In this paper, the non-contact control of magnetic implants by changing the external magnetic field in the magnetic stereotaxic system is introduced, and the feasibility of making them move along the arc trajectory is analyzed. Through COMSOL software, the process of moving the miniature magnetic implant along the arc trajectory is simulated, the change of the micro-magnetic implant trajectory after the external magnetic field was changed, the relative position relationship between the large permanent magnets was determined, and the mechanical analysis of the miniature magnetic implant moving along the arc trajectory was carried out. In this experiment, we fix a large permanent magnet, only move the second permanent magnet, first, observe the process of small permanent magnets moving along a straight trajectory, determine the position of the large permanent magnet magnetic field when it contacts the small permanent magnet, and then, analyze the force of the small permanent magnet through the force calculation module, and determine the relative position relationship between the two large permanent magnets by comparing $F_x$ and $F_y$, and when the small permanent magnet will start to move along the arc trajectory. Then, according to the previous data, we move two adjacent large permanent magnets at the same time at a certain interval, record the movement trajectory of the small magnet, finally, with the force calculation module of the COMSOL software, force analysis of small permanent magnets moving along arc trajectories. The data from this experiment will be used to determine the relative position relationship between two large permanent magnets adjacent to each other during the actual experiment, and under what conditions the small permanent magnets will move along the arc trajectory. The purpose of this experiment is to provide theoretical and data support for the subsequent practical experiments of the magnetic stereotactic system, and all parameters in the COMSOL software are derived from the actual measurement data, so as to improve the reliability of the simulation results.

**Keywords:** Human health; Magnetic field; COMSOL Software; Permanent magnets; Force analysis.
**Computer simulation experiments**

**Experimental Objective**

To control the miniature magnetic implant non-contact by the magnetic stereotaxic system to make it move along the arc trajectory.

**Experimental design**

Establish a coordinate system in 3D space, small cylindrical permanent magnets are located in the center of the coordinate system, large permanent magnets are set on the +X and +Y axes, parameters are set in the simulation software according to the experimental material data, and geometric models are constructed.

Simulation experiment parameter settings

1. \( d_{ion} = 100 \text{mm} = 0.1 \text{m} \) (Large permanent magnet diameter);
2. \( t_{ion} = 10 \text{mm} = 0.01 \text{m} \) (Large permanent magnet thickness);
3. \( d_{NFB} = 1 \text{mm} = 0.001 \text{m} \) (Small permanent magnet diameter);
4. \( l_{NFB} = 2 \text{mm} = 0.002 \text{m} \) (Small permanent magnet thickness);
5. The small permanent magnet boundary is limited to a cylinder with a radius of 0.1 [m] and a height of 0.5 [m];
6. Large permanent magnets have a maximum distance of 0.41 [m] from the center of 3D space and a closest distance of 0.11 [m], the movable distance of large permanent magnets is 0.3 [m].

**Simulation experiment material property settings**

Permanent magnets:

1. Conductivity \( \sigma = 1/1.4 \text{[uohm}\times\text{m}] = 0.71\text{[S/m]} \);
2. Relative permittivity \( \varepsilon_r = 1 \) [1];
3. Recovery permeability \( \mu_{rel} = 1.02 \);
4. Residual flux density norm \( B_{res} = 1.3 \text{[T]} \);

Air:

1. Conductivity \( \sigma = 0 \text{[uohm}\times\text{m}] = 0 \text{[S/m]} \);
2. Relative permittivity \( \varepsilon_r = 1 \) [1];
3. Recovery permeability \( \mu_{rel} = 1 \).

In this simulation experiment, the external magnetic field of the magnetic stereotaxic system is composed of four large permanent magnets [12, 13], and the small permanent magnets simulate implants. Computer simulation software chooses COMSOL 6.0 [14–16].
All the above parameters are theoretical parameters and can be set according to the material parameters required for actual experiments.

Depending on the parameter settings, create a geometric model in 3D space:

![Geometric model](image)

**Fig. 3. Geometric models based on parameters in COMSOL software**

**Equations and formulas for simulation experiments**

In this simulation experiment, the external magnetic field of the magnetic stereoscopic positioning system is composed of large permanent magnets, and the magnetic field of the permanent magnets is a static magnetic field. Therefore, "magnetic field, no current (MFNC)" was selected in the COMSOL physics.

