Cilt 11, Sayı 1, Sayfa 136-141, 2022 Volume 11, Issue 1, Page 136-141, 2022

Araştırma Makalesi https://doi.org/10.46810/tdfd.1057096 Research Article

Türk Doğa ve Fen Dergisi
Turkish Journal of Nature and Science
www.dergipark.gov.tr/tdfd

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

Yunis TORUN[1*]

[1] Sivas Cumhuriyet Üniversitesi, Mühendislik Fakültesi, Elektrik Elektronik Mühendisliği Bölümü, Sivas, Türkiye
Yunis TORUN ORCID No: 0000-0002-6187-0451

Corresponding author: ytorun@cumhuriyet.edu.tr

(Received: 12.01.2022, Accepted: 19.02.2022, Online Publication: 25.03.2022)

Keywords
Orthopedic Drill, Disturbance Observer, Bone Drilling

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.

Ortopedik Matkaplar İçin Bozucu Gözlemci Tabanlı Kemik Doku Değişim Tahmin Yaklaşımı Benzetimi

Anahtar Kelimeler
Ortopedik Matkap, Bozucu Gözlemci, Kemik Delme

Öz: Günümüzde ortopedi, kulak burun boğaz gibi cerrahi alanlarda çeşitli operasyonlarda ortopedik matkaplar kullanılmaktadır. Ortopedik matkapların doku içerisindeki kat ettiği yol manuel olarak cerrahlar tarafından kontrol edilmektedir ve manuel kontrol sinir, doku gibi bölgelerde hasar oluşturma riskine yol açmaktadır. Çalışmamızda mevcut matkap tasarımlarına ve sorunlarına karşı yenilikçi bir model sunulmaktadır. Önerilen modelde yük momentindeki değişim ve matkap ucundaki doku değişikliğinden kaynaklanan sürtünme kuvveti değişimi bozucu etki olarak ele alınmış, bu bozucu etkilerin gözlemlenmesine olanak sağlayan bir bozucu gözlemci geliştirilmiştir. Bozucu etkilerinin gözlemlenmesi, normal şartlarda ölçülemeyen yük moment değişimlerinin ve sürtünme katsayısının değişimini verdiğinden dolayı, delme esnasında doku değişiminin algılanmasına olanak sağlamaktadır. Önerilen yöntemi başarımı benzetim çalışmaları ile kanıtlanmıştır.

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.

$$V_{ab} = R(i_a - i_b) + L\frac{d}{dt}(i_a - i_b) + e_a + e_b \quad (1)$$

$$V_{bc} = R(i_b - i_c) + L\frac{d}{dt}(i_b - i_c) + e_b + e_c \quad (2)$$

$$V_{ca} = R(i_c - i_a) + L\frac{d}{dt}(i_c - i_a) + e_c + e_a \quad (3)$$

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;

$$T_e = B\dot{\theta} + J\ddot{\theta} + T_L \quad (4)$$

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:

$$V_{ab} + V_{bc} + V_{ca} = 0 \quad (5)$$

$$i_a + i_b + i_c = 0 \quad (6)$$

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

$$2V_{ab} + V_{bc} = 3Ri_a + 3L\frac{d}{dt}i_a + 2e_a - e_b - e_c \quad (7)$$

$$-V_{ab} + V_{bc} = 3Ri_b + 3L\frac{d}{dt}i_b + 2e_b - e_a - e_c \quad (8)$$

The produced electrical torque by the three-phase, star-connected BLDC is given in Equation 9.

$$T_e = (e_a i_a + e_b i_b + e_c i_c)/\dot{\theta}_m \quad (9)$$

The mathematical equations of trapezoidal Back-EMF voltages are expressed as in Equations 10, 11 and 12:

$$e_a = (k_e/2\dot{\theta}_m)Trapezoidal(\theta_e) \quad (10)$$

$$e_b = (k_e/2\dot{\theta}_m)Trapezoidal(\theta_e - 2\pi/3) \quad (11)$$

$$e_c = (k_e/2\dot{\theta}_m)Trapezoidal(\theta_e - 4\pi/3) \quad (12)$$

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

$$Trapezoidal(\theta_e) = \begin{cases} 1 & 0 \le \theta_e \le {}^{2\pi}/_3 \\ 1 - \frac{6}{\pi(\theta_e - {}^{2\pi}/_3)} & {}^{2\pi}/_3 \le \theta_e \le \pi \\ -1 & \pi \le \theta_e \le {}^{5\pi}/_3 \\ 1 - \frac{6}{\pi(\theta_e - {}^{5\pi}/_3)} & {}^{5\pi}/_3 \le \theta_e \le 2\pi \end{cases} \quad (13)$$

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

$$T_e = \frac{k_e}{2}\left[Trapezoidal(\theta_e)i_a + Trapezoidal(\theta_e - \frac{2\pi}{3})i_b + Trapezoidal(\theta_e - \frac{4\pi}{3})i_c\right] \quad (14)$$

When the electrical torque equation expressed as T_e in Equation 4 is arranged, the speed w of the rotor of the motor is given in equations 15b and 16.

$$T_e = J\frac{dw}{dt} + Bw + T_L \quad (15a)$$

$$T_e - T_L = J\frac{dw}{dt} + Bw \quad (15b)$$

$$w(s) = \frac{T_e - T_L}{Js + B} \quad (16)$$

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

Table 1. Motor parameters used in the simulation study [18]

$R(\Omega)$	$L(H)$	K_{emf} $(V.s/rad)$	J (Nms^2/rad)	B (Nms/rad)
2.875	0.0085	175	0.0008	0.0001

2.2. Implementation of Disturbance Observer Design

The systems in which the effects of unknown or uncertain disturbance effects on the system can be observed without the use of external additional detectors are called disturbance observers [22,23]. Disturbance observers are used to observe immeasurable states and variables which are commonly used in force control applications, robotic manipulators, and many systems process control system [22,24,25].

There are several advantages of using an observer-based method for estimating state of the drilling in bone drilling operation. Observer is a system, which is used to reconstruct the states of a dynamic system by using input signal measurements. They are used in many applications such as feedback control, system stability monitoring and fault detection [26]. The disturbance observer was developed in the late 1980s as a new type of observer for the control of mechatronic systems, and they are used to predict the unknown inputs of the system, unlike state observers which are used to reconstruct the unknown states of a system [27]. Disturbance observers increase the stability and performance of the control system by predicting unknown disturbances affecting the control systems. Also, a disturbance observer can be used in a control system to reduce the number of costly detectors needed [28].

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.

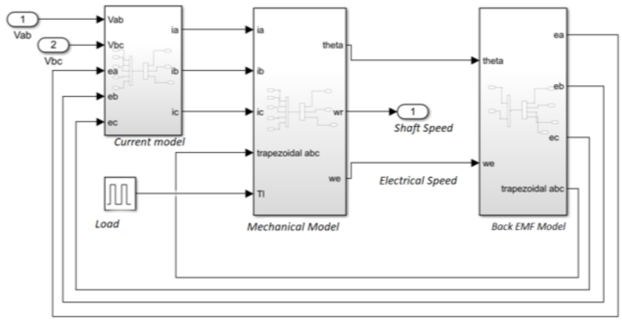

Figure 1. The simulation diagram of Brushless DC motor.

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

In this section, during the bone drilling process, the effect of the variation of the load torque and friction coefficient during the bicortical drilling path is modeled by using MATLAB/Simulink. While performing the simulation study, two models expressing the effects of either varying load torque or varying friction coefficient have been constructed. Considering the change in the load torque firstly; the effect of the electrical torque obtained from the mechanical model of the motor on the motor speed and position together with the load torque defined as T_e, T_L is taken as basis in the design of the disturbance observer. Simulink model of disturbance observer based load torque change detection is shown in Figure 2. A square waveform with 2Nm amplitude load torque, T_L, has been applied to BLDC model to mimic the real drilling path. The variation of the friction coefficient has been assumed 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.

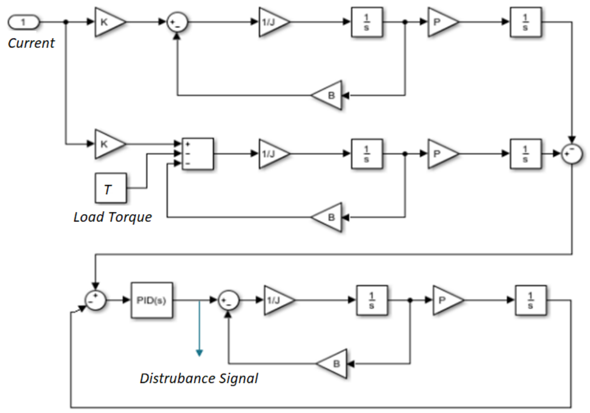

Figure 2. The model of disturbance observer based load torque change detection

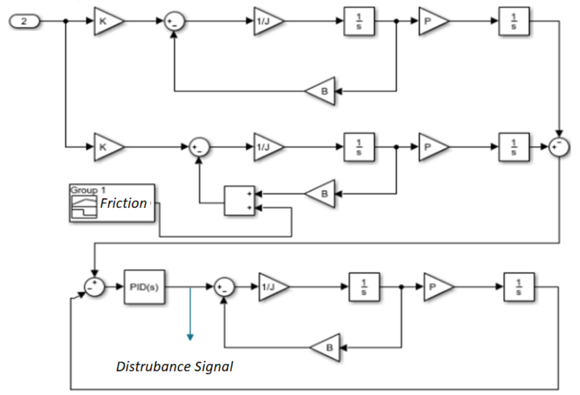

Figure 3. The model of disturbance observer-based friction coefficient variation detection

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.

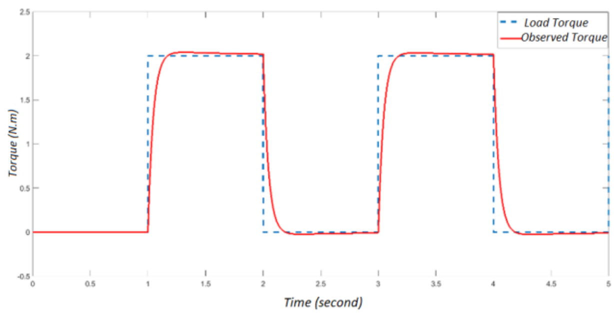

Figure 4. Applied synthetic load torque versus observed load torque with disturbance observer

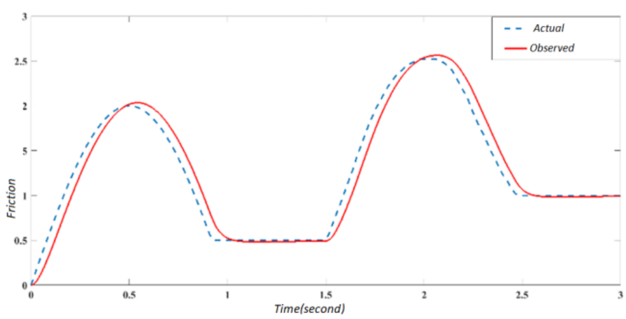

Figure 5. Applied synthetic friction versus observed friction with disturbance observer.

Observed load torque is close to the applied load torque at the steady-state, however, the sudden changes in the load torque cause the difference in the transient response of the disturbance observer. The rise time, delay time, and settling time have been measured as 140ms, 65 ms and

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 1mm/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.

ACKNOWLEDGMENTS

This study was financially supported by Sivas Cumhuriyet University Scientific Research Grant Program (CUBAP) with M-737 project code and “Power Analysis and Optimization in Robotic Medical Drills” project name. The author would like to thank Dr. Ozhan PAZARCI and Ahmet OZTURK for their valuable comments based on their drilling experience.

REFERENCES

[1] Bertollo N, Robert W. Drilling of Bone: Practicality, Limitations and Complications Associated with Surgical Drill-Bits. Biomech. Appl., 2012. https://doi.org/10.5772/20931.

[2] Gönen E. Minimally invasive surgical techniques for the treatment of the shaft fractures of the long bones. Türk Ortop ve Travmatoloji Birliği Derneği Derg 2012;11:78–88. https://doi.org/10.5606/totbid.dergisi.2012.11.

[3] Farouk O, Krettek C, Miclau T, Schandelmaier P, Guy P, Tscherne H. Minimally invasive plate osteosynthesis: Does percutaneous plating disrupt femoral blood supply less than the traditional technique? J Orthop Trauma 1999. https://doi.org/10.1097/00005131-199908000-00002.

[4] Torun Y, Öztürk A. A New Breakthrough Detection Method for Bone Drilling in Robotic Orthopedic Surgery with Closed-Loop Control Approach. Ann Biomed Eng 2020;48. https://doi.org/10.1007/s10439-019-02444-5.

[5] Modi RA, Nayak RP. Detection of Breakthrough During Bone-Drilling in Orthopaedic Surgery 2014;1:794–8.

[6] Torun Y, Ozturk A, Hatipoglu N, Oztemur Z. Detection of Bone Excretion with Current Sensor in Robotic Surgery. UBMK 2018 - 3rd Int. Conf. Comput. Sci. Eng., 2018. https://doi.org/10.1109/UBMK.2018.8566443.

[7] Öztürk A. Robotik cerrahi matkaplarda güç analizi ile matkap ucu çıkış tespiti. Cumhuriyet Üniversitesi Fen Bilimleri Enstitüsü, 2019.

[8] Torun Y, Pazarci O, Ozturk A. Current Approaches to Bone-Drilling Procedures with Orthopedic Drills. Cyprus J Med Sci 2020;5:93–8. https://doi.org/10.5152/cjms.2020.1242.

[9] Augustin G, Zigman T, Davila S, Udilljak T, Staroveski T, Brezak D, et al. Cortical bone drilling and thermal osteonecrosis. Clin Biomech 2012;27. https://doi.org/10.1016/j.clinbiomech.2011.10.010.

[10] Praamsma M, Carnahan H, Backstein D, Veillette CJH, Gonzalez D, Dubrowski A. Drilling sounds are used by surgeons and intermediate residents, but not novice orthopedic trainees, to guide drilling motions. Can J Surg 2008.

[11] Ho D, Li T, Meng QH. Bone Drilling Breakthrough Detection via Energy-Based Signal. Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. EMBS, vol. 2018-July, 2018. https://doi.org/10.1109/EMBC.2018.8512621.

[12] Zheng G, Nolte LP. Computer-Assisted Orthopedic Surgery: Current State and Future Perspective. Front Surg 2015;2. https://doi.org/10.3389/fsurg.2015.00066.

[13] Torun Y, Pazarci Ö. Parametric Power Spectral Density Estimation-Based Breakthrough Detection for Orthopedic Bone Drilling with Acoustic Emission Signal Analysis. Acoust Aust 2020;48. https://doi.org/10.1007/s40857-020-00182-6.

[14] Torun Y, Ozturk A, Hatipoglu N, Oztemur Z. Breakthrough detection for orthopedic bone drilling via power spectral density estimation of acoustic emission. 2018 Electr Electron Comput Sci Biomed Eng Meet EBBT 2018 2018:1–5. https://doi.org/10.1109/EBBT.2018.8391464.

[15] Ying Z, Shu L, Sugita N. Autonomous Penetration Perception for Bone Cutting during Laminectomy. 2020 8th IEEE RAS/EMBS Int. Conf. Biomed.

Robot. Biomechatronics, IEEE; 2020, p. 1043–8. https://doi.org/10.1109/BioRob49111.2020.9224375.

[16] Seibold M, Maurer S, Hoch A, Zingg P, Farshad M, Navab N, et al. Real-time acoustic sensing and artificial intelligence for error prevention in orthopedic surgery. Sci Rep 2021;11:3993. https://doi.org/10.1038/s41598-021-83506-4.

[17] Osa T, Abawi CF, Sugita N, Chikuda H, Sugita S, Tanaka T, et al. Hand-Held Bone Cutting Tool with Autonomous Penetration Detection for Spinal Surgery. IEEE/ASME Trans Mechatronics 2015;20:3018–27. https://doi.org/10.1109/TMECH.2015.2410287.

[18] Hingmire A, Pimple BB. Simulation and Analysis Studies of Speed Control of Brushless DC Motor Using Hall Sensors. 2018 Int. Conf. Smart Electr. Drives Power Syst., 2018, p. 384–7. https://doi.org/10.1109/ICSEDPS.2018.8536062.

[19] Safi SK. Analysis and simulation of the high-speed torque performance of brushless DC motor drives. IEE Proc - Electr Power Appl 1995;142. https://doi.org/10.1049/ip-epa:19951808.

[20] Aydoğdu Ö. Fırçasız doğru akım motorlarının genetik tabanlı bulanık denetleyici ile sensörsüz kontrolü. Selçuk Üniversitesi Fen Bilimleri Enstitüsü, 2006.

[21] Li X. Model-Based Design of Brushless Dc Motor Control and Motion Control Modelling for Robocup Ssl. 2015.

[22] Chen WH, Ballance DJ, Gawthrop PJ, O'Reilly J. A nonlinear disturbance observer for robotic manipulators. IEEE Trans Ind Electron 2000;47:932–8. https://doi.org/10.1109/41.857974.

[23] Alkaya A, Eker I. Luenberger observer-based sensor fault detection: Online application to DC motor. Turkish J Electr Eng Comput Sci 2014;22. https://doi.org/10.3906/elk-1203-84.

[24] Mohammadi A, Tavakoli M, Marquez HJ, Hashemzadeh F. Nonlinear disturbance observer design for robotic manipulators. Control Eng Pract 2013;21. https://doi.org/10.1016/j.conengprac.2012.10.008.

[25] Wen X. Enhanced disturbance-observer-based control for a class of time-delay system with uncertain sinusoidal disturbances. Math Probl Eng 2013;2013. https://doi.org/10.1155/2013/805687.

[26] Radke A, Gao Z. A survey of state and disturbance observers for practitioners. Proc. Am. Control Conf., vol. 2006, 2006. https://doi.org/10.1109/acc.2006.1657545.

[27] Lee SC, Ahn HS. Sensorless torque estimation using adaptive Kalman filter and disturbance estimator. Proc. 2010 IEEE/ASME Int. Conf. Mechatron. Embed. Syst. Appl. MESA 2010, 2010. https://doi.org/10.1109/MESA.2010.5552094.

[28] Kouhei O, Shibata M, Murakami T. Motion control for advanced mechatronics. IEEE/ASME Trans Mechatronics 1996;1. https://doi.org/10.1109/3516.491410.

[29] Eriksson AR, Albrektsson T, Albrektsson B. Heat caused by drilling cortical bone: Temperature measured in vivo in patients and animals. Acta Orthop 1984;55. https://doi.org/10.3109/17453678408992410.

[30] Bachus KN, Rondina MT, Hutchinson DT. The effects of drilling force on cortical temperatures and their duration: An in vitro study. Med Eng Phys 2000;22. https://doi.org/10.1016/S1350-4533(01)00016-9.

[31] Torun Y, Malatyalı S. Power Analysis of Robotic Medical Drill With Different Control Approaches. Cumhur Sci J 2020;41:527–33. https://doi.org/10.17776/csj.661666.

[32] Amewoui F, Le Coz G, Bonnet AS, Moufki A. Bone drilling: an identification of heat sources. Comput Methods Biomech Biomed Engin 2020;23. https://doi.org/10.1080/10255842.2020.1813418.

[33] Alam K, Piya S, Al-Ghaithi A, Silberschmidth V. Experimental investigation on the effect of drill quality on the performance of bone drilling. Biomed Tech 2020;65. https://doi.org/10.1515/bmt-2018-0184.

[34] Boiadjiev G, Chavdