



Force Mapping of 3D-Printed Scoliosis Braces at Varying Tightness Levels Using Calibrated FSR Sensors

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Abstract—This study proposes a personalized, 3D-printed scoliosis brace integrated with Force-Sensitive Resistor (FSR) sensors to quantify biomechanical stress under varying clinical conditions. Using 3D scanning, CAD modeling, and Fused Deposition Modeling (FDM) with polypropylene, a patient-specific orthosis was fabricated for a subject with lumbar scoliosis. Two calibrated FSR sensors were embedded bilaterally at the lumbar-costal junction, where maximal compressive forces are typically concentrated. Data collection was performed under nine combined conditions of brace tightness (loose, medium, tight), posture (sitting, standing), and nutritional state (fasting, full), with each scenario repeated thrice over five-minute sessions. A three-way ANOVA revealed that tightness level, posture, and nutritional state each had statistically significant effects on applied force ($p < 0.001$), and Cohen's d values confirmed strong effect sizes across comparisons. The highest pressures occurred during tight brace use in a full, seated state. This study demonstrates the feasibility of real-time stress mapping in scoliosis braces, informing both orthotic customization and clinical guidelines for optimal brace adjustment. Future studies will extend this approach to larger patient cohorts and explore adaptive braces capable of dynamically modulating pressure based on physiological changes.

Keywords—scoliosis brace, force-sensitive resistor, orthotic force mapping, 3D printing, polypropylene, biomechanical stress, sensor calibration, personalized orthosis.

I. INTRODUCTION

Scoliosis is a multifactorial, three-dimensional spinal deformity defined by a lateral curvature of the spine greater than 10° , typically accompanied by vertebral rotation and sagittal misalignment [1]. The condition predominantly arises during adolescence, coinciding with rapid growth periods, and is most commonly diagnosed as Adolescent Idiopathic Scoliosis (AIS), affecting approximately 2–3% of the adolescent population, with a higher prevalence among females [2,3]. If left untreated, scoliosis can lead not only to postural and aesthetic concerns but also to respiratory dysfunction, reduced physical performance, and psychosocial issues [2].

Bracing constitutes the primary conservative treatment for moderate scoliosis cases, particularly in skeletally immature individuals [4]. Traditional orthotic systems, such as the Milwaukee, Boston, Lyon, and Chêneau braces, have been widely utilized for decades, each employing different biomechanical correction strategies [5,6]. Despite their clinical efficacy in halting curve progression, these braces often suffer

from limitations in patient compliance due to discomfort, suboptimal pressure distribution, restricted mobility, and social stigma related to their bulky appearance [7,8,9].

Recent advances in digital technologies, including computer-aided design (CAD), 3D body scanning, and additive manufacturing (3D printing), have enabled the development of personalized scoliosis braces that promise enhanced anatomical conformity and biomechanical effectiveness [10,11,12]. However, a significant gap remains in the objective quantification of the mechanical forces that these orthoses exert on the body. Traditional evaluations primarily rely on radiographic imaging and clinical observations, which do not provide continuous or dynamic insights into the pressure applied by braces during daily activities.

FSR sensors offer a practical and efficient solution to this limitation. FSRs are thin, flexible sensors that detect and quantify force through changes in electrical resistance when subjected to pressure [13]. Their compactness (<0.5 mm thickness), mechanical flexibility, and responsiveness to varying loads make them ideal for integration into wearable orthotic systems [13,14,15]. When embedded within a scoliosis brace, FSR sensors can provide real-time, continuous monitoring of the pressure distribution across the brace-body interface, thereby enabling a data-driven approach to orthosis optimization.

This study aims to fill the current gap in scoliosis treatment by quantitatively measuring the biomechanical stresses generated by scoliosis braces using calibrated FSR sensors integrated into a personalized 3D-printed orthosis produced via Fused Deposition Modeling (FDM). Existing clinical assessments rely heavily on subjective feedback and static imaging, lacking real-time data on the pressures exerted by braces during daily activities. By systematically evaluating force distribution across different brace tightness levels, postures, and nutritional states, this research provides objective insights into how orthotic pressure dynamically interacts with the body. The findings are expected to guide the development of more effective, comfortable, and adaptive brace designs tailored to individual patient needs.