In the constitutive relations \( B-H \), the magnetization model [17] needs to introduce the magnetization vector field \( M \), and the magnetic field strength \( H \), which are expressed as:

\[
H = \frac{B}{\mu_0} - M
\]

or:

\[
B = \mu_0 (H + M),
\]

where \( \mu_0 \) is the magnetic permeability; \( B \) is Magnetic flux density.

The remaining flux density is then selected in the magnetization model with the following expression:

\[
B = \mu_0 \mu_{rec} H + B_r ;
\]

\[
B_r = \|B_r\| e,
\]

where \( B \) is the magnetic flux density; \( \mu_0 \) is the vacuum permeability; \( \mu_{rec} \) is recoil permeability; \( B_r \) is residual flux density; \( \|B_r\| \) is residual flux density norm; \( e \) is residual flux direction.

**Simulation results**

The large permanent magnet located on the \( +X \) axis begins to move towards the center position. When the first large permanent magnet is 0.36 \([\text{m}]\) from the center position, its magnetic field gradually touches the small permanent magnet.

![Simulation result](image)

**Fig. 4. The magnetic field of a large permanent magnet gradually touches the small permanent magnet**
When its magnetic field touches a small permanent magnet, the small permanent magnet begins to approach the first large permanent magnet.

When the small permanent magnet moves to the boundary position, it is blocked by the boundary and stays on the boundary.

The first large permanent magnet began to move away, and the second large permanent magnet gradually approached, at this time, the magnetic field lines around the small permanent magnet could be clearly seen, but the same simulation software could not intuitively see that the magnetic field of the second large permanent magnet touched the small permanent magnet.

To study the movement of small permanent magnets along arc trajectories under non-contact control, therefore, we use the "Force Calculation" module included in the software to analyze the force of small permanent magnets located at boundary locations. The distance between the first large permanent magnet and the center is $\text{dis}_{ion}$, the distance of the second large permanent magnet from the center is $\text{dis}_{ion1}$, $F_x$ is the $X$-axis component of the force experienced by the small permanent magnet, and $F_y$ is the on-$Y$-axis component of the force experienced by the small permanent magnet.

First, let's assume that the first large permanent magnet stays 0.22 [m] from the center and only the second large permanent magnet is running.

Table 1. Force analysis of a small permanent magnet at the boundary position when the position of the first large permanent magnet remains unchanged and the second large permanent magnet gradually approaches the center position

<table>
<thead>
<tr>
<th>$\text{dis}_{ion}$ [m]</th>
<th>$\text{dis}_{ion1}$ [m]</th>
<th>$F_x$ [N]</th>
<th>$F_y$ [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.22</td>
<td>0.24</td>
<td>$7.199 \times 10^{-9}$</td>
<td>$5.408 \times 10^{-9}$</td>
</tr>
<tr>
<td>0.22</td>
<td>0.23</td>
<td>$7.916 \times 10^{-9}$</td>
<td>$6.877 \times 10^{-9}$</td>
</tr>
<tr>
<td>0.22</td>
<td>0.22</td>
<td>$8.715 \times 10^{-9}$</td>
<td>$8.561 \times 10^{-9}$</td>
</tr>
<tr>
<td>0.22</td>
<td>0.21</td>
<td>$9.883 \times 10^{-9}$</td>
<td>$11.541 \times 10^{-9}$</td>
</tr>
<tr>
<td>0.22</td>
<td>0.20</td>
<td>$11.180 \times 10^{-9}$</td>
<td>$15.123 \times 10^{-9}$</td>
</tr>
<tr>
<td>0.22</td>
<td>0.19</td>
<td>$12.598 \times 10^{-9}$</td>
<td>$19.332 \times 10^{-9}$</td>
</tr>
<tr>
<td>0.22</td>
<td>0.18</td>
<td>$14.321 \times 10^{-9}$</td>
<td>$26.112 \times 10^{-9}$</td>
</tr>
</tbody>
</table>

