Evaluating Respiratory Effects of 3D-Printed Scoliosis Bracing in Different Physiological States

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***Abstract*—Respiratory function is a critical physiological parameter often affected in individuals using scoliosis braces due to thoracic compression. Assessing respiratory parameters, especially Vital Capacity (VC), is essential to understand how orthotic interventions influence lung function. This study investigates the impact of scoliosis brace compression on VC under varying tightness levels and physiological states. A personalized 3D-printed orthosis was designed for a subject with lumbar scoliosis and fabricated using Fused Deposition Modeling (FDM) with polypropylene material. Respiratory measurements were conducted using the BIOPAC SS11LB airflow sensor while the subject was seated in a relaxed position. VC was recorded in both fasted and postprandial states across three brace tightness levels: loose, medium, and tight. Results showed a significant reduction in VC as brace tightness increased, with the highest reduction observed under tight brace conditions. Additionally, postprandial VC values were consistently lower than fasted measurements, indicating that physiological fullness further exacerbates thoracic restriction. These findings highlight the importance of considering both orthotic compression and nutritional status in respiratory assessments of scoliosis patients. The study provides valuable insights for developing patient-specific bracing strategies that balance spinal correction with minimal respiratory compromise.**

Keywords—Scoliosis brace, Vital Capacity, 3D printing, respiratory function, postprandial state, orthosis compression, personalized orthotics.

I. INTRODUCTION

Adolescent Idiopathic Scoliosis (AIS) is a complex three-dimensional deformity of the spine that not only alters spinal alignment but also significantly affects thoracic structure and pulmonary function. Particularly in thoracic scoliosis, the distortion of the rib cage, vertebral rotation, and reduced chest wall compliance contribute to restrictive ventilatory patterns [1,2]. Such respiratory limitations are especially critical during adolescence, a developmental stage essential for attaining full pulmonary potential [3].

In this context, the use of patient-specific scoliosis braces becomes increasingly important. Standard braces may not adequately accommodate the unique anatomical and physiological characteristics of each individual, potentially leading to excessive thoracic compression and further respiratory compromise. In contrast, personalized orthoses—designed based on the patient's spinal curvature, torso geometry, and clinical needs—offer a more balanced approach. These custom-made solutions aim to optimize spinal correction while minimizing negative impacts on respiratory function, thereby improving both therapeutic efficacy and patient comfort.

Conservative treatment approaches, notably rigid bracing, are widely used to prevent curve progression in AIS. However, the external compression applied by braces can further restrict thoracic expansion, potentially exacerbating existing pulmonary limitations [4]. Prior studies have demonstrated that braces can lead to reductions in lung volumes such as Forced Vital Capacity (FVC) and Forced Expiratory Volume in 1 second (FEV1), indicating a restrictive impact on breathing mechanics [5]. However, the specific effects of scoliosis braces on Vital Capacity (VC)—a direct measure of the maximal volume of air exhaled after a full inhalation—under relaxed, seated conditions remain insufficiently studied.

VC is a critical parameter in evaluating the maximal ventilatory capacity and thoracic mobility of individuals with scoliosis, especially under orthotic constraint. Unlike Tidal Volume, which measures normal, passive breathing, VC provides a clearer picture of the full expansion potential of the lungs, offering essential insights into the restrictive impact of brace application [1,5].

Monitoring respiratory function during brace use is particularly important because adolescents wearing scoliosis braces often engage in routine daily activities—such as sitting, walking, studying, and eating—while under orthotic constraint. During these activities, impaired thoracic mobility caused by the brace can lead to increased respiratory effort and reduced ventilatory efficiency. If unmonitored, such limitations may contribute to chronic discomfort, fatigue, and suboptimal pulmonary development. Therefore, assessing the impact of brace tightness on breathing mechanics under realistic conditions is crucial for ensuring both the clinical effectiveness and tolerability of scoliosis treatment.

To better illustrate the relationship between VC and other lung volumes, a graphical representation of the respiratory cycle is provided in Figure 1. This schematic clearly demonstrates how VC integrates the various lung capacities within the respiratory physiology framework.

