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Development of a Dynamic Digital Phantom Capable of Modeling Head and Neck Motion

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ABSTRACT

The process of patient positioning for head and neck (HN) radiation therapy (RT) procedures can be difficult without knowledge of physiological motion constraints due to neck vertebrae. This work seeks to develop a dynamic biomechanical digital phantom of the HN that enables accurate simulation of HN motion with realistic anatomical constraints for use in automated patient positioning in HNRT. A dynamic digital phantom was developed to model HN motion while enforcing realistic biomechanical constraints. Unlike conventional static phantoms, this model allows patient anatomy to be evaluated across a continuous range of positions, reflecting clinically relevant variations. Biomechanical constraints are applied to limit articulation to physically plausible motions. Multiple approaches were implemented to model these constraints, including predefined limits on rotation and translation about anatomically motivated pivot points, as well as finite element-based simulations of cervical vertebrae motion. Together, these methods constrain surface deformation and articulation in a manner consistent with observed patient anatomy while preserving flexibility in regions prone to motion, such as the neck. Preliminary testing of this digital phantom shows the potential for accurate reproduction of HN motion. The imposed biomechanical constraints have been seen to prevent non-physical articulations while allowing clinically relevant variability in posture in early tests. This work demonstrates the feasibility and utility of a dynamic digital HN phantom incorporating biomechanical constraints, with potential applications in the optimization and validation of patient positioning for radiation therapy.

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INTRODUCTION

- Head and neck radiation therapy (HNRT) requires accurate patient positioning, yet physiological motion constraints of the cervical vertebrae are poorly characterized in current workflows[1].
- Inaccurate positioning due to unpredictable HN motion can compromise treatment delivery and increase risk to surrounding healthy tissue.
- Many digital HN phantoms are static[2] and are unable to capture the range of HN postures.
- This work presents the development of a dynamic digital phantom capable of simulating realistic HN motion, enabling improved validation and optimization of automated positioning systems.

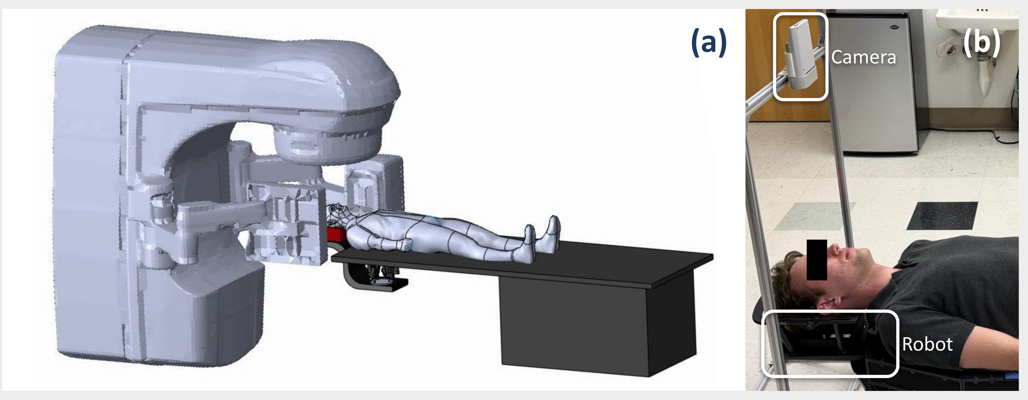

Figure 1. (a) A rendering of the clinical setup of a patient on an automated positioning system connected to a treatment LINAC. (b) An example setup of a volunteer positioned on a robotic system in order to allow for automated correction of HN position.

METHODS

- A dynamic digital phantom was designed to represent HN anatomy across a continuous range of positions. This was done using two methods.
- Method 1: Finite Element Model (FEM)
  - FEM techniques have previously been used to model neck motion and injuries[3].
  - Vertebrae are modeled as cylinders connected via spring-based ball joints, Figure 3, simulating push/pull forces and resist over-rotation.
  - Spring constants between each vertebrae are tuned to enforce realistic ranges of motion.
  - The model tracks vertebrae locations to detect collisions and further constrain motion.
- Method 2: Artificially Applied Rotational Constraints
  - Neck motion has previously been described using a set of limited rotations around a number of set rotational points[4].
  - Explicit kinematic limits are imposed at anatomically motivated pivot points to restrict articulation to physically plausible motions.
  - Different types of HN rotation use different points of rotation, as shown in Figure 4.

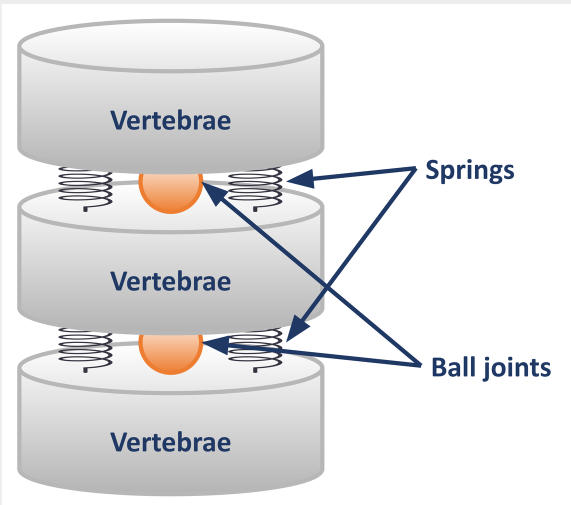

Figure 2. Finite element model of neck vertebrae. Each vertebrae are represented as a cylinder. Vertebrae are connected to neighboring vertebrae through ball joints. Motion is constrained by connecting springs, each with a tunable spring constant. This allows for limitation of motion in flexion and bending, as well as rotation.

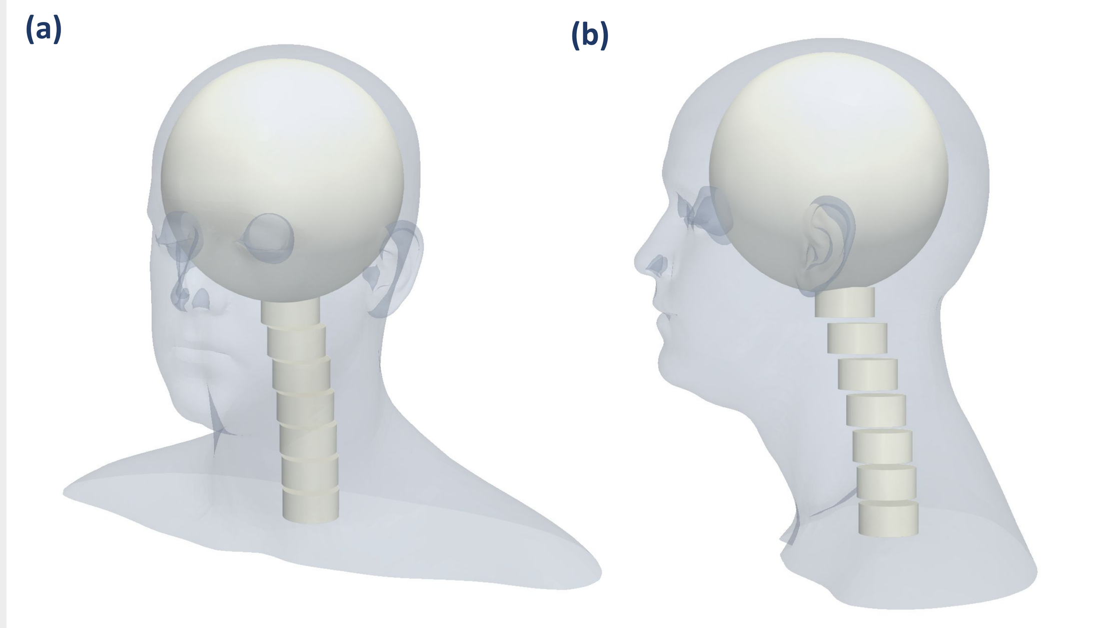

Figure 3. FEM neck vertebrae model implementation.

