Simulation of Disturbance Observer-Based Bone Tissue Change Prediction Approach for Orthopedic Drills

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Abstract: Orthopedic drills are currently used for various operations in surgical fields such as orthopedics, ear, nose, and throat surgery. The path that orthopedic drills travel through the tissue is controlled manually by surgeons, and manual control leads to the risk of damaging areas such as nerves and tissues. In our study, an innovative approach is presented against existing drill designs and breakthrough detection problems. In the proposed model, the change in the load torque and the change in friction force caused by the tissue change in the drilling path are considered as a disturbance effect, and a disturbance observer has been developed that allows these disturbances to be observed. Observation of the disturbance effects allows the perception of the hardness of tissue change during drilling since it gives the change of load torque changes and friction coefficient, which cannot be measured under normal operation. The performance of the proposed approach has been proven by simulation study.

1. INTRODUCTION

Bone drilling is used primarily in orthopedic surgery, but also in many surgical interventions such as thoracic surgery, plastic surgery, otolaryngology [1]. During surgery, implants such as screws, nails, wires and plates are used to fix the bone as a result of post-traumatic fractures in the body [2,3]. Cylindrical holes are drilled in the bone with the appropriate drill bit attached to orthopedic drills and implants are placed in these holes [1]. One of the risks in the usage of surgical drills is the potential of the drill bit to damage nerve, vessel and muscle tissues during the drilling process [4,5]. The rapidly rotating drill wraps around the surrounding tissues uncontrollably or the drill bit's inability to stop its movement immediately after exiting the second cortex of the bone is the reason for the potential of surgical drills to damage the tissues [4,6,7]. Breakthrough detection can be defined as the detection of the thrust force when the drill bit exits the second cortex [4,8]. During orthopedic surgical procedures, the force applied by the surgeon for the advancement of the drill bit varies since changing tissue hardness. The factors that affect the performance of the drilling process includes surgeon's dexterity, 'feel piercing' [9], phonological 'audible piercing' [10,11]. The drilling force perceived by the surgeon is a relative
concept. The drill bit penetration rate, the health/condition of the bone, and the drill type used in the operation affect the drilling force.

There are three types of approaches to detect the breakthrough in bone drilling in the literature. One of these approaches is the Computer Assisted Orthopedic Surgery approach in orthopedic surgery operations, which is based on the combination of medical imaging, skeletal-muscular system and the positioning of the surgical instrument in 3D space, and semi-robotic systems [12]. The second approach is the studies to integrate breakthrough detection sensors as force, vibration, acoustic, and torque sensors into the existing orthopedic drills [13–17]. Due to the cost-effectiveness of robotic and imaging systems, as well as the mounting and cost disadvantages of various sensors integrated into orthopedic drills, there has been a third approach for estimating tissue changes during drilling with real-time system dynamics analysis in recent years. In this approach, there are some studies to predict tissue change by analyzing the effects of changes in system dynamics on the closed-loop signal by using closed-loop signals used in drill control [4]. In orthopedic drills where direct current motors are used, the change of load torque and friction force indirectly causes a change in the closed-loop error signal, and this change allows the estimation of tissue change with a trained artificial intelligence-based breakthrough detection algorithm [4,7].

When the common literature was examined, no study was found to detect tissue change during a surgical drilling by estimating the disturbance with the disturbance observer. In this study, a new bone tissue change detection approach based on observing the change of the disturbance observer-based load torque and friction coefficient is presented. The mathematical model of the Brushless Direct Current Motor (BLDC) used in the orthopedic drill was constructed, then the quantitative value of the disturbance effect was observed with a closed-loop Proportional Integral Derivative (PID) controller, which will minimize the difference between the actual model and the model with disturbance applied. In the simulation studies, it has been proven that the change of the load torque and friction coefficient given to the system and whose waveforms are known, can be observed quantitatively with the developed disturbance observer.

2. MATERIAL AND METHOD

The disturbance observer-based torque and friction observer approach has been developed with the BLDC mathematical model, which is widely used in orthopedic drills. The change of load torque and friction gives meaningful information about the state of the drilling according to the hardness of the cortical and spongy bone types [4,13]. MATLAB/Simulink was preferred for simulation based on drill motor parameters [18], with the purpose of making real-time analysis, creating the mathematical model of the disturbance observer-based system.

2.1. Brushless Direct Current Motor and Its Mathematical Model

In the study, a brushless direct current motor (BLDC) was used due to its features such as high efficiency at low power, silent operation, low maintenance and low cost, absence of electrical arcs and minimum electrical losses. The following assumptions have been made in order to make the mathematical modeling of BLDC [19,20].

• All stator resistances and inductances are assumed to be equal and constant.
• The motor is not saturated.
• Eddy current and hysteresis effects in the magnetic materials of the machine have an insignificant effect on the rotational current.
• Semiconductors in the power switching circuit are ideal.
• All phases have the same Back-EMF waveform.
• Iron losses are negligible.

The flexibility of the rotor and shaft is assumed to be zero. A viscous friction model is used in the simulated model [21]. The relationship between the input voltage of a three-phase, star-connected BLDC and the phase currents and Back-EMF can be expressed mathematically as shown below.

\[ V_{ab} = R(i_a - i_b) + L \frac{d}{dt}(i_a - i_b) + e_a + e_b \]  
\[ V_{bc} = R(i_b - i_c) + L \frac{d}{dt}(i_b - i_c) + e_b + e_c \]  
\[ V_{ca} = R(i_c - i_a) + L \frac{d}{dt}(i_c - i_a) + e_c + e_a \]

In the equations 1, 2 and 3, V represents the phase-to-phase voltage, R represents the resistance of each phase, L represents the inductance of each phase, and the Back-EMF voltages are represented as e_a, e_b, and e_c, respectively. Electromechanical behavior of the motor according to the law of motion can be stated as;

\[ T_e = B \dot{\theta} + J \ddot{\theta} + T_L \]  

In equation 4, T_e represents electrical torque, \( \dot{\theta} \) represent mechanical speed, B represents viscous friction coefficient, J represents rotor inertia, T_L represents load torque. It is also expressed in the relations given in Equations 5 and 6 between voltages and currents:

\[ V_{ab} + V_{bc} + V_{ca} = 0 \]  
\[ i_a + i_b + i_c = 0 \]

Based on Equations 5 and 6, only two voltage values are needed for modeling and when expressed as in Equations 7 and 8;

\[ 2V_{ab} + V_{bc} = 3Ri_a + 3L \frac{d}{dt}i_a + 2e_a - e_b - e_c \]  
\[ -V_{ab} + V_{bc} = 3Ri_b + 3L \frac{d}{dt}i_b + 2e_b - e_a - e_c \]

The produced electrical torque by the three-phase, star-connected BLDC is given in Equation 9.
The mathematical equations of trapezoidal Back-EMF voltages are expressed as in Equations 10, 11 and 12:

\[
\begin{align*}
e_a &= (k_e/2\theta_m)\text{Trapezoidal}(\theta_e) \\
e_b &= (k_e/2\theta_m)\text{Trapezoidal}(\theta_e - 2\pi/3) \\
e_c &= (k_e/2\theta_m)\text{Trapezoidal}(\theta_e - 4\pi/3)
\end{align*}
\]

Here, \( k_e \) and \( \theta \) represent the back-EMF constant and the electric angle, respectively. Also, \( P \) stands for the number of poles. Moreover, trapezoidal \( (\theta_e) \) is a function defined as a trapezoidal wave, and a period of this function is as in Equation 13.

\[
\text{Trapezoidal}(\theta_e) = \left\{ \begin{array}{ll}
1 & \text{for } 0 \leq \theta_e \leq 2\pi/3 \\
1 - \frac{6}{\pi(\theta_e - 2\pi/3)} & \text{for } 2\pi/3 \leq \theta_e \leq \pi \\
-1 & \text{for } \pi \leq \theta_e \leq 5\pi/3 \\
1 - \frac{6}{\pi(\theta_e - 5\pi/3)} & \text{for } 5\pi/3 \leq \theta_e \leq 2\pi
\end{array} \right.
\]

When equations 10, 11 and 12 are used in Equation 9, the expression of \( T_e \) is obtained as in Equation 14.

\[
T_e = \frac{k_e}{2} \left[ \text{Trapezoidal}(\theta_e) i_a + \text{Trapezoidal}(\theta_e - \frac{2\pi}{3}) i_b + \text{Trapezoidal}(\theta_e - \frac{4\pi}{3}) i_c \right]
\]

The electrical and mechanical BLDC parameters which are used in the simulation study are given in Table 1 [18].

<table>
<thead>
<tr>
<th>( R(\Omega) )</th>
<th>( L(H) )</th>
<th>( K_{emf} )</th>
<th>( J )</th>
<th>( B )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.875</td>
<td>0.0085</td>
<td>175</td>
<td>0.0008</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

