Fluid structure coupling simulation analysis of vibration assisted 3D bioprinting extruder

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Abstract. Aiming at the problem of high wall shear stress at the nozzle of micro extrusion biological 3D printing technology, this paper proposes a method of reducing the viscosity of biological ink through vibration, so as to reduce the shear stress and improve printing efficiency and cell vitality. The 3D bioprinting extrusion device is taken as the research object, and the influence of vibration parameters on the printing process is studied on by fluid structure coupling simulation of the extrusion device.

1. Introduction
Biological 3D printing technology has been widely used in tissue engineering and regenerative medicine, drug testing, pathological model and so on[1]. Because it can efficiently generate evenly distributed cells in the scaffold, and can load different types of cells into the required scaffold area. Compared with non biological 3D printing, due to the technical limitations related to cells or tissues, cell printing has additional complexity in the selection of cell types and biological inks. For example, high temperature is not allowed in cell printing to ensure cell viability, while melt printing is one of the most commonly used methods in non biological 3D printing. In order to meet the needs of this process, a variety of research and technology have been integrated into cell printing, including engineering, physics, cell biology, medicine and biomaterials science[2].

Biological 3D printing technology has made many breakthroughs in the past decade, but it also faces some challenges and problems. Generally speaking, high viscosity biological ink needs high pressure to print through the micro nozzle, which will produce high wall shear stress in the printing process, and this pressure will lead to low cell viability[3]. Therefore, many researchers reduce the viscosity of biological ink to ensure that sufficient cell viability is obtained[4]. In addition, some researchers have tried to reduce shear stress by using larger size nozzle to improve cell viability, although using a larger nozzle will reduce print resolution[5-7].

It is necessary to develop a 3D printing process with enough printing resolution. Based on the shear thinning characteristics of 3D printing ink, a vibration 3D bioprinting method is proposed to reduce the viscosity of printing materials, reduce shear stress, improve printing efficiency and cell vitality.

2. Analysis principle of fluid structure coupling
The flow of fluid should follow the conservation law of physics including mass and momentum. For general liquids, the conservation law can be described by the following governing equations.

Mass conservation equation:
\[ \frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot \left( \rho \mathbf{v} \mathbf{v} \right) = \mathbf{0} \]  

(1)

Momentum conservation equation:

\[ \frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot \left( \rho \mathbf{v} \mathbf{v} - \mathbf{f}_f \right) = \mathbf{f}_f \]  

(2)

where \( \mathbf{f}_f \) is the liquid volume force vector; \( \rho \) is the fluid density; \( \mathbf{f}_f \) is the fluid shear force tensor; \( \mathbf{v} \) is the time; \( \mathbf{v} \) is the velocity vector.

The conservation equation of tube structure is as follows:

\[ \frac{\partial \rho_f \mathbf{v}}{\partial t} + \nabla \cdot \left( \rho_f \mathbf{v} \mathbf{v} - \mathbf{f}_f \right) = \mathbf{f}_f \]  

(2)

where \( \rho_f \) is solid density; \( \mathbf{f}_f \) is solid volume force vector; \( \mathbf{f}_s \) is solid shear force tensor; \( \mathbf{d}_s \) is local acceleration vector of pipe structure. Fluid solid coupling follows the most basic conservation principle, and the stress and displacement of fluid and solid are equal at the interface of fluid solid coupling\[^8\]. Namely:

Displacement compatibility equation:

\[ \mathbf{d}_s = \mathbf{d}_f \]  

(3)

Force balance equation:

\[ \frac{\partial \rho_f \mathbf{v}}{\partial t} + \nabla \cdot \left( \rho_f \mathbf{v} \mathbf{v} - \mathbf{f}_f \right) = \mathbf{f}_f \]  

(4)

where \( \mathbf{d}_s \) is the displacement of solid; \( \mathbf{d}_f \) is the displacement of fluid; \( n_f \) is the node number of fluid; \( \mathbf{f}_s \) is the shear force vector of solid; \( n_s \) is the node number of solid. In this paper, the pipeline vibration induced fluid vibration is studied, and the calculation results of fluid analysis are transferred to the structural equation through the fluid structure coupling surface by using the bidirectional fluid structure coupling method.