II. MATERIALS AND METHODS

This study utilized a customized scoliosis orthosis designed for an individual with a 10° lumbar curvature. The subject's torso

geometry was captured using a combination of photogrammetry and structured-light laser scanning, ensuring a high-fidelity 3D model of the anatomy [17]. The scan data were processed in a CAD environment, where the orthosis was digitally modeled with attention to corrective force zones, ventilation areas, and sensor integration sites [10,11]. The final design was exported in STL format for fabrication.

The orthosis was produced via Fused Deposition Modeling (FDM) using polypropylene (PP) filament due to its biocompatibility and mechanical resilience [18]. Printing was performed with a nozzle temperature of 200–250°C, a bed temperature of 80°C, and a 0.2 mm layer height. Post-processing involved mechanical sanding and wet polishing to enhance surface comfort.

To measure the forces applied by the brace, two FSR 402 series FSR sensors were embedded symmetrically at the lumbar-costal transition region, identified as the point of highest compressive stress during brace tightening [13,14,15]. The sensors were strategically placed at the lumbar-costal transition region—an anatomical site identified as being subjected to the highest compressive stress during brace tightening [14,15]. Figure 1 illustrates the precise zones within the orthosis where the sensors were positioned to capture pressure dynamics during use.

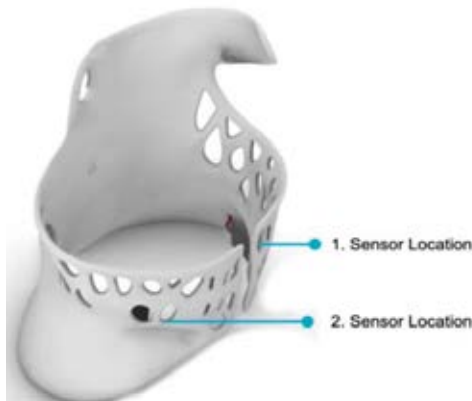


Figure 1. Visual representation of the sensor placement zones within the scoliosis orthosis

Additionally, Figure 2 shows the actual appearance of the personalized 3D-printed brace while worn by the subject, demonstrating the fit and anatomical conformity of the orthosis.

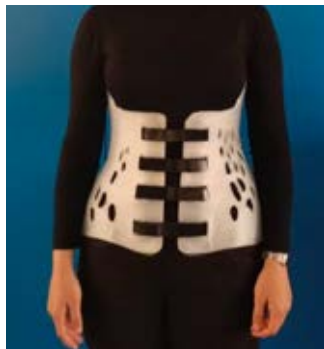


Figure 2. The personalized 3D-printed scoliosis brace worn by the subject during data acquisition.

The physical characteristics and specifications of the FSR sensors employed in this study are shown in Figure 3, highlighting their suitability for integration into orthotic designs without compromising structural integrity or patient comfort.

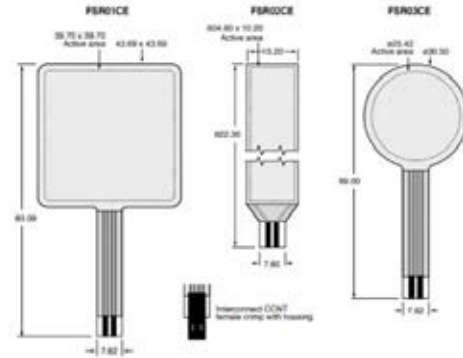


Figure 3. Dimensions of Different FSR Types [16]

Sensor calibration was carried out using a digital force gauge by applying known weights incrementally on each FSR sensor. Corresponding voltage outputs were recorded via Arduino's analog input pins, which were connected using a standard voltage divider circuit. The sensors were powered through the 5V pin of the Arduino, with signal output linked to analog pins A0 and A1 for FSR1 and FSR2, respectively. Calibration data were then processed in MATLAB, where a second-degree polynomial regression model was fitted to convert voltage readings into Newtons with high accuracy.

Force data were collected across different brace tightness levels (loose, medium, tight), under sitting and standing postures, and during fasting and full nutritional states. Each condition was recorded for five minutes and repeated three times to ensure consistency. The Arduino system continuously logged analog voltage outputs, which were then converted to force values via the calibration equation in MATLAB. Visualization and initial preprocessing of the data were also conducted in MATLAB.

