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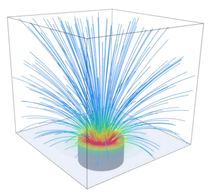
An Individual-Based Computational Framework for Magnetic Biofabrication Using Tissue Spheroids



Introduction

This work investigates magnetic biofabrication (MBF) and the effects of magnetic stimulation on the mechanical properties of tissue constructs derived from human periosteum-derived stem cells (hPDCs). MBF is a promising technique due to its speed, scalability, remote controllability, and the added benefit of external stimulation during tissue assembly. However, precise control over the process remains a challenge. To address this, we developed a mechanistic model that predicts the morphology and mechanical behavior of tissue constructs formed by magnetized spheroids. The model captures the assembly of spheroids under magnetic influence, offering insight into how magnetic forces shape tissue structure and properties.

Individual-based model



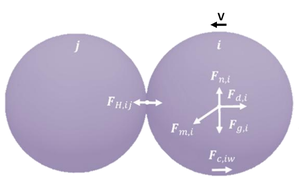
In tissue constructs made with MBF, large magnetic forces influence the spheroids. These forces, given by:

$$\boldsymbol{F}_{mag} = N_{NP}\mu_0 V_{NP} f(|\boldsymbol{H}|)(\boldsymbol{H} \cdot \boldsymbol{\nabla})\boldsymbol{H}$$

(Wirthl, et al. (2023))

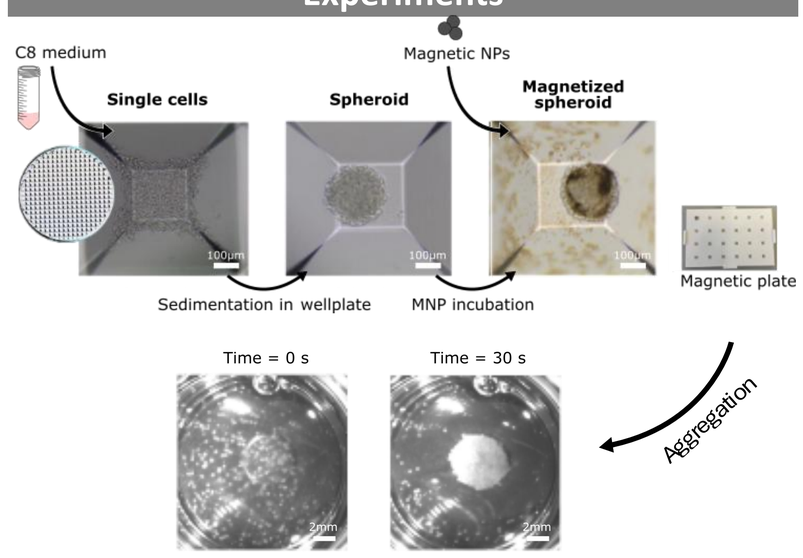
drive rapid aggregation into a single large structure and continue to act during tissue fusion. A fast timescale model to describe the tissue construct formation:

Assembly model



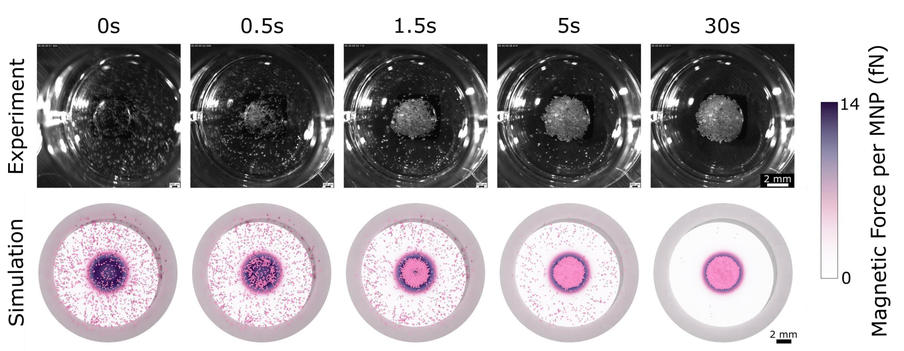
Spheroids are modeled as spherical particles that aggregate under an external magnetic force. All acting forces are combined into an equation of motion for each particle.