From the above table, we find that when the distance from the second large permanent magnet to the center position is less than the distance from the first large permanent magnet to the center position, the $Y$-axis component of the force of the small permanent magnet is greater than the $X$-axis component. That is, when $\text{dis}_{ion1} < \text{dis}_{ion}$, $F_y > F_x$. To verify this result, we set the first large permanent magnet to be located 0.18 [m] from the center and re-analyzed the force on the small permanent magnet.
According to Table 1 and Table 2, we can clearly see that when the distance from the first large permanent magnet to the center position is greater than the distance from the second large permanent magnet to the center position, the force on the $Y$ axis of the small permanent magnet is greater than the component force on the $X$ axis, that is, when $\text{dis} \_\text{ion1} < \text{dis} \_\text{ion} \; , \; F_x < F_y \; .$

In order to facilitate practical experiments, we set the distance from the first large permanent magnet to the center position and the distance from the second large permanent magnet to the center position to be 0.05 [m], that is, when the first large permanent magnet begins to move 0.05 [m] to the center position, the second large permanent magnet begins to approach the center position, and the two large permanent magnets move at the same speed.

During the movement of the two large permanent magnets, we perform a force analysis on the small permanent magnets again. In order to determine the position of the two large permanent magnets when the small permanent magnet initially moves, the position of the small permanent magnet does not change during the analysis, and always stays at the boundary position. It can be determined that when the first large permanent magnet is closest to the center, the small permanent magnet is affected by its magnetic field and stays at the boundary position on the $+X$ axis, so the initial positions of the two large permanent magnets are $\text{dis} \_\text{ion} = 0.11 \text{[m]} \; , \; \text{dis} \_\text{ion1} = 0.16 \text{[m]} \; , \; \text{respectively.}$

<table>
<thead>
<tr>
<th>$\text{dis} _\text{ion} \text{[m]}$</th>
<th>$\text{dis} _\text{ion1} \text{[m]}$</th>
<th>$F_x \text{[N]}$</th>
<th>$F_y \text{[N]}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.18</td>
<td>0.21</td>
<td>22.726×10$^{-9}$</td>
<td>13.959×10$^{-9}$</td>
</tr>
<tr>
<td>0.18</td>
<td>0.20</td>
<td>24.941×10$^{-9}$</td>
<td>17.814×10$^{-9}$</td>
</tr>
<tr>
<td>0.18</td>
<td>0.19</td>
<td>27.614×10$^{-9}$</td>
<td>23.142×10$^{-9}$</td>
</tr>
<tr>
<td>0.18</td>
<td>0.18</td>
<td>31.381×10$^{-9}$</td>
<td>31.143×10$^{-9}$</td>
</tr>
<tr>
<td>0.18</td>
<td>0.17</td>
<td>35.683×10$^{-9}$</td>
<td>41.613×10$^{-9}$</td>
</tr>
<tr>
<td>0.18</td>
<td>0.16</td>
<td>40.918×10$^{-9}$</td>
<td>56.554×10$^{-9}$</td>
</tr>
<tr>
<td>0.18</td>
<td>0.15</td>
<td>48.237×10$^{-9}$</td>
<td>81.361×10$^{-9}$</td>
</tr>
</tbody>
</table>

It can be clearly seen from Table 3 that when the first large permanent magnet begins to gradually move away, the second large permanent magnet gradually approaches, $F_x$ gradually decreases, $F_y$ gradually increases, when the second large permanent magnet moves 0.11 [m] from the center position, $F_y$ reaches the maximum, and then the second large permanent magnet begins to gradually move away and $F_y$ gradually decreases. Thus, when the distance from the second large permanent magnet to the center position is less than the distance from the first large permanent magnet to the central position, that is, when $\text{dis} \_\text{ion1} < \text{dis} \_\text{ion} \; , \; F_x < F_y \; , \; \text{at which point the small permanent magnet begins to move along the boundary towards the second large permanent magnet.}$