For the statistical analysis, a three-way ANOVA was employed to examine the effects of brace tightness, posture, and nutritional state, and their possible interactions on the measured forces. Three-way ANOVA was chosen as it allows evaluation of not only the main effects of each independent variable but also their interaction effects on the dependent variable (force) [1]. Additionally, Cohen's d effect size was calculated for pairwise comparisons to quantify the magnitude of differences between tightness levels, providing a standardized measure of effect strength [2]. Pearson correlation coefficients were computed to assess the consistency between the two FSR sensors, ensuring the reliability of measurements across all conditions.

III. RESULTS

The force measurements obtained from the embedded FSR sensors revealed a consistent and significant increase in applied forces as the brace tightness progressed from loose to tight configurations. The highest force values were recorded under the tight-full-sitting condition, where the combined effects of

orthotic compression, posture, and postprandial abdominal expansion contributed to maximal stress on the torso.

Descriptive analysis showed that the average force measured by FSR1 increased from 1.99 N (loose) to 5.26 N (tight), while FSR2 increased from 1.30 N to 2.89 N under the same conditions. The minimum and maximum force values for each sensor across all conditions are presented in Figure 4, indicating the range of forces applied.

Analysis of stage (tightness) and condition (posture and nutritional state) interactions is depicted in Figure 5, illustrating how force values escalate, particularly under tight and full conditions.

Condition-wise comparisons of the measured forces are shown in Figure 6, highlighting the differential impacts of posture and feeding state on pressure levels. The full-sitting condition consistently produced the highest readings across both sensors.