2.2. Implementation of Disturbance Observer Design

2.3. Detection of Changes in Load Torque and Friction Coefficient by Using Disturbance Observer

In this study, MATLAB/Simulink was preferred for simulation, in order to carry out real-time simulations, creating a mathematical model of the BLDC and disturbance observer-based system, and interpreting the simulations according to motor parameters. The block diagram of the simulated BLDC model is given in Figure1. The disturbance observer used for torque estimation in brushed direct current motors (DC), which was reported with research work by Lee and Ahn [27], has been adapted for BLDC and determined bone tissue changing in an orthopedic drill with observing the change in friction coefficient and load torque in the current study.
zero for the first model as shown in Figure 3. The models mentioned in Figure 2 and Figure 3 consist of three sub-models in which the upper model represents the mathematical model without any disturbance, the middle model represents the model encountered with disturbance, the lower model represents the disturbance observer which produces the quantity of disturbance with the difference of ideal model output and disturbance applied model output. A PID controller that processes the rotor position difference at the outputs of the two models is used [27]. The coefficients of the PID controller determined by the MATLAB/Simulink PID Tuning Toolbox with the obtained transfer function were found as 0.0081, 0.0014 and 0.0044 for P, I and D, respectively. Secondly, the variation of the friction coefficient is determined for with friction observer. Depending on the amount of friction, the heat generated during the bone drilling process may cause thermal injuries around the hole drilled between the drill bit and the bone[29,30]. As shown in Figure 3, a friction pattern which mimics the friction of the drilling path has been applied as friction variation.

3. RESULTS AND DISCUSSIONS

The proposed models have been constructed in Simulink for simulation works. Since the hardness of a cortical bone changes according to the drilling path as mentioned in the work of Torun and Öztürk [4], we have simulated the change of load torque and friction coefficient as drilling one hole on bicortical bone. A detailed discussion about bicortical drilling path could be found with further reading of recent literature works[4,5,7,8,11,16,31]. For estimating the load torque, it is assumed that one-hole drilling is performed within 5 seconds. Drill bit contacts the first cortical layer at 1st second, then exits the first cortical layer and contacts the sponge layer at 2nd second, finally breakthrough occurs when drill bit exists the second cortical layer at 4th second. The actual load torque which was applied to model, and the observed value of the load torque are shown in Figure 4.

For estimating the friction coefficient between the drill bit and bone tissue a similar scenario has been assumed. Friction varies according to drill bit geometry, drill speed, and the hardness of drilled tissue as mentioned in [32,33]. In this work, it has been tried to form a synthetic friction coefficient waveform for the bicortical drilling path with knowledge of recent literature[4,6,31] which focuses on the changes in the dynamic of the drilling for bicortical bone. Drill bit contacts with the first cortical layer at zero instant. Friction increases as the drill bit travels through the first layer then decreases when it reaches the spongy bone. The friction value is lower in the sponge bone since the hardness of the sponge layer was lower than the cortical layer. The drill bit contacts the second cortical entry at the 1.5 second. Finally, breakthrough occurs as the drill bit exits the second cortical layer at 2.5 second. The synthetic wave form of friction coefficient and observed with disturbance observer have been shown in Figure 5.

![Figure 2. The model of disturbance observer based load torque change detection](image)

![Figure 3. The model of disturbance observer-based friction coefficient variation detection](image)

![Figure 4. Applied synthetic load torque versus observed load torque with disturbance observer](image)

![Figure 5. Applied synthetic friction versus observed friction with disturbance observer.](image)
183 ms, respectively. The observed friction coefficient lags the synthetic friction coefficient with a 120 ms delay as shown in Figure 5. Since the objective of the study was to obtain the change of the tissue being drilled, it is important to observe the change of the load torque and friction with a reasonable time duration rather than obtaining the actual value of load torque and friction coefficient. Simulations show that change of load torque and friction could be obtained lower than 200ms later after the change of the drilled tissue. 200ms corresponds to the 0.2 mm drilling path with a drilling feed rate of 1 mm/second (60mm/minutes) which is one of the nominal feed rate for bone drilling [33]. The 0.2 mm drilling path length can be regarded as a breakthrough error whose acceptable range lies within 1-2mm [34] to avoid damaging vital organs when drilling cortical bone.

As a result of the simulations, it was seen that the signals of the changing load torque value and the friction coefficient in the model were in a form that is similar to the signals at the observer output. This confirms that the orthopedic surgical drill, whose design will be developed in real-time, will be capable of detecting tissue changes in the transition through the bone layers during surgery and will be sufficiently sensitive and accurate for the detection of breakthrough.

4. CONCLUSION

In this study, disturbance observer, which observes the changes in load torque that is directly proportional to the thrust force generated during the bone drilling process and the change in viscous friction coefficient is designed in the Matlab/Simulink simulation environment. As a result of the simulations that have been carried out in the MATLAB/Simulink environment, it has been observed that the signals of the changing torque value and friction coefficient in the model are in a form that is similar to the signals at the observer output. This specifies that the orthopedic surgical drill is capable of detecting tissue changes as it passes through the layers of bone during surgery and has sufficient sensitivity and accuracy for breakthrough detection. Real-time implementation of the proposed approach on sheep-femur drilling with BLDC based drill will be performed in future works.

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