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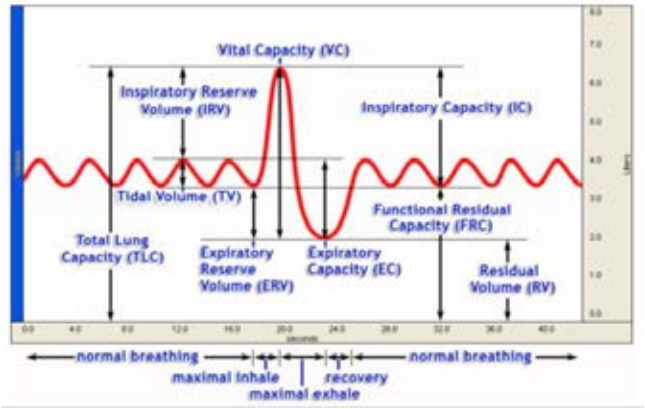

Figure 1. Graphical representation of lung volumes within the respiratory cycle [1]

By focusing solely on VC assessments under static conditions, this study aims to provide empirical evidence on how orthotic compression affects respiratory mechanics in AIS. The findings are anticipated to guide clinicians and orthotists in optimizing brace designs and adjustment protocols that safeguard respiratory health while ensuring effective spinal correction.

II. Materials and Methods

This study was conducted on a female subject presenting a 10° lumbar scoliosis curvature, verified through radiographic analysis based on the Cobb method, which is the gold standard for quantifying spinal curvature by measuring the angle between the most tilted vertebrae above and below the curve apex.. The experimental objective was to investigate the effects of varying scoliosis brace tightness on pulmonary function, specifically Vital Capacity, in a relaxed, seated posture.

Prior to respiratory data collection, the subject wore the custom-designed scoliosis orthosis for a continuous period of 42 hours to ensure physiological adaptation and minimize acute stress responses, surpassing the generally recommended 24-hour familiarization period. The orthosis was fabricated through a workflow beginning with 3D scanning, utilizing both photogrammetry and structured-light laser scanning, ensuring high anatomical fidelity. The obtained mesh data were processed in a Computer-Aided Design (CAD) environment, where the brace was parametrically modeled with ventilation zones, corrective force regions, and adjustable straps.

Manufacturing was carried out using Fused Deposition Modeling (FDM) with polypropylene (PP) filament. The print parameters included a nozzle temperature of 200–250°C, bed temperature of 80°C, 0.2 mm layer height, and 2% infill density. Post-processing involved sanding with P100 abrasive paper, further abrasion, and 600-grit wet polishing for skin contact safety.

For respiratory data collection, a BIOPAC SS11LB Airflow Transducer was connected to the BIOPAC MP36 data acquisition system. The airflow sensor, with a flow range of ±115 L/min and sensitivity of 0.5 mV/L/min, was externally positioned via a mouthpiece. A nose clip was applied to prevent nasal airflow, ensuring complete measurement of oral ventilation. During each trial, the subject performed a maximal inhalation followed by a maximal exhalation to determine VC. Measurements were conducted in a seated, relaxed posture to control for postural influence. The experimental configuration is depicted in Figure 2.

Figure 2. Experimental setup showing the BIOPAC SS11LB airflow transducer connected to the MP36 system for VC measurement during brace wear.

Three brace tightness conditions—Loose, Medium, and Tight—were applied by adjusting the Velcro straps, and VC was recorded for each condition. For every tightness level, the subject completed three measurement trials, each lasting approximately one minute, with the highest VC value retained for analysis. All procedures were conducted under standardized laboratory conditions to ensure data consistency and reliability.

The collected airflow data were sampled at a frequency of 2000 Hz and exported as .txt files for signal processing in MATLAB. The processing pipeline involved:

- Application of a low-pass filter to remove high-frequency noise.
- Detection of inspiratory and expiratory peaks to delineate respiratory cycles.
- Calculation of VC by measuring the maximal amplitude difference between full inhalation and exhalation.
- Visualization through time-domain plots to assess waveform integrity and comparative analysis across tightness conditions.

This data processing was performed using custom MATLAB scripts, ensuring reproducibility and standardized analysis across all experimental sessions. The processed data were subsequently analyzed statistically to identify the impact of orthotic compression on VC. Since the respiratory data were collected from a single subject across repeated trials under varying conditions, formal parametric tests such as t-tests were not applicable due to insufficient degrees of freedom. Instead, descriptive statistics—including mean, range, and percentage change—were calculated to interpret trends across conditions. Additionally, one-way ANOVA was applied illustratively to assess the variability in mean VC values under different brace tightness and nutritional states, providing preliminary insight into potential condition-dependent effects. Statistical methodologies are detailed in the subsequent section.

III. RESULTS

In this study, the effects of varying scoliosis brace tightness on Vital Capacity (VC) were examined under two physiological conditions: hungry and full states. Additionally, a baseline measurement was recorded in the without-brace condition to establish the subject's maximum pulmonary capacity.