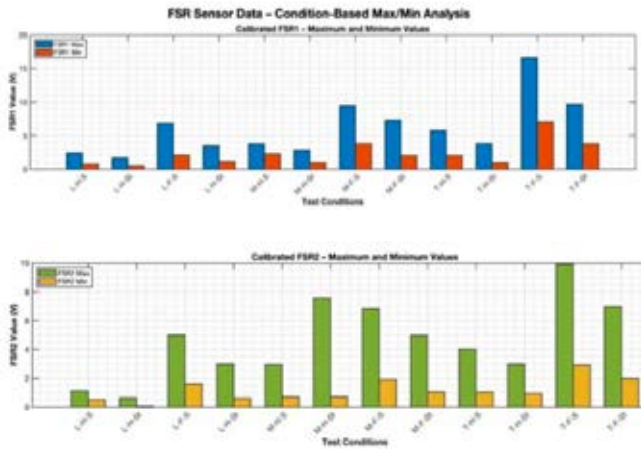


Figure 4. Minimum and Maximum Values of Force Sensors

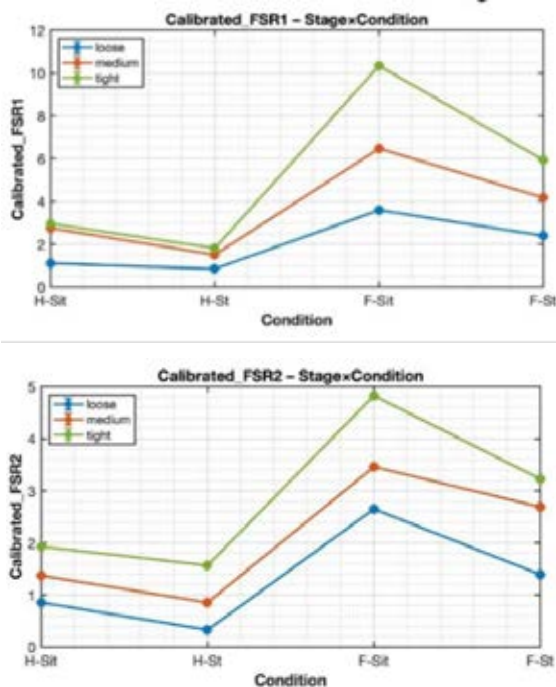


Figure 5. Stage x Condition Interaction of Force Sensors

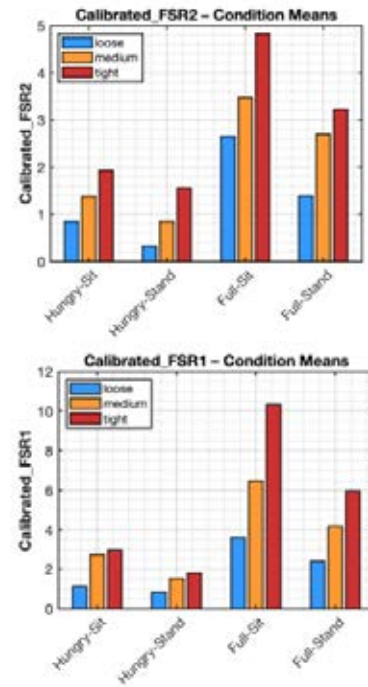


Figure 6. Condition x Wise Comparisons of Force Sensors

Statistical evaluation via three-way ANOVA confirmed that brace tightness, posture, and nutritional state each had significant main effects on applied force ($p < 0.001$), with large effect sizes ($\eta^2 > 0.20$). Moreover, strong positive correlations were observed between FSR1 and FSR2 outputs across all conditions ($r > 0.90$, $p < 0.001$), indicating measurement reliability, as shown in Table 1.

Collectively, these findings demonstrate that the magnitude of mechanical stress induced by the scoliosis orthosis is modulated not only by brace tightness but also by the user's physiological state and posture. The FSR sensor system effectively captured these dynamics, providing a comprehensive and quantifiable assessment of orthotic pressure behavior under varying conditions.

TABLE I. STATISTICAL SUMMARY OF MAIN EFFECTS AND PAIRWISE COMPARISONS

Comparison	Mean Force (N)	Cohen's d	p-value
Loose vs Medium (FSR1)	1.99 → 3.73	1.05	< 0.001
Loose vs Tight (FSR1)	1.99 → 5.26	1.26	< 0.001
Medium vs Tight (FSR1)	3.73 → 5.26	0.54	< 0.001
Loose vs Medium (FSR2)	1.30 → 2.10	0.71	< 0.001
Loose vs Tight (FSR2)	1.30 → 2.89	1.25	< 0.001
Medium vs Tight (FSR2)	2.10 → 2.89	0.57	< 0.001

IV. DISCUSSION

This study offers a quantitative approach to evaluating scoliosis braces by integrating calibrated FSR sensors within a custom-designed, 3D-printed orthosis. While previous research has predominantly focused on radiographic assessments or qualitative clinical observations, the biomechanical stresses generated by braces during use remain insufficiently quantified in dynamic conditions. Although some prior studies have proposed pressure sensor systems for orthotic evaluation [14,15], the precise impact of variables such as brace tightness, posture, and nutritional state on localized pressure dynamics is not yet fully elucidated.

Our results demonstrate that increasing brace tightness leads to significant elevations in the applied forces, aligning with fundamental biomechanical principles that tighter adjustments increase corrective pressure. These findings are consistent with Fuss et al. (2021), who highlighted the potential of integrating pressure sensors into customized scoliosis braces for real-time monitoring, though their study lacked systematic evaluations across physiological states [15]. Furthermore, the observed modulation of applied forces by posture and nutritional state suggests that the internal body environment and positioning critically influence orthotic stress distributions—an aspect not extensively covered in prior literature.

The strong correlation between the two symmetrically placed FSR sensors ($r > 0.90$) underscores the reliability and consistency of the measurement system developed in this study. The statistical significance of all three independent variables—brace stage, posture, and nutritional status—supports the robustness of the sensor-based methodology for orthotic evaluation. These insights align with the broader call in the literature for more dynamic and patient-responsive assessment methods in conservative scoliosis treatment [14, 15].

By enabling real-time biomechanical data acquisition, this approach addresses a critical gap in clinical practice: the lack of continuous and dynamic monitoring of orthotic pressures during daily activities. Such data-driven insights could inform the development of adaptive or intelligent brace systems capable of modulating force application based on the patient's physiological and postural variations, as advocated by Giggins et al. (2014) in the context of rehabilitation technologies [16].

Compared to traditional assessments that often rely on subjective patient feedback or static imaging, this study contributes an empirical foundation for optimizing orthotic designs and personalization strategies. Nevertheless, further research with larger sample sizes and diverse patient profiles is warranted to generalize these findings and to explore the feasibility of integrating real-time feedback systems into routine clinical practice.

In conclusion, the present findings contribute to the evolving understanding of biomechanical interactions in scoliosis bracing and provide a stepping stone for future developments in sensor-enhanced orthotic solutions. This knowledge is expected to aid in refining brace designs, improving patient-specific adjustments, and advancing the broader field of intelligent, sensor-integrated medical devices.

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