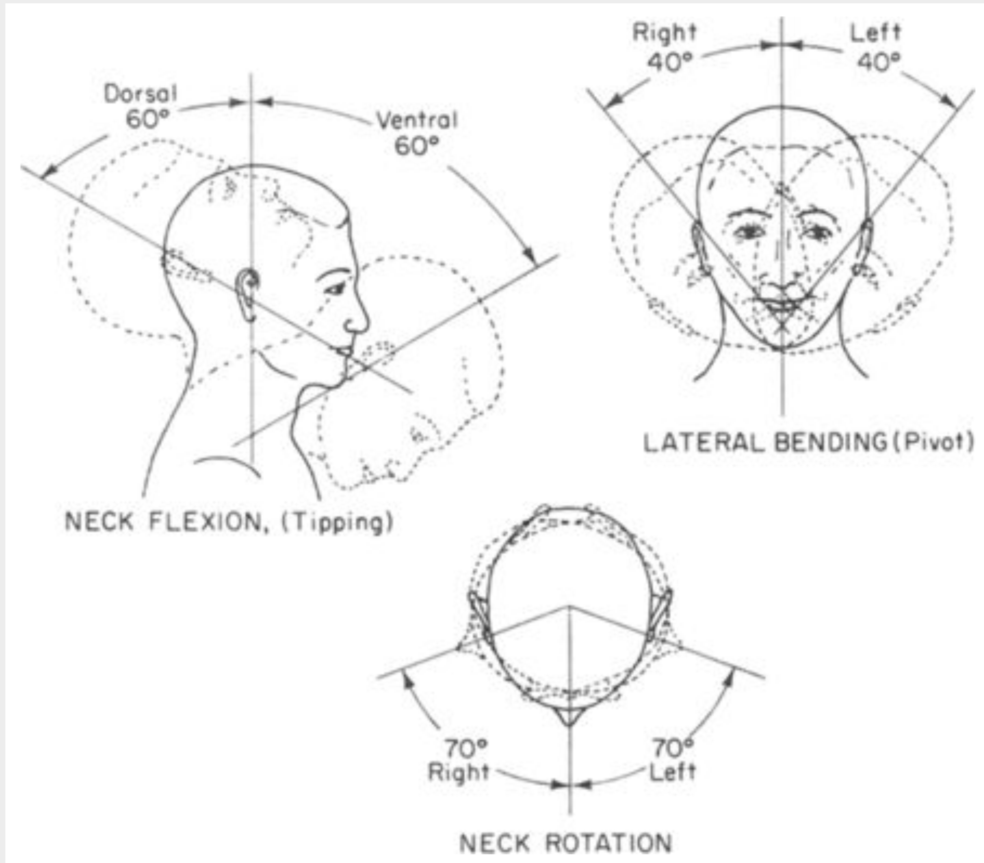

Figure 4. Established limits of head and neck rotation around different rotational points. Figure from Gilman, *et al.*[4]

RESULTS

- Preliminary testing demonstrates that the phantom successfully reproduces a realistic range of HN motion without generating physically impossible articulations.
- The FEM spring-joint system effectively limited over-rotation at individual vertebral levels while permitting clinically relevant compound movements.
- Artificially applied rotational constraints provided stable, predictable boundary conditions at key anatomical pivot points.
- Some unrealistic motion was achieved when rotational limits were reached for multiple pivot points simultaneously, showing the need for a more refined version of this model.
- Both models were able to be used to model realistic skin deformations arising from changes in HN posture.

