosis (AIS). AIS is a complex three-dimensional deformity of the spine. The deviation of the spine in the coronal plane is greater than 10° [1], the thorax protrudes outward, and the thoracic vertebrae flatten in the sagittal plane. This often manifests as a gradual deformity in appearance, with asymmetrical shoulder and hip heights, accompanied by common back pain [2]. After adulthood, these symptoms may worsen and even require surgical treatment [3]. Patients left untreated for a long time may experience pain or abnormal conditions in breathing and the heart [2,4]. Therefore, when AIS is discovered, corresponding treatment should be carried out immediately to address the deformity or delay the operation time to prevent repeated "growth rod" surgeries [5]. Most AIS treatments rely on braces, such as Milwaukee braces, Boston braces, Cheneau braces, and other rigid braces, to help patients suppress or correct scoliosis.

In recent years, traditional braces have evolved from basic gypsum braces to customizable and digitalized improved ones by integrating engineering technologies. For instance, Rigo has designed a new classification system, dividing scoliosis into five major categories and then analyzing the specific location details. Based on the classification, braces are precisely intended to fit the pathological characteristics of patients better. Boston Brace 3D combines CAD/CAM technology to make brace design more efficient and better fit the body types of different patients. It can also customize the pad strength to make clinical practice more standardized. Meanwhile, the soft design of the flexible brace allows patients to move freely and breathe naturally without any restrictions, enhancing the wearing comfort. Not only that, the combined application of the built-in sensing system and the brace also provides a guarantee for real-time monitoring and reflecting clinical compliance and feedback regulation.

This review systematically explores the engineering design and clinical application of lumbar stents for scoliosis. First, the stents' classification and different structures are reviewed, and the corresponding stents are analyzed through specific clinical cases. Secondly, summarize the mechanical principles in the design of supports, such as the three-point pressure system and the anti-tilt moment, etc. Meanwhile, the patient's comfort level, compliance, and current design flaws are discussed. Finally, with the existing literature, analyze the effects of stents' clinical application, advantages, and disadvantages. By integrating engineering knowledge and clinical impact, this paper aims to provide systematic thinking and a literature basis for further optimizing lumbar braces for scoliosis and offer references and inspiration for subsequent related research and product development.

2. Structure and Functions of Lumbar Support Devices

2.1 Scaffold Structure and Design

According to their clinical uses and structural features, scoliosis orthoses can be classified into rigid and flexible braces [6]. According to the different ranges of correction, it can be further classified into cervical, thoracolumbar, and lumbosacral braces (CTLSO) and thoracolumbar and lumbosacral braces (TLSO) [7]. Rigid braces are usually thermoplastic, featuring a stable structure and strong corrective force, and are the most common choice for orthopedic correction. Typical representatives include the Milwaukee orthosis (CTLSO type), the Boston orthosis, and the Cheneau orthosis (all of which are TLSO type). Rigid braces usually have a frame composed of a plastic shell, with an open back and high-density spacers inside. They apply force to the trunk through a three-point pressure system, thereby achieving dual correction effects in the coronal and sagittal planes [8]. Among them, the Boston brace is mainly used for the correction of thoracolumbar scoliosis, with an emphasis on stability control. The Cheneau brace emphasizes three-dimensional correction. It forms support and decompression zones through the asymmetrical concave-convex structure on the shell, and its shell-like structure exerts force on the spine in multiple planes to correct coronal, sagittal, and cross-sectional deformities [9].

However, while rigid braces offer effective correction, they also have problems such as limited movement, poor comfort, potential muscle weakness, flat back deformity, or skin compression injuries, which affect long-term compliance. In contrast, flexible braces such as SpineCor and Spinealite are constructed using elastic bands, fabrics, or composite materials. They have a flexible structure that fits the body well and can retain some freedom of trunk movement, thereby improving patients' wearing comfort and compliance [10]. However, due to the relatively small external force it can apply, it is suitable for early or mild scoliosis cases, and its therapeutic effect is slightly inferior to that of rigid braces.

In terms of materials, traditional rigid braces are mostly made of thermoplastic materials such as polyethylene (PE), polypropylene (PP), or polycarbonate (PC), which have good plasticity, strength, and lightness, and are suitable for customized processing. Its interior is usually embedded with closed-cell foam materials of different densities (such as EVA or PE-Lite), which are used to buffer pressure, enhance stability, and improve the sense of adhesion. Flexible braces are mainly made of elastic fabrics, high molecular composite materials, or polyurethane, emphasizing structural adjustability and snug fit to meet the needs of daily activities.

From a biomechanical perspective, the rigid brace effectively restricts the displacement and rotation of the spinal deformity segment through a clear lever arm configuration and a three-point support system. Among them, the Boston brace focuses more on coronal and sagittal plane control, while the Cheneau brace considers axial rotation restriction and the restoration of thoracic symmetry [10]. Flexible braces mainly rely on material tension and structural elasticity to generate corrective force, allowing specific trunk muscles to participate and guide trunk movement rather than forcing fixation. In recent years, dynamic and intelligent braces have further integrated biomechanical feedback mechanisms and sensor systems, such as TSA drivers and pressure monitors, which can actively adjust the deformation of the brace according to the patient's posture changes, achieving individualized and real-time posture intervention. This represents the transformation direction of orthosis design from static fixation to dynamic intervention.