Experiments



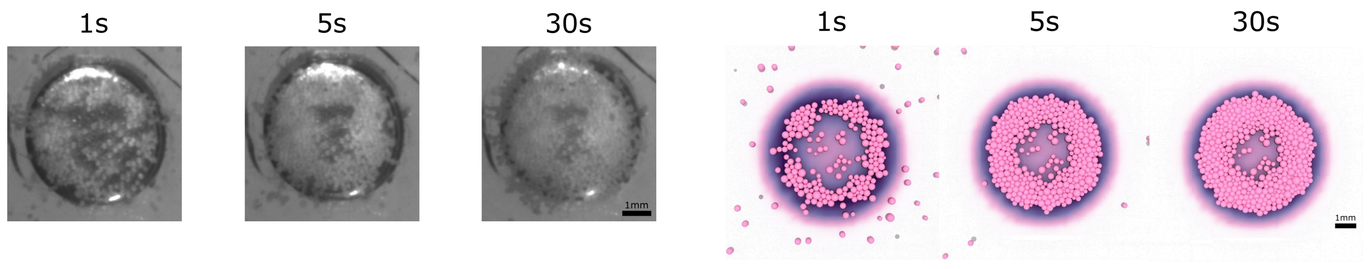
Results

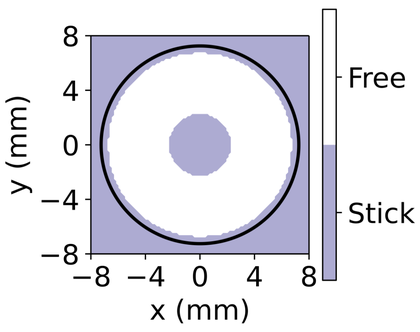
Model reproduces assembly dynamics and structure



The aggregation dynamics were modeled within the first minute after placing the spheroids in the magnetic field. Magnetic aggregation occurred almost immediately, and our model successfully predicted both the final tissue shape and the speed of spheroid aggregation.

Static friction governs ring-like aggregation patterns

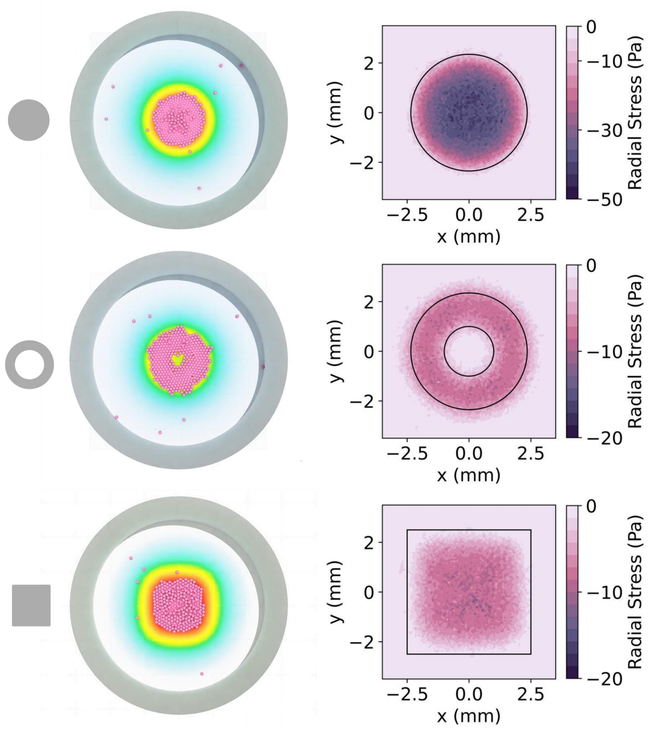




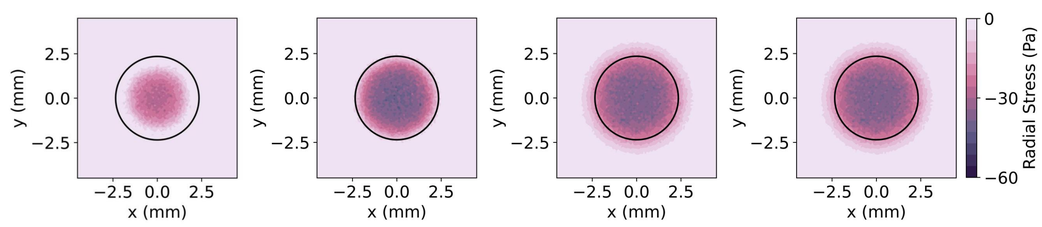
At strong magnetic forces, experiments show stable ring-shaped spheroid assemblies. Models that include only viscous friction cannot reproduce this behavior. To explain the experiments, we include surface sticking in the model. Spheroids remain arrested when the tangential magnetic force is below a threshold set by the spheroid–substrate contact area. This sticking rule allows ring-like patterns as seen in experiments. The balance between sideways and downward magnetic forces determines where spheroids can move or stay stuck on the surface. As spheroid density increases, interactions between spheroids push them inward, causing the ring to slowly move toward the center, as observed in both experiments and simulations.

