

Incorporating Cortical Bone Property Variability into Simulations of Isolated Ribs under Anterior-Posterior Bending

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Introduction

- Rib fractures are among the common injuries in vehicle collisions [1].
- Experiments report significant variability in isolated rib structural response under anterior-posterior bending [2] and in cortical bone material properties [3].
- The relative contribution of geometric and material variability to the rib structural response remains unclear.
- **Objective:** Evaluate the effect of external geometry and cortical bone material variability on force-displacement corridors, using subject-specific FEM simulations under deterministic and stochastic material configurations.

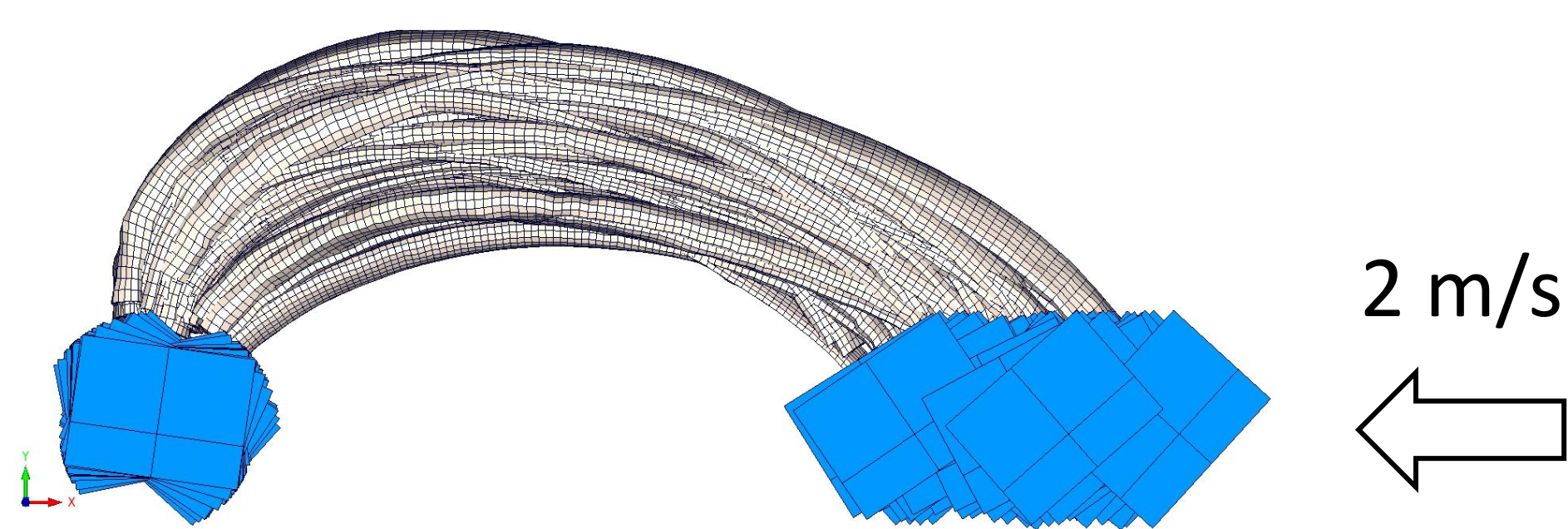


Fig. 1. FE models of ribs under anterior-posterior bending. 213 subject-specific rib geometries.

Methods

- 213 adult subject-specific rib geometries obtained via laser scans from the IBRC at The Ohio State University. Samples by level: L4:8, L5:37, L6:156, and L7:12.
- FEM models solved in LS-DYNA Explicit.
- Cortical bone: bilinear elastoplastic and parametric material properties (Table 1).
- Two virtual experiments, each with three material configurations. 1278 simulations in total.
 - Deterministic: $s = \{-2, 0, 2\}$. Fixed material parameter across geometries.
 - Stochastic: $s \sim U(-2, 2)$. Random material parameter per geometry.
- Force-displacement corridors computed with ARCGen [4].

Table 1. Parametric material properties of rib cortical bone [5].

Property	Equation	Unit
Elastic modulus	$E(s) = 14700 + 2000 \cdot s$	MPa
Yield strength	$\sigma_y(s) = 100.7 + 12.9 \cdot s$	MPa
Plastic modulus	$P(s) = 1940 + 500 \cdot s$	MPa

Results

- Deterministic ARCGen average end forces: 60.16, 83.41, and 106.32 N. (Fig. 2)
- Stochastic ARCGen average end forces: 82.94, 83.07, and 82.82 N. (Fig. 3)

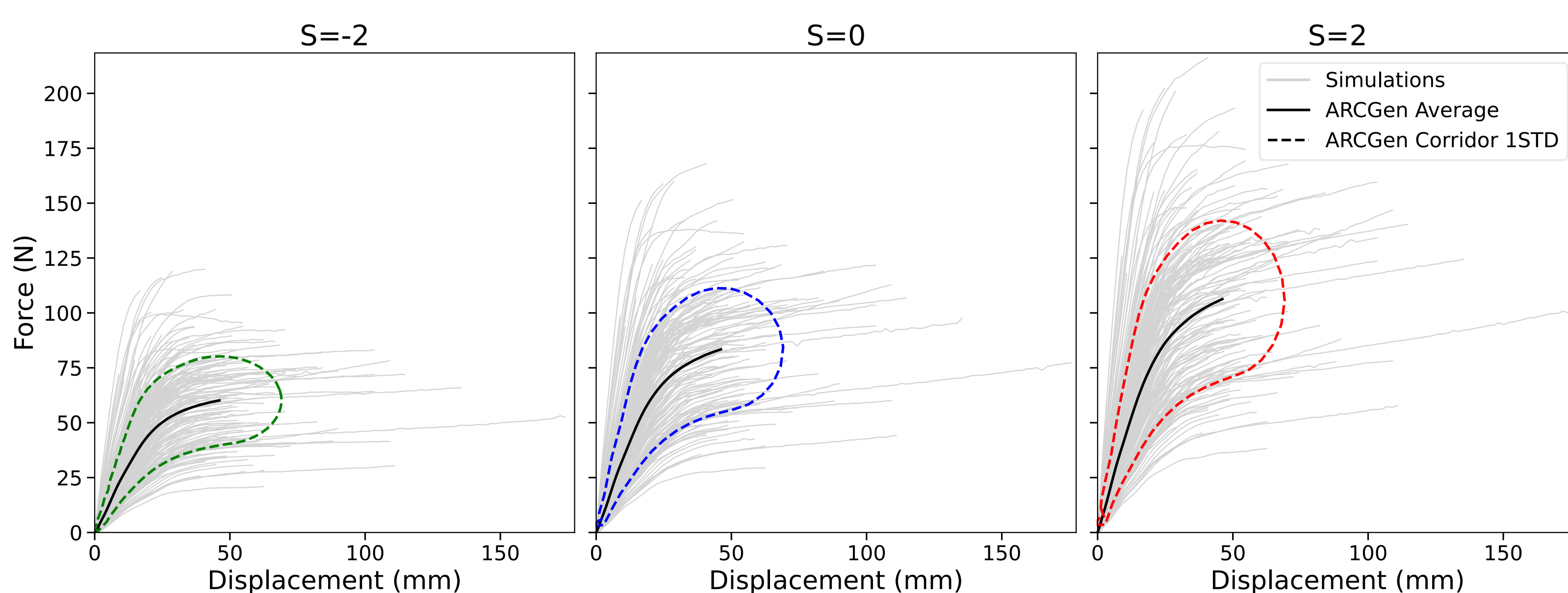


Fig. 2. Force at vertebral rib end and displacement of the sternal rib end for three deterministic s values. ARCGen corridors (± 1 standard deviation).

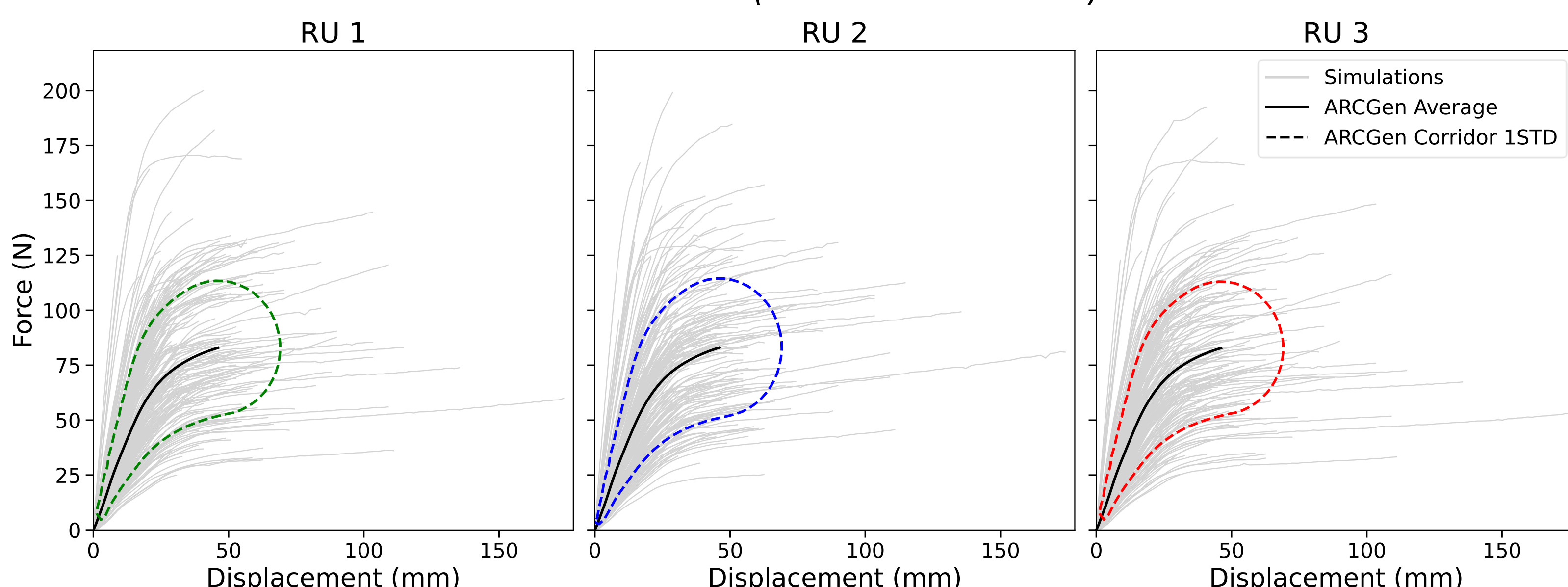


Fig. 3. Three random realizations. Force at vertebral rib end and displacement of the sternal rib end. ARCGen corridors (± 1 standard deviation).

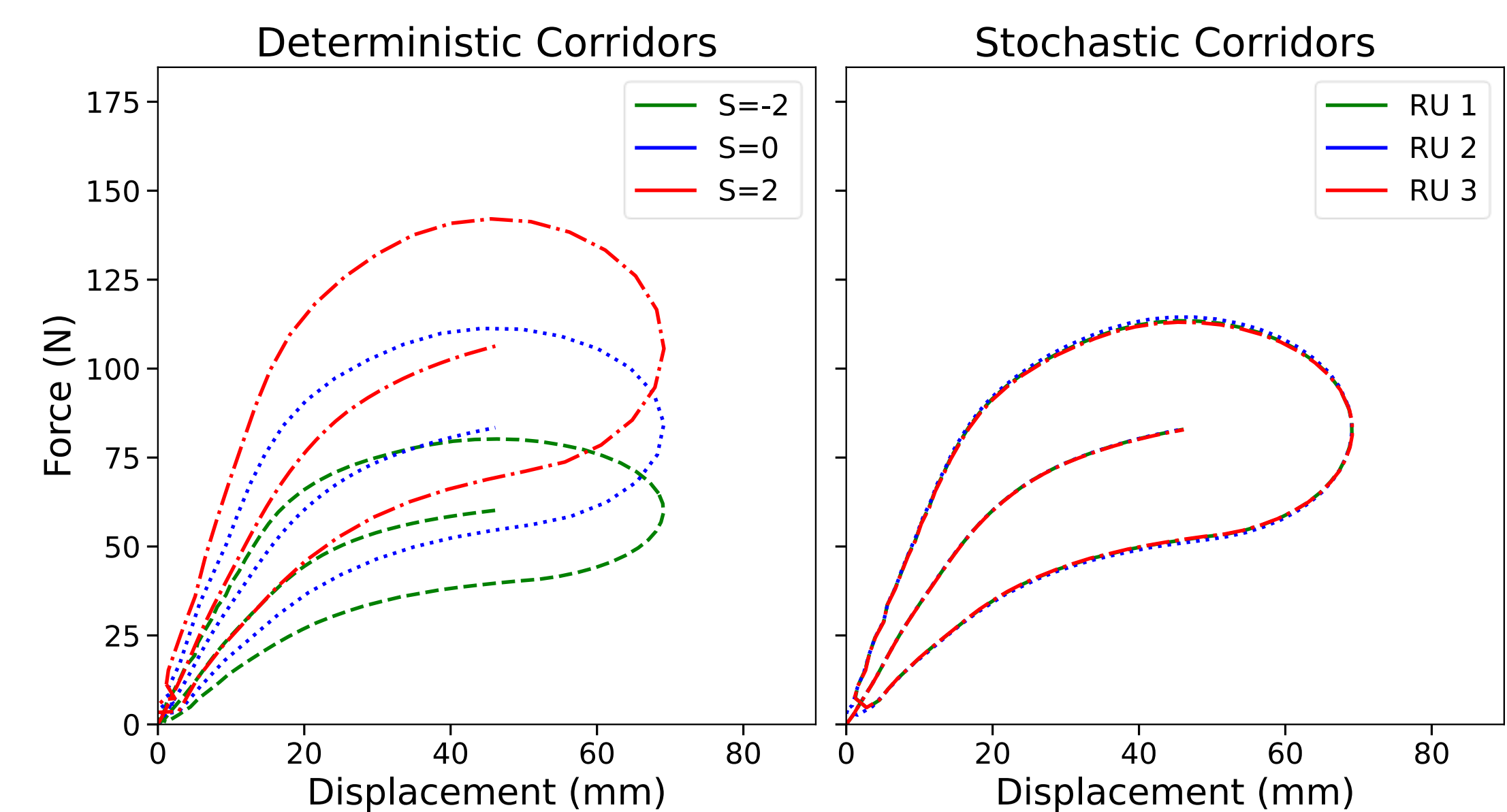


Fig. 4. ARCGen corridors (± 1 standard deviation). Comparison between deterministic configurations and stochastic realizations.

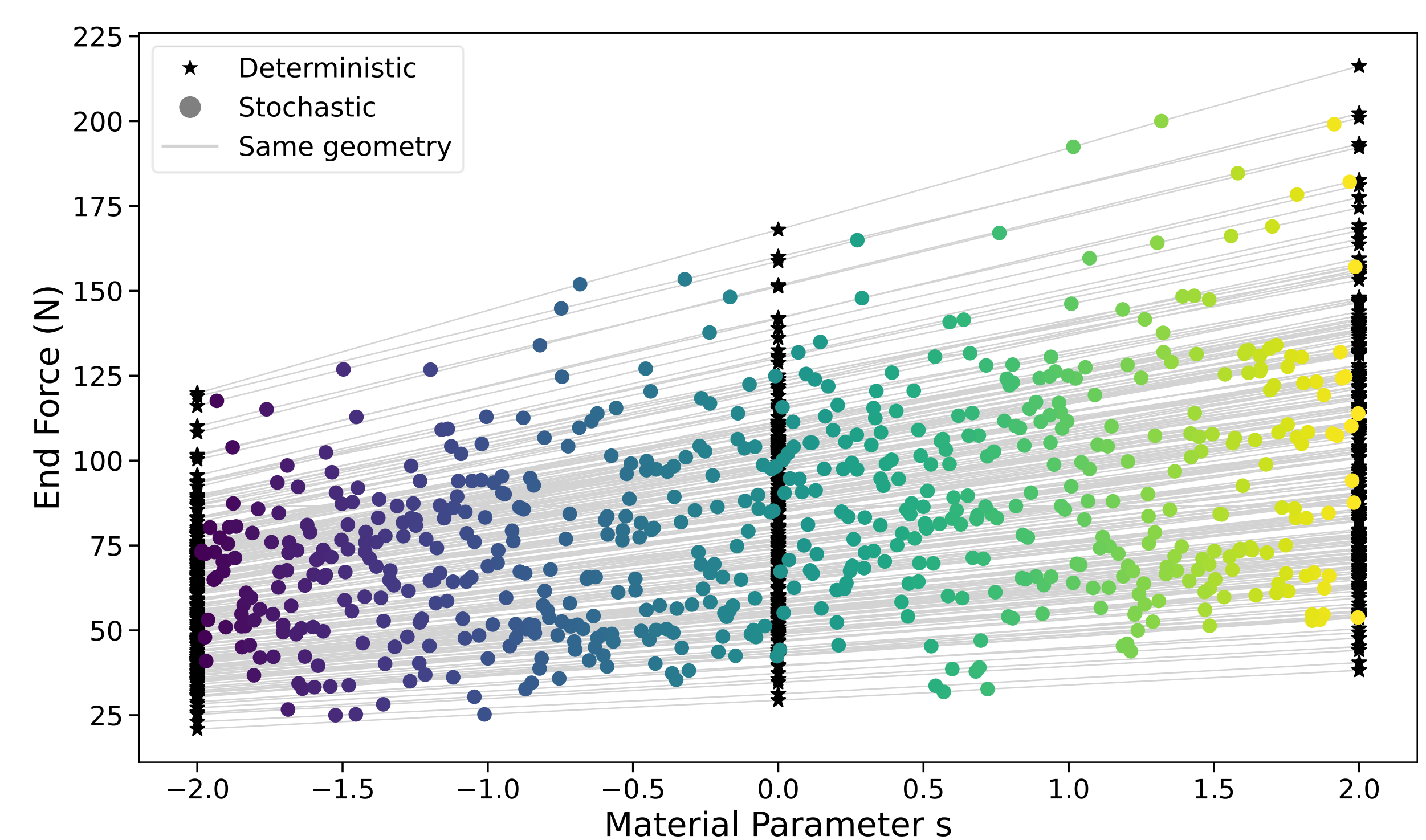


Fig. 5. Change of end force due to geometric and material variability.

Discussion

- Each corridor in the deterministic case (Fig. 2) represents the geometric variability, which alone has a considerable effect on the force, e.g., with average material properties ($s=0$, Fig. 2), the end forces lie in the range of 29 to 168 N. This highlights the importance of geometry representation of ribs in HBMs and possible effects when morphing.
- An increase in the parameter s , and consequently in material stiffness, raises the average force and widens the corridor (Fig. 4, left). This shows that geometric effects are amplified at higher material properties and suggests that the sensitivity to geometry may be better explored in stiffer material configurations, e.g., in a population subsample of young adults.
- In the stochastic case, corridors reflect combined geometric and material variability. Despite differences in individual curves across realizations (Fig. 3), the corridors coincide (Fig. 4, right), suggesting that for population-level rib mechanics, knowing the distribution of material parameters matters more than identifying subject-specific material properties.
- Each geometry stiffens at a different rate with increasing s (Fig. 5), suggesting that material response relationships from one geometry cannot be directly transferred or scaled to another.
- Limitations: constant cortical bone thickness (1 mm) and the trabecular bone properties ($s=0$, [5]). Simulation end time was set to the experimental fracture time of the corresponding rib geometry.

Conclusions

- Cortical bone properties modify the force-displacement average and corridor width.
- Increasing material stiffness amplifies the effect of geometric variability on the structural response.
- Population-level corridors are governed by the material property distribution rather than by subject-specific material assignment.

References

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