3. Clinical Application

In clinical practice, standard scoliosis braces (such as those from Boston, Cheneau, and Milwaukee) are widely used to correct spinal deformities, relieve lumbar pressure, and alleviate pain, especially playing a significant role in the non-surgical treatment of adolescent idiopathic scoliosis (AIS). The large-scale prospective clinical study (BRAIST) by Stuart L. Weinstein et al. followed 242 AIS patients for a long time. It divided them into the brace-wearing group and the simple observation group. The results showed that the treatment success rate after wearing the brace was 72%, significantly higher than 48% in the observation group. The progression rate of scoliosis in the brace group was also significantly lower, indicating that it has a positive effect in delaying the disease progression [11].

Furthermore, James H. Wynne et al. conducted a retrospective analysis and systematically evaluated the short-term efficacy of the Boston 3D brace based on the SRS and SOSORT criteria. Research shows that in the single-bend group, among a total of 51 people, 23 (initial 25-30°) remained ≤30°, 9 (initial 31-40°) decreased to ≤30°, and only 2 needed surgery. In the double-bend group, there were a total of 127 people. Among them, 36 people (initial 25-30°) remained ≤30°, 23 people (initial 31-40°) decreased to ≤30°, but 6 people still underwent surgery, and 9 people deteriorated to >50°. Therefore, it can be concluded that most patients' conditions were effectively controlled under the intervention of the brace, and some even achieved significant improvement in the bending Angle. Although a few patients still require subsequent surgery, the results indicate that the new Boston brace has a promising future in maintaining treatment stability and improving compliance [12].

Significant differences exist in the responses of different types of scoliosis to brace treatment. Taking the Boston brace study by Athanasios Tsirikos et al. For example, among 97 AIS patients with an initial Cobb Angle of 20° - 40°, 73.2% (71 cases) did not require surgical intervention after brace treatment. It indicates that it has a significant therapeutic effect in the adolescent group whose bones have not matured during the rapid growth period. This result is attributed to the relatively simple onset pattern of AIS, the predictable progression of the disease course, the more targeted brace design, and the easier grasp of the treatment timing [9].

In contrast, the treatment outcome for adolescent patients with early-onset scoliosis (EOS) is relatively poor. Only about 20% of patients do not require surgical intervention after brace treatment. Still, the treatment can delay the surgery by an average of 5 years, which buys precious time for thoracic development and avoids the secondary risks of early vertebral fusion. JIS has a relatively young onset age, usually 3 to 10. The period from onset to bone maturation is significant, and there is still a relatively high risk of progression during brace treatment. In addition, the compliance of young patients is relatively low. Due to problems such as movement restrictions and sleep disorders caused by braces, it is difficult for them to achieve sufficient wearing time, which affects the final therapeutic effect.

For non-idiopathic scoliosis (non-IS), such as neuromuscular, congenital, or secondary scoliosis, the efficacy of braces is even more limited. Relevant studies show that only about 30% of patients can avoid surgery. However, treatment can still delay the operation time and create conditions for developing key systems such as the heart and lungs. Because such patients often have structural skeletal deformities, such as hemivertebrae, abnormal vertebral fusion, or muscle strength imbalance, external force cannot correct them. They lack active muscle participation, weakening the brace's physical intervention effect.

Scoliosis braces have high therapeutic value in idiopathic cases, especially in AIS, which occurs during adolescence. Although the corrective ability is limited for patients with JIS and non-IS, the clinical significance of delaying the progression of the disease can still be achieved through the rational use of braces.

4. Principles and Functions of Bracket Design

4.1 Posture Maintaining Support

Spinal braces maintain the correct corrective position by applying pressure to the lumbar vertebrae through external fixation and restricting movement. Moreover, using the three-point pressure system in biomechanics, through the principles of action and reaction forces and lever balance, combined with the force conditions of three points in the same plane but not in the same straight line, can be corrected [13]. From the coronal perspective, the pressure is applied at the principal pressure point, which is the protruding apex of scoliosis, pushing the midline of the spine back. At the same time, the two forces on both sides provide reverse support.

The Rigo classification system uses biomechanics to describe the corrective principles of Cheneau braces and their derivatives: using a three-point pressure system on the frontal plane to correct scoliosis, using paired rotational forces on the horizontal plane to correct spinal torsion, and adjusting the physiological curvature on the side to make the posture more natural. The pressure-sensing system studied by Franz Konstantin Fuss et al. further demonstrated a significant pressure difference in different areas within the brace. Patients are affected by the pressure in various situations, such as breathing, sitting, and lying down. This indicates that the brace not only applies pressure to specific areas of the spine but is also a system that needs to regulate the pressure.

