Mechatronic Investigation of Wound Healing Process by Using Micro Robot

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Abstract—The purpose of this study is to find ideal forces for reducing cell stress in wound healing process by micro robots. Because of this aim, we made two simulations on COMSOL® Multiphysics with micro robot to find correct force. As a result of these simulation, we created force curves to obtain the minimum force and friction force that could lift the cells from the surface will be determined. As the potential of the system for two micro robots that have 2 mm x 0.25 mm x 0.4 mm dimension SU-8 body with 3 NdFeB that have 0.25 thickness and diameter, simulation results at maximum force in the x-axis calculated with 4.640 mN, the distance between the two robots is 150 µm. The aim of this study is to present the force curves created with the help of micro robots to find correct forces for the experimental and control groups. Thus, the minimum force that can lift the cells from the surface will be determined. Moreover, theoretical background of wound healing processes, chemical, physical or biological parameters should be tested for their ability to induce or inhibit the endothelial cell migration.

Cell migration is affected by many intracellular pathways and extracellular stimuli such as growth factors, mechanical stress, and chemical interactions [5]. It has been demonstrated in many studies that dynamic cell cultures present in vivo environment in more detail. As a result, dynamic cell cultures, especially those integrated into microfluidic chips, exhibit more natural properties than cultures within microfluidic chips. Micro robots that used in healthcare need to perform their tasks in fluid environments with low Reynolds number [6]. Because of their sizes, they tend to face high friction forces and inertia when operating in these environments. It is possible to transmit power to the micro robot via wireless network, instead of the micro robot working with little or no power storage [7].

We have two issues in the present study case. Firstly, the cellular studies want standardization for micro robotic wounding dimension. The methods that used for scratching cells have different variations and these methods could give some different micro robotic wounding dimensions. In the other hand, these problem can solved many methods like laser applications. However, applications of these methods give another problem that stressed cells. The stress effect can be minimized by creating a uniform wound of equal diameter and correct forces for the experimental and control groups. Thus, the effect of the medicines on the rate of recovery will be interpreted more accurately.

The aim of this study is to present the force curves created by the base micro robot on the wounding micro robot. The curves are calculated according to the distance between these robots. The magnitude of the force required to micro robotic wounding will be obtained with a simulation-based force curve. Thus, the minimum force that can lift the cells from the surface will be determined.
The simulation was added the mathematical model. This technique for such applications lies in the standardized wound healing model capable of generating various wound shapes with uniform widths within microfluidic chip platform. With the method examined in this study, standardized wound models that can be used in different cell biology studies can be realized.

II. MATHEMATICAL MODEL

In this section, the mathematical model for the creating wound by using the micro robot subject to the liquid environment is presented. The micro robot contains 3 NdFeB (neodymium) cylindrical-shaped permanent magnets with a 0.25 mm diameter and 0.25 mm thickness and is manipulated diamagnetically. The major parameters of the system are shown in Table I.

| Symbol | Parameter                      | Unit       |
|--------|--------------------------------|------------|
| F_B    | Buoyancy Force                 | N          |
| F_M    | Magnetic Force                 | N          |
| F_G    | Gravitational Force            | N          |
| F_E    | Electrostatic Force            | N          |
| F_A    | Adhesive Force                 | N          |
| F_D    | Drag Force                     | N          |
| N      | Reaction Normal Force          | N          |
| Re     | Reynolds Number                | -          |
| A      | Cross-Sectional Area           | m²         |
| μ_r    | Magnetic Permeability of Space |           |
| μ_o    | Magnetic Conductivity Number   | Wh/Am      |
| H      | Magnetic Field                 | A/m        |
| M_dia  | Magnetization Vector           | A/m        |
| χ      | Magnetic Susceptibility Factor |           |
| B      | Magnetic Flux Density          | T          |

The continuity equation is written in Eq. 1 for incompressible flows along the channel:

$$\nabla \cdot \mathbf{u} = 0$$  \hspace{1cm} (1)

The Reynolds Number is expressed in Eq. 2 [8].

$$R_e = \frac{\rho \cdot v \cdot D_h}{\mu}$$  \hspace{1cm} (2)

The momentum equation is described as [9]:

$$\rho \frac{\partial \mathbf{u}}{\partial t} = -\nabla P + \rho \mathbf{g} + \eta \nabla^2 \mathbf{u} + \mathbf{F}_M$$  \hspace{1cm} (3)

In this equation, \( \rho \) is density, \( \mathbf{v} \) is flow velocity, \( \mu \) is viscosity \( P \) is pressure. The force that is produced by magnet on the micro-robot is applied in the channel and affected force is given in Eq. 4.

$$d\mathbf{F} = \mu_0 \nabla (\mathbf{M} \cdot \mathbf{H})$$  \hspace{1cm} (4)

The magnetization of the magnet is \( \mathbf{M} \), and the magnetic field strength is \( \mathbf{H} \) in this formula. On the micro-robot, the total magnetic force is expressed in Eq. 5.

$$\mathbf{F}_m = \int_V d\mathbf{F} dV$$  \hspace{1cm} (5)

The forces in cylindrical coordinates are written as respectively Eq. 6, 7, 8:

$$\mathbf{F}_z = \int_V d\mathbf{F}_z - \mu_0 \int_V \frac{\partial}{\partial z} (M_0 H_z) (Z \ axis)$$  \hspace{1cm} (6)

$$\mathbf{F}_y = \int_V d\mathbf{F}_y - \mu_0 \int_V \frac{\partial}{\partial y} (M_0 H_z) (Y \ axis)$$  \hspace{1cm} (7)

$$\mathbf{F}_x = \int_V d\mathbf{F}_x - \mu_0 \int_V \frac{\partial}{\partial x} (M_0 H_z) (X \ axis)$$  \hspace{1cm} (8)

The force calculation in cylindrical coordinates is made with the uniform medium assumption. Consequently, the diamagnetic force is defined in Eq. 9.

$$d\mathbf{F} = M_{dia} (\nabla \mathbf{B}) dV$$  \hspace{1cm} (9)

The diamagnetic force in x, y, z axis are as follows [10]:

$$F_{dia,x} = \frac{X_{dia}}{2\mu_0} \int_S \int_S \int_S \left( \frac{\partial |B|^2}{\partial x} \right) dV$$  \hspace{1cm} (10)

$$F_{dia,y} = \frac{X_{dia}}{2\mu_0} \int_S \int_S \int_S \left( \frac{\partial |B|^2}{\partial y} \right) dV$$  \hspace{1cm} (11)

$$F_{dia,z} = \frac{X_{dia}}{2\mu_0} \int_S \int_S \int_S \left( \frac{\partial |B|^2}{\partial z} \right) dV$$  \hspace{1cm} (12)

According to Ostrogradsky’s divergence law, the diamagnetic forces can be simplified, and they describes as [11]:

$$F_{dia,x} = \frac{\chi_d}{\mu_0} \int_S |B|^2 n_x ds$$  \hspace{1cm} (13)

$$F_{dia,y} = \frac{\chi_d}{\mu_0} \int_S |B|^2 n_y ds$$  \hspace{1cm} (14)

$$F_{dia,z} = \frac{\chi_d}{\mu_0} \int_S |B|^2 n_z ds$$  \hspace{1cm} (15)

Buoyancy force, drag force, commonly known as non-gravitational forces, and gravitational force affect the micro-magnet of the micro-robot and are defined as:

$$F_G = m_m g$$  \hspace{1cm} (16)

$$F_B = V_m \rho f g$$  \hspace{1cm} (17)

$$F_D = \frac{1}{2} \rho_d f A v^2$$  \hspace{1cm} (18)
\( m_m, V_m, \rho_f \) and \( C_d \) are the micro-magnet mass, volume, fluid density, and drag coefficient, respectively. The drag force coefficient function can be stated as [12]:

\[
C_d = \frac{24}{Re} \left( 1 + \frac{Re^{2/3}}{6} \right)
\]  

(19)

Affected other forces on micro robot that are electro-static force, adhesive force, reaction normal force and friction force. The net force in x axis is sum of x component of magnetic force, friction force and drag force in Eq. 21. The net force in z axis is sum of reaction normal force, z component of magnetic force, adhesive force, buoyancy force, electro-static force and gravitational force in Eq. 20.

\[
F_{net,z} = N + F_{M,z} + F_A - F_G - F_{ES} - F_B
\]  

(20)

\[
F_{net,x} = F_{M,x} - F_f - F_D
\]  

(21)

III. SIMULATION RESULTS

Two analyzes were carried out with the COMSOL® Multi-physics Version 5.3 (CPU License No: 17076072), which is one of the finite element analysis programs, in order to determine the forces applied by the micro robots to each other during the wound opening process and to calculate the friction force. SU-8 is selected as the micro robot body. The characteristics of the two analyzes are shown in Table II.

| Parameter          | Electromagnetic Force | Friction Force |
|--------------------|-----------------------|----------------|
| Study Type         | Stationary            | Time-Dependent |
| Length             | 500 \( \mu \)m        | 1 second       |
| Step               | 10 \( \mu \)m         | 0.01 second    |
| Physics            | mfnc                  | spf - solid - fsip |

A. Electromagnetic Force Analysis

In the first analysis, the analysis was performed by increasing the distance along the x-axis between the centerline of robots with 10 micrometers. The analysis was repeated with parametric sweep until the distance 500 micrometers with 10 micrometer steps. The analysis environment is shown in Fig. 1. Magnetic fields, no currents (mfnc) physics are used with a stationary analysis. The electromagnetic forces between the base robot and the wounding robot are calculated, and the forces in the x and z axes are shown in Fig. 2 and 3, respectively. It has seen the highest value of 4.64 mN among robots with an offset of 150 \( \mu \)m in the x-axis. At a distance of 150 \( \mu \)m between two robots, the electromagnetic force of 5.5 mN occurs in the z direction. Since there is displacement between the robots in x-axis and they stabilize each other in the z-axis, there is no significant relationship in the y-axis. However, since 3 magnets are used in line and symmetrically for the xz plane, the pitch moment cannot be produced. Thanks to this analysis, the offset value between them will be able to be determined depending on the force required to scratch the cell line from the surface in wound healing models.

B. Friction Force Analysis

In this study, manipulation in this technique is provided by magnetic interaction in the robot configuration. Unlike, other robot studies that interact with the magnetic field. However, the manipulated robot moves by scraping the surface without being levitated here, as it will perform the surface scraping function. Due to the nonlinear nature of the magnetic field, the electromagnetic force acting on the manipulated robot will not be uniform over time. Therefore, the friction coefficient between the SU-8 body and the glass was chosen as 0.05. Stationary analysis was performed to obtain the initial conditions of the analysis. The geometry of friction analysis was designed that simulates the movement of the robot inside the microchip. The overview of the analysis and the image of the velocity
magnitude after the initial conditions are shown in Fig. 1. The time-dependent analysis of 1 second was performed with 0.01 second steps. The movement speed of the robot on the surface was chosen as 0.005 m/s. As can be seen from the analysis result, the maximum static friction force is 1.32 nN for the SU-8 robot with the size of 2 mm x 0.25 mm x 0.4 mm.

As a result of the analyses, the value that is maximum static friction force in the friction analysis can be obtained at which offset value in the electromagnetic force analysis. The value corresponding to that point in electromagnetic force analysis is the distance between the wounding robot and the base robot. In addition, when the lifting forces of the cells to be used in the wound creating process are added, the distance values that should be between the robots can be calculated from electromagnetic analysis.

IV. CONCLUSION

This study demonstrated the required distance between robots for a micro robotic wound opening technique using 3 NdFeB cylindrical shaped permanent magnets with 0.25 mm diameter and 0.25 mm thickness and SU-8 as the body material. The electromagnetic analysis shows electromagnetic forces depending on the distance between the robots. The system can produce a maximum electromagnetic force of 4.64 mN along the x-axis. The graph of the friction force generated by the surface without cells is also shown for a robot with body dimensions of 2 mm x 0.25 mm x 0.4 mm. The friction force and the required force to lift the cells from the surface used in a system allow us to calculate the minimum distance between the robots. In addition to this, the electromagnetic and friction force graphs shows boundaries of the system. By using these graphs, the ideal distance between robots can be obtained experimentally to lift the cells from the surface with the least stress for ideal wound generating process. In future studies, the electromagnetic and friction force graphs for the dynamic cell environment can be studied with the analysis of micro robots in the flow.

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