Magnet geometry determines spatial stress distributions

Using the model, we predict how magnet geometry controls stress distributions and resulting aggregate shape in spheroid assemblies. Spheroids with identical MNP content are assembled above cylindrical, ring-shaped, or square magnets. For each case, the radial component of the mechanical stress is extracted. All configurations exhibit compressive stresses. Cylindrical magnets generate strongly localized central compression, ring magnets shift the stress maximum to intermediate radii, and square magnets produce a more uniform stress field. These results demonstrate that magnet geometry enables prediction and control of both stress patterns and aggregate shape in magnetic spheroid assemblies.

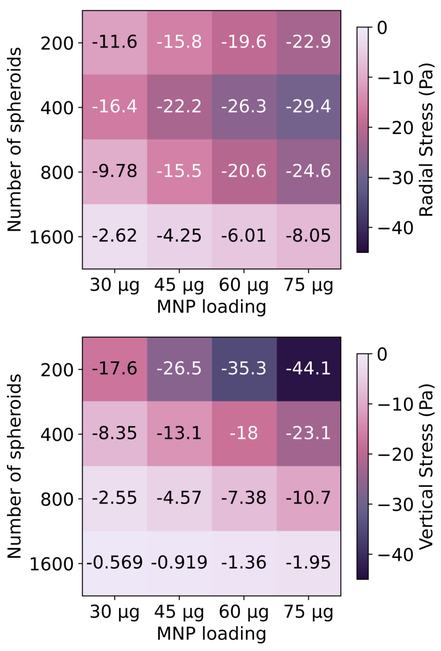


Spheroid number and loading determine stress pattern



At fixed MNP content, increasing the number of spheroids initially increases central compression due to stronger spheroid–spheroid interactions. At high spheroid numbers, this effect saturates as spheroids mainly occupy the periphery and the magnetic loading per spheroid decreases.

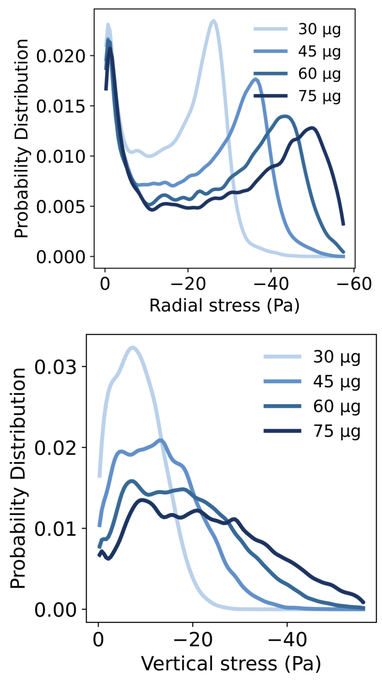
Average stress



Mean radial stress peaks at intermediate spheroid numbers, balancing collective forces and reduced magnetic loading per spheroid. Vertical stress decreases with spheroid number, as it is set by forces on individual spheroids.

Single-spheroid stress

Radial stress is bimodal, with weakly stressed spheroids at the edge and strongly compressed spheroids at the center. Vertical stress remains narrowly distributed, reflecting individual spheroid magnetic loading.



Conclusion

We show that magnetic spheroid assembly is a process that can be explained with a small number of physical interactions. By combining experiments with an individual-based model, we find that assembly dynamics are controlled by surface drag, while a finite sticking force is required to reproduce patterns such as ring-like structures. Magnetic assembly also creates non-uniform stress patterns that depend on magnet shape and spheroid number, with a clear difference between collective in-plane stresses and vertical loading on individual spheroids. Together, these results provide a predictive framework for magnetic biofabrication, allowing control over both structure and mechanical environment through magnet design and magnetic loading.

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