A computational optimization approach to scoliosis brace design – Preliminary results

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INTRODUCTION: The design of braces for adolescent idiopathic scoliosis is a problem that could potentially benefit from computational solutions. There is a broad body of research on simulation of the human spine, including simulation of scoliosis, as well as braces and their effects on the body. Some sparse works leverage these simulation models to evaluate the quality of digital brace designs [1,2], but the computational approach to scoliosis brace design remains largely underused.

In this study we aim to formulate brace design as a computational optimization problem and develop methods for automatic design of scoliosis braces from patient input data. We study the major components of this approach: (i) The parameterization of the brace geometry, which captures the design space; (ii) the definition of a design objective function that balances a clinical quality metric and a patient comfort metric; (iii) a biomechanical model of the patient's torso that allows automatic evaluation of the design objective as a function of design parameter choices; and (iv) an optimization algorithm that explores automatically the design space.

METHODS: We start our methodology by first defining the shape and parameters of the brace. For the initial unoptimized brace, we take a section of the patient's torso surface corresponding to the scoliotic section of the spine. This initial shape will then be transformed to provide pressure on the torso, and thus forces on the spine that produce an incremental correction. Computer optimization of the brace shape requires a compact parameterization of its geometry. There are many possible approaches to define this parameterization, such as the use of control points and parametric surface definitions. Our approach relies heavily on the three-point brace design methodology, and parameterizes the brace based on horizontal scale and eccentricity at three different heights.

To guide the change of the brace shape, we need a merit function that quantifies the impact on the spine from a clinical standpoint. In our preliminary implementation, we use the Cobb angle. However, optimizing the Cobb angle might produce braces that are uncomfortable or even impossible to wear. Therefore, we also add the total force applied by the brace on the body as a balance metric, penalizing designs that would be too uncomfortable. A proper weight adjustment of the clinical and comfort metrics produces designs that are both effective and comfortable to wear.

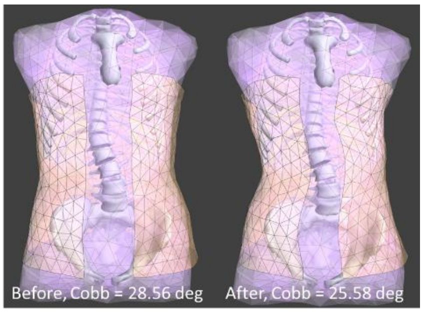
The evaluation of the design function due to changes of the brace shape requires a biomechanical model of the torso and the spine. This model must capture the transformation of the vertebrae of the spine, contact forces applied on the torso surface, and the transfer of these forces to the spine through the ribcage and the soft tissue in the torso. We leverage a model that uses a multi-body representation of bones, coupled with a neo-Hookean parameterization of the elasticity of soft tissue [3].

Given the parameterization of the brace geometry, the design function, and the model of torso and spine, we can rely on numerical optimization methods to automatically search for brace geometries that produce optimal designs. In our current implementation, we choose the bounded L-BFGS optimization algorithm. This algorithm offers a good balance of speed and convergence, and it requires the evaluation of the gradient of the objective function.

RESULTS: We used input data from one scoliosis patient to test our model and optimization approach. The starting Cobb angle of this patient was 28.56 degrees. We have evaluated the success of the optimization approach by comparing two different sets of brace parameters: one larger set including brace scale and eccentricity, and a smaller set including only scale, under the hypothesis that the larger set should allow larger reduction of the Cobb angle. The following table summarizes the results under both conditions.

Parameter set	Cobb angle	Total applied force	Optimization steps	Computation time
Scale and eccentricity	25.58	87.51 N	14	30m 47s
Scale only	27.87	95.71 N	8	36m 32s

DISCUSSION: The optimization using all 9 parameters (scale and eccentricity) achieves a 3-degree decrease in Cobb angle while exerting a mild force of 87.51 N on the body (See the image on the side). Reducing the number of parameters to 3 (just brace scale at three different heights) leads to a decrease in Cobb angle of less than 1 degree, and a slightly larger force. These preliminary results demonstrate that the computational optimization approach succeeds to leverage a higher-dimensional parameterization of the brace geometry to find a more effective design, without incurring into patient discomfort.



SIGNIFICANCE: This study outlines the development of a computational optimization approach to brace design. It demonstrates the effectiveness of the approach on a simulated setting, and suggests its benefit for automating the design of personalized scoliosis braces.

REFERENCES:

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