In the hungry, without-brace condition, the subject achieved a VC of 3.884 liters, representing the highest capacity recorded throughout the study. This measurement served as a critical reference point to evaluate the restrictive effects of the brace. Although the VC measurement for the postprandial, without-brace condition was not available at the time of reporting, it will be included in future analyses to complete the dataset.

Upon application of the 3D-printed scoliosis brace, a clear and progressive reduction in VC was observed as the tightness of the brace increased. In the fasted state, the VC was measured as 2.362 L in the loose condition, 1.405 L in the medium condition, and 1.162 L in the tight condition. This reflects a 70% reduction in VC from the unbraced state to the tight brace condition, underscoring the significant mechanical restriction imposed by maximal brace compression.

Similarly, in the postprandial state, VC measurements exhibited a downward trend with increasing brace tightness. The VC was recorded as 1.382 L with the brace loosely fitted, 1.019 L at medium tightness, and 0.743 L under tight conditions. Notably, the postprandial VC values were consistently lower than the corresponding fasted values across all levels of brace tightness. This suggests that gastrointestinal distension following food intake may further restrict thoracic expansion, exacerbating the brace's restrictive effect on lung capacity. All recorded VC values across the experimental conditions are summarized in Table 1, enabling a direct comparison between states and brace tightness levels.

TABLE I. VITAL CAPACITY MEASUREMENTS BY BRACE TIGHTNESS AND NUTRITIONAL STATE.

Condition	VC (L)
Without Brace - Hungry	3.884
Without Brace - Full	2.319
Brace Loose - Hungry	2.362
Brace Medium - Hungry	1.405
Brace Tight - Hungry	1.162
Brace Loose - Full	1.382
Brace Medium - Full	1.019
Brace Tight - Full	0.743

To visually represent these trends, the data are plotted in Figure 3, illustrating the sharp decline in VC with increasing brace tightness and the additional restrictive influence of the postprandial state.

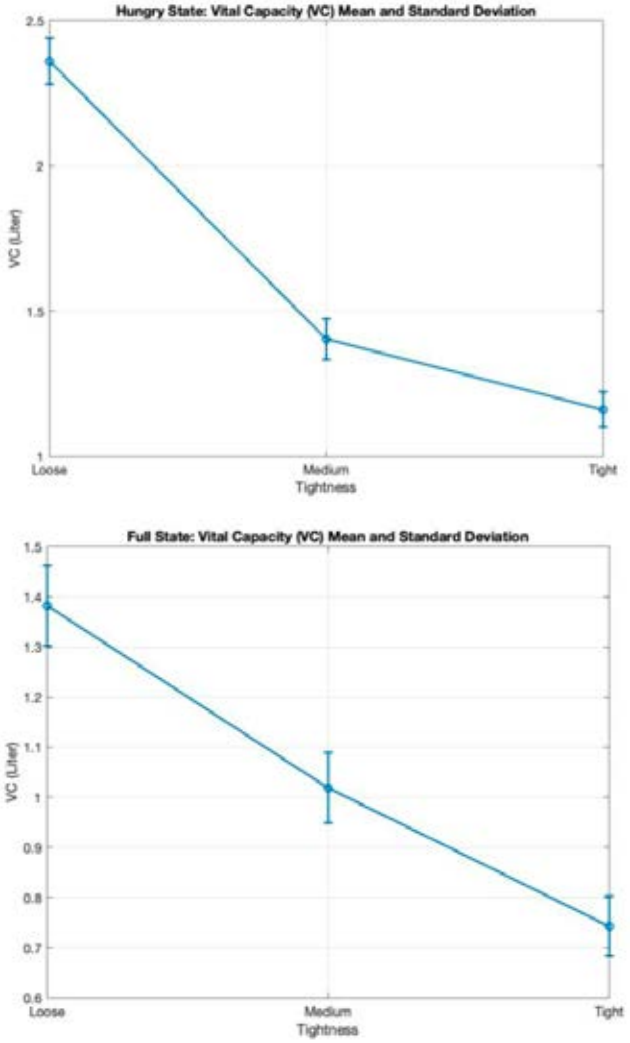

Figure 3. Comparison of Vital Capacity (VC) across brace tightness levels in both hungry and full states

These findings clearly demonstrate the restrictive impact of scoliosis bracing on pulmonary capacity, which is further compounded by physiological states such as postprandial fullness. The data highlight the importance of considering both brace adjustment and patient physiological state when evaluating respiratory function in brace-treated scoliosis patients.