4.2 Patient Comfort and Stent Compliance

Stuart L. Weinstein et al. 's research found that the duration of wearing braces correlates highly with the degree of scoliosis control. Among the data of 116 people, the average wearing duration was 12.1±6.5 hours per day. The treatment success rate of patients wearing braces for 0-6 hours per day was 41%, while that of patients wearing braces for ≥12.9 hours per day reached 90-93%. Therefore, we can further conclude that patient compliance is one of the key factors influencing the therapeutic effect. We have learned that the main reasons affecting compliance include wearing discomfort. This is because some rigid braces can cause the body to feel pressured and painful, and in some cases, it may lead to skin problems [11]. Another factor is the impact of appearance. Some teenagers do not wear it for long due to aesthetic issues or psychological burdens, resulting in less-than-ideal correction results. Secondly, there is the limitation of movement. Rigid braces can restrict movement, causing difficulty bending over, sitting, or standing. The last issue is that the individual fit of the braces is relatively poor. Traditional braces are mainly formed by thermoplastic plates first, and then the molds are adjusted based on the doctor's experience. All these are primarily based on conventional templates and thus cannot meet the needs of different patients well.

These problems have led to patients' low compliance with rigid braces, insufficient wearing time of the braces, and failure to achieve the expected therapeutic effect. Therefore, nowadays, more patients choose to use soft braces.

5. Limitations and Optimization Directions

5.1 Limitations

The therapeutic effect of braces in clinical practice has been fully affirmed, but they are made through gypsum or thermoplastic molds and processed according to fixed templates. This "semi-customized" brace neglects that patients have different body shapes, spinal curves, etc. This can lead to poor fit, uneven pressure distribution, low comfort, and poor patient compliance, affecting treatment outcomes.

In the research of Rigo et al., it was pointed out that the traditional brace design did not classify according to the three-dimensional deformity types of individual patients, which was prone to "misdiagnosis", and examples were given: A girl with a cobb Angle of 34° on her right chest was misdiagnosed as having "four-curve scoliosis" and wore a poorly designed brace for a year, which led to a continuous aggravation of the scoliosis Angle to 48° and 55° outside the brace[10]. Secondly, Ali et al. also clearly stated that although rigid braces are very effective in correcting scoliosis, they can also cause discomfort, such as weakened muscles near the spine and a flat back [14]. In addition, Fuss et al. also noted that traditional braces lack real-time feedback devices, making it difficult for doctors to promptly understand the pad pressure at the apex of spinal curvature. Without objective assessment methods, they can only rely on experience to make blind adjustments.

In addition, some patients, especially teenagers, have a relatively low psychological tolerance for braces, which can also lead to feelings of inferiority and anxiety among them, thus preventing them from completing the entire treatment course. Therefore, the support still needs to be improved in all aspects.

5.2 Optimization Direction

In recent years, many researchers have been improving and optimizing brackets in different aspects, such as structural design, modeling, and materials, to overcome traditional braces' shortcomings in terms of adaptability and comfort.

Regarding modeling customization, the Boston brace relies on computer-aided design/computer-aided manufacturing (CAD/CAM) to complete the brace production step. For instance, in Wynne's research, the braces used were more in line with the actual body types of different patients, could customize the position and force of the pad, and also made the clinical process more standardized. The therapeutic effect was also considerable, sometimes correcting the Cobb angle of patients by ≥6° [12].

Secondly, in terms of comfort, Ali et al. proposed a soft brace structure modeled based on the finite element model (FEM). FEM can help simulate the corrective force of active soft braces and predict the changes in the Cobb angle. Through experiments, it was found that the Cobb Angle improved by 15.96%, which has clinical significance. This indicates that this brace can significantly enhance the patient's comfort while maintaining a certain corrective force [14].

Finally, regarding pressure regulation and feedback, Fuss et al. developed a low-cost yet sufficiently precise pressure sensing system that can be installed in TLSO braces and reflect pressure changes under dynamic conditions such as breathing and activity. This provides doctors with objective data to fine-tune the brace and observe whether the pad pressure of the fixture design is sufficient, rather than relying solely on feeling.

6. Conclusion

This article clarifies the engineering basis and application effects of different scoliosis stents in clinical rehabilitation. Rigid braces have been widely used due to their stable three-point pressure system, and their corrective effects have been verified in multiple experiments and clinical Settings. However, its structure restricts the patient's activities and may lead to flat back or skin diseases, reducing their comfort and long-term compliance. Therefore, many studies have focused on flexible braces. Although they are still in the research stage and have no clinical follow-up data, their flexibility and comfort have already demonstrated their advantages. In addition, digitalization, CAD/CAM technology, sensor feedback technology, and finite element models have also been applied in the design and development of scaffolds, making the scaffolds more personalized and more precisely fit different patients.

Overall, the future optimization directions of lumbar braces can be expanded from structural adjustment mechanisms, pressure feedback systems, and digital modeling to enhance the success rate of correcting deformities and patient compliance and provide more reliable support for the conservative treatment of scoliosis.

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