<table>
<thead>
<tr>
<th>$\text{dis} _\text{ion} \text{[m]}$</th>
<th>$\text{dis} _\text{ion1} \text{[m]}$</th>
<th>$F_x \text{[N]}$</th>
<th>$F_y \text{[N]}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.11</td>
<td>0.16</td>
<td>443.82×10$^{-9}$</td>
<td>97.217×10$^{-9}$</td>
</tr>
<tr>
<td>0.12</td>
<td>0.15</td>
<td>234.78×10$^{-9}$</td>
<td>120.96×10$^{-9}$</td>
</tr>
<tr>
<td>0.13</td>
<td>0.14</td>
<td>188.50×10$^{-9}$</td>
<td>148.66×10$^{-9}$</td>
</tr>
<tr>
<td>0.14</td>
<td>0.13</td>
<td>167.14×10$^{-9}$</td>
<td>202.43×10$^{-9}$</td>
</tr>
<tr>
<td>0.15</td>
<td>0.12</td>
<td>157.48×10$^{-9}$</td>
<td>289.53×10$^{-9}$</td>
</tr>
<tr>
<td>0.16</td>
<td>0.11</td>
<td>152.98×10$^{-9}$</td>
<td>442.38×10$^{-9}$</td>
</tr>
<tr>
<td>0.17</td>
<td>0.12</td>
<td>100.73×10$^{-9}$</td>
<td>270.51×10$^{-9}$</td>
</tr>
<tr>
<td>0.18</td>
<td>0.13</td>
<td>67.94×10$^{-9}$</td>
<td>176.42×10$^{-9}$</td>
</tr>
<tr>
<td>0.19</td>
<td>0.14</td>
<td>46.69×10$^{-9}$</td>
<td>115.81×10$^{-9}$</td>
</tr>
<tr>
<td>0.20</td>
<td>0.15</td>
<td>32.37×10$^{-9}$</td>
<td>75.34×10$^{-9}$</td>
</tr>
<tr>
<td>0.21</td>
<td>0.16</td>
<td>22.83×10$^{-9}$</td>
<td>52.09×10$^{-9}$</td>
</tr>
</tbody>
</table>
The small permanent magnet begins to move along the boundary towards the second large permanent magnet.

The closer to the second large permanent magnet, the greater the influence of its magnetic field on the small permanent magnet, that is, the greater the $F_y$, but at this time the small permanent magnet is still affected by the magnetic field of the first large permanent magnet, that is, $F_x$ gradually decreases, which makes the small permanent magnet move along the boundary to the second large permanent magnet.

The small permanent magnet is captured by the magnetic field of the second large permanent magnet and stays on the boundary of the $+Y$ axis. That is, when the second large permanent magnet is closest to the center, i.e., $dis_{ion} = 0.11 [m]$, the small permanent magnet has moved to the boundary position along the arc trajectory.

As the two large permanent magnets move away, the small permanent magnets remain at the boundary position. In order to determine the average velocity of a small permanent magnet moving along an arc trajectory towards a second large permanent magnet, we need...
to perform a force analysis on the movement of the small permanent magnet. $n$ is the angle of the arc trajectory of the small permanent magnet moving along the boundary.

Table 4. Force analysis during the movement of small permanent magnets

<table>
<thead>
<tr>
<th>$\text{dis _ion [m]}$</th>
<th>$\text{dis _ion1 [m]}$</th>
<th>$n$</th>
<th>$F_x [N]$</th>
<th>$F_y [N]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.130</td>
<td>0.140</td>
<td>0</td>
<td>188.50 $\times 10^{-9}$</td>
<td>148.66 $\times 10^{-9}$</td>
</tr>
<tr>
<td>0.135</td>
<td>0.135</td>
<td>15</td>
<td>176.37 $\times 10^{-9}$</td>
<td>172.81 $\times 10^{-9}$</td>
</tr>
<tr>
<td>0.140</td>
<td>0.130</td>
<td>30</td>
<td>167.14 $\times 10^{-9}$</td>
<td>202.43 $\times 10^{-9}$</td>
</tr>
<tr>
<td>0.145</td>
<td>0.125</td>
<td>45</td>
<td>159.59 $\times 10^{-9}$</td>
<td>236.59 $\times 10^{-9}$</td>
</tr>
<tr>
<td>0.150</td>
<td>0.120</td>
<td>60</td>
<td>157.48 $\times 10^{-9}$</td>
<td>289.53 $\times 10^{-9}$</td>
</tr>
<tr>
<td>0.155</td>
<td>0.115</td>
<td>75</td>
<td>155.41 $\times 10^{-9}$</td>
<td>353.71 $\times 10^{-9}$</td>
</tr>
<tr>
<td>0.160</td>
<td>0.110</td>
<td>90</td>
<td>152.98 $\times 10^{-9}$</td>
<td>442.38 $\times 10^{-9}$</td>
</tr>
</tbody>
</table>

In order to intuitively see the force change of the small permanent magnet during the moving process, according to the above table, we draw a line diagram of the two component forces $F_x$ and $F_y$ of the small permanent magnet during the moving process.

![Fig. 8. Force analysis of small permanent magnets as they move along an arc trajectory](image)

**Simulation experiment conclusion**

Through the above simulation experiments, we find that in the process of moving the small permanent magnet to the second large permanent magnet, as the $F_x$ gradually increases, $F_y$ gradually decreases, and the force direction of the small permanent magnet gradually points to the $Y$ axis direction, therefore, the small permanent magnet moves along the boundary towards the second large permanent magnet, and the trajectory is an arc. According to Tables 1–3, we find that when the distance of the second large permanent magnet from the center position is less than the distance of the first large permanent magnet from the center, that is, at $\text{dis \_ion1} < \text{dis \_ion}$, the direction of the magnetic field around the small permanent magnet located at the boundary position of the $X$-axis changes, the $F_y$ increases, and the small permanent magnet begins to move towards the second large permanent magnet. Through Table 4, we calculate the changes of $F_x$ and $F_y$ during the movement of small permanent magnets along the boundary when the $\text{dis \_ion}$ and $\text{dis \_ion1}$ differ by 0.05 [m], and determine the relative positions of
the two large permanent magnets for subsequent practical experiments.

Through the simulation experiment of COMSOL software, we can clearly observe that by changing the external magnetic field, under non-contact control, small permanent magnets can move along an arc trajectory. This shows that it is feasible to non-contact control the implant to move along the arc trajectory in the magnetic stereotaxic system, and at the same time provides a theoretical basis for subsequent experiments.

References


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АНАЛІЗ МОЖЛИВОСТІ ПЕРЕМІЩЕННЯ ІМПЛАНТУ ПО ДУГОВІЙ ТРАЄКТОРІЇ ПІД БЕЗКОНТАКТНИМ КОНТРОЛЕМ У МАГНІТНИЙ СТЕРЕОТАКСИЧНІЙ СИСТЕМІ

У статті подано безконтактне керування магнітними імплантами способом зміни зовнішнього магнітного поля в магнітній стереотаксичній системі та проаналізовано можливість їх переміщення по дуговій траекторії. За допомогою програмного забезпечення COMSOL змодельовано процес переміщення мініатюрного магнітного імпілана по дуговій траекторії, досліджено зміну траекторії мікромагнітного імпланта, визначено взаємне розташування великих постійних магнітів та проведено механічний аналіз переміщення мініатюрного магнітного імпланта по дуговій траекторії.

В цьому експерименті ми фіксуємо великий постійний магніт, рухаємо лише другий постійний магніт, спочатку спостерігаємо процес руху малого постійного магніту, а потім аналізуємо силу малого постійного магніту за допомогою модуля розрахунку сили і коли маленький постійний магніт почне рухатись по дуговій траекторії. Далі, згідно з попередніми результатами, ми переміщуємо два сусідні великих постійних магнітів одночасно з певним інтервалом, записуємо траєкторію руху малого магніту, і, нарешті, за допомогою модуля розрахунку сили програмного забезпечення COMSOL здійснюємо силовий аналіз руху малих постійних магнітів по дугових траекторіях. Результати проведеного експерименту будуть використані для визначення взаємного розташування двох великих постійних магнітів, розташованих поруч під час дослідження, для з’ясування того, за яких умов малі постійні магніти будуть рухатись по дуговій траекторії. Метою цього експерименту є забезпечення теоретичної та інформаційної підтримки для подальших практичних досліджень магнітної стереотаксичної системи, коли всі параметри в програмному забезпечені COMSOL отримані на основі провідних показників вимірювань для підвищення вірогідності результатів симуляції.

Ключові слова: здоров'я людини; магнітне поле; програмне забезпечення COMSOL; постійні магніти; силовий аналіз.

Бібліографічні описи / Bibliographic descriptions