IV. DISCUSSION AND CONCLUSION

This study presents an empirical investigation into the effects of scoliosis brace compression on Vital Capacity, uniquely contextualized within both fasted and postprandial physiological states. The findings corroborate and extend existing literature that underscores the restrictive impact of orthotic interventions on pulmonary function in individuals with scoliosis.

In line with previous studies, a progressive reduction in VC was observed with increasing brace tightness. For instance, Kennedy et al. (1989) demonstrated that thoraco-lumbar braces significantly reduce respiratory mechanics in adolescents with idiopathic scoliosis, with notable decrements in VC under rigid

bracing conditions [5]. Similarly, Noble-Jamieson et al. (1986) reported that the application of spinal braces in neuromuscular patients led to impaired respiratory capacity, attributed to diminished thoracic expansion [6]. The present findings, revealing up to a 70% reduction in VC from the unbraced to the tightest brace condition, are consistent with these earlier observations, albeit with a more personalized and systematically calibrated orthotic approach.

A distinct contribution of this study lies in the integration of the postprandial state as an experimental variable. The data demonstrated that VC values in the postprandial condition were consistently lower than their fasted counterparts across all brace tightness levels. This aligns with Malbrain (2007), who detailed the adverse respiratory effects of elevated intra-abdominal pressure, suggesting that gastric distension post-meal can further compromise diaphragmatic excursion and thoracic compliance [7]. This dual influence—orthotic compression combined with physiological fullness—highlights the importance of considering nutritional timing and patient state during orthotic fitting and respiratory assessments.

Another pivotal insight from this study is the use of a customized 3D-printed brace, offering a tailored fit that likely amplifies the restrictive effect compared to conventional, mass-produced orthoses. The precision of the 3D printing process and the inclusion of adjustable straps allowed for controlled modulation of tightness, which is often lacking in standard bracing approaches. This personalized design strategy may explain the relatively higher percentage of VC reduction compared to prior reports, such as the 15-20% VC reduction observed with Thoraco-Lumbo-Sacral Orthoses (TLSO) in traditional designs.

Moreover, by employing a BIOPAC SS11LB airflow sensor with a high sampling frequency and advanced MATLAB-based signal processing, this study ensured high-resolution quantification of VC changes. This methodological rigor enhances the validity of the findings and paves the way for real-time respiratory monitoring systems that could be embedded in future smart orthoses. Despite these strengths, the study acknowledges certain limitations. The analysis was conducted on a single subject, limiting the generalizability of the findings. However, the directional trends observed are robust and align with established biomechanical principles, suggesting that the interaction between brace compression and physiological states warrants further investigation.

In comparison to Rozek-Piechura et al. (2024), who studied the effects of the Cheneau brace combined with Schroth exercises on pulmonary function, this study isolates the mechanical impact of the brace itself without confounding rehabilitation exercises, offering a pure assessment of orthotic restriction on VC [8]. Clinically, these findings emphasize the necessity for orthotists and clinicians to consider patient-specific factors such as nutritional status, daily activity patterns, and respiratory function when prescribing and adjusting scoliosis braces. The observed exacerbation of restrictive effects postprandially suggests that brace wear schedules might benefit from synchronization with patients' feeding times to minimize respiratory burden. Future research should expand this inquiry with a larger cohort, incorporate continuous respiratory monitoring across different activities and postures, and explore adaptive orthotic designs capable of dynamically modulating pressure based on physiological feedback.

In summary, this study advances the understanding of how scoliosis braces interact with respiratory mechanics, particularly vital capacity (VC), under varying compression levels and physiological states. According to the results, VC dropped from 3.884 L (Without Brace – Hungry) to 1.162 L (Brace Tight – Hungry), which corresponds to a 70.1% reduction, clearly illustrating the substantial restrictive effect of high brace tightness. Likewise, the postprandial (full) state led to consistently lower VC values across all brace conditions—for example, in the tight brace condition, VC declined from 1.162 L (Hungry) to 0.743 L (Full), a 36% additional reduction due to physiological fullness. These findings strongly indicate that both brace tightness and nutritional state significantly influence pulmonary function, and should therefore be key considerations during orthosis design, adjustment, and wear-time scheduling. The integration of 3D printing, embedded sensors, and physiological context in this study represents a step toward more adaptive, patient-specific scoliosis management strategies. Future studies should expand this framework using larger sample sizes and continuous monitoring approaches.

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