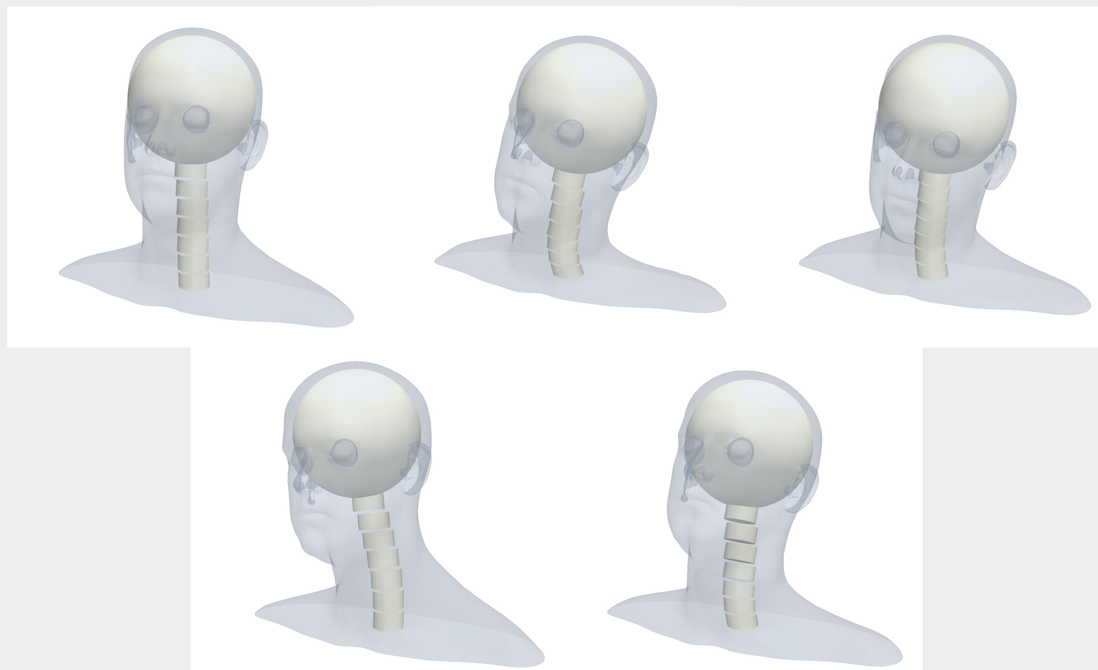

Figure 5. An array of deformed head and neck positions achieved using the finite element model. Skin surface deformations are derided from the consequences of vertebrae position.

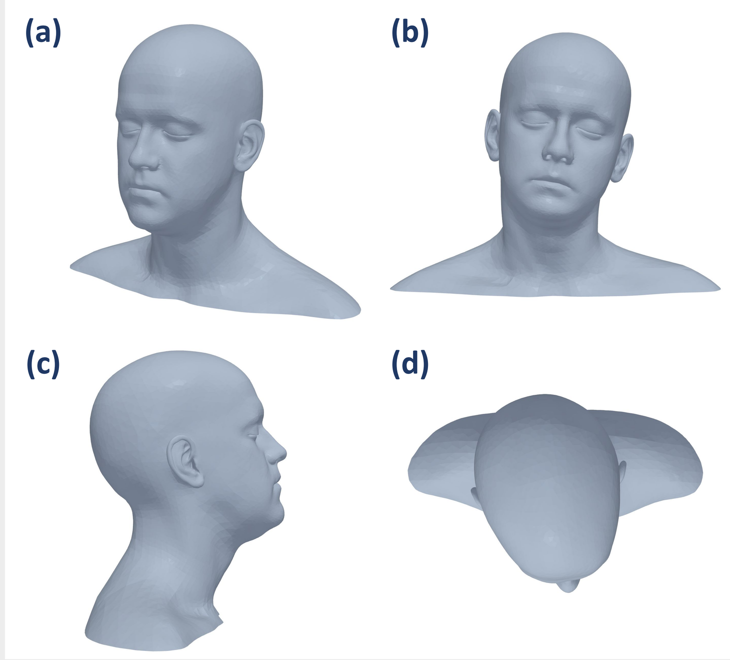

Figure 6. Head and neck positional perturbations achieved using the artificial constraints model. The model can produce realistic head positions and skin deformations. (a) The neutral position. (b) Lateral head bending. (c) Neck flexion. (d) Neck rotation.

DISCUSSION

- The two approaches yet explored both show potential for use in modeling of HN positioning constraints in order to improve HNRT workflows
- Spring constant tuning in the FEM is done manually, motivating the integration of a neural network to automate and optimize this process.
- A future goal to improve this effort is to generate phantoms directly from CT scans, allowing for patient-specific modeling.
- Future work will combine the techniques explored here into a hybrid model in order to improve both the accuracy and generalizability of the phantom.
- Using ML model to predict HN motion constraints may also prove to be a useful method and warrants investigation.

CONCLUSIONS

- A dynamic digital HN phantom incorporating biomechanical constraints has been developed and demonstrates feasibility for simulating realistic cervical spine motion.
- Two strategies, a spring-based finite element model and artificially applied rotational limits, were implemented in preliminary testing.
- Early results indicate the methods successfully prevent non-physical articulations of vertebrae and tissue while allowing for postural variability.
- This work establishes a foundation for improved automated patient positioning workflows in HNRT.

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