3. Finite element analysis of fluid structure coupling in vibration

3.1 Parameter selection simulation

The finite element model of 3D bioprinting extrusion nozzle was established by using the finite element software ANSYS Workbench. The needle tube was selected as the research object. The geometric model of the needle tube was shown in figure 1. The inner diameter of the pipe was 15mm, the outlet diameter was 0.2mm, the wall thickness was 1.5mm, and the material was steel. Common alginate hydrogels were selected for printing materials. The flow field inside the needle tube and the needle tube was taken as the simulation analysis model.

- Hydrogel materials are incompressible non-Newtonian fluids.
- In the extrusion process, there is no steady laminar flow without wall slip, and there is no velocity between the radial direction of the fluid.
- In the extrusion process, the flow velocity is slow and the influence of inertia force and gravity force is ignored.
- Due to the high viscosity of the material, there is no relative slip between the solution and the channel wall.

Hydrogel ink is generally not a Newton fluid. For non-Newton fluids, it can be expressed in the equation (5):

\[ \tau = \eta \dot{\gamma} = K \dot{\gamma}^n \]  

(5)

where \( \eta \) and \( \dot{\gamma} \) are viscosity and shear rate respectively, \( K \) is the consistency coefficient, which is a measure of viscosity, but not equal to the viscosity value. The higher the viscosity is, the higher the K.
value is, and \( N \) is the liquidity index. In this paper, sodium alginate solution is used as the fluid material. The flow length model size and material parameters are shown in the table 1.

Table 1. Flow field model size and material parameters.

| Material density(\( \rho \)) | Consistency coefficient(\( K \)) | Flow index(\( n \)) | Temperature(\( T \)) |
|-------------------------------|---------------------------------|--------------------|---------------------|
| 1030 kg/m\(^3\)              | 6 Pa\( \cdot \)s\(^n\)         | 0.84               | 25℃                 |

In order to simply observe the effect of nozzle vibration conditions on wall shear stress, the relationship between vibration and wall shear stress can be estimated. The relationship between wall shear stress and nozzle pressure drop is known\(^9\):

\[
\tau_w = \frac{D \cdot \Delta P}{4L}
\]  

(6)

Where \( D \) is the diameter of the nozzle, \( L \) is the length of the nozzle, and \( \Delta P \) is the pressure drop along the nozzle. The pressure drop along the nozzle is obtained through the simulation analysis, and it is taken into equation (6) to calculate the shear force at the nozzle. The normal extrusion process in the printing process is simulated. The pressure distribution in the needle tube is shown in figure 2, it can be calculated that the pressure difference between the nozzle section and the outlet is 686045Pa, and the shear force is 2638.6Pa.

3.2. Simulation analysis of fluid structure coupling

Radial sinusoidal excitation is applied to the needle, the parameters range of the simulation analysis is shown in table 2. The pressure difference between the inlet and outlet of the nozzle under different vibration conditions is obtained through simulation, and the relationship between the pressure...
difference and time is obtained by monitoring under 500Hz, 20μm dynamic conditions, as shown in figure 3. When the pressure is stable, the pressure difference changes periodically with the vibration frequency. When calculating the shear force, the maximum value of the stable pressure difference is substituted into equation (6).

Table 2. vibration conditions for amplitudes and frequencies

| Amplitude(μm) | Frequency (Hz) |
|---------------|----------------|
| 5             | 500 1000 1500 2000 |
| 10            | 500 1000 1500 2000 |
| 20            | 500 1000 1500 2000 |

Figure 3. The pressure difference at the nozzle changes with time.

Figure 4. Shear force change diagram under different vibration conditions.
4. Conclusion
Based on the shear thinning characteristics of bioink, sinusoidal vibration excitation is applied to the extruded needle tube. Through the simulation analysis of the fluid pressure distribution in the needle tube during the extrusion process, results showed that the increase of frequency and amplitude can lead to the decrease of shear force at the nozzle. When the radial sinusoidal vibration with a parameter of 20 µm and 1500Hz is applied, the influence on the shear force of the fluid flowing through the nozzle is the biggest, and at this time, the shear force is reduced by 220Pa, which can effectively increase the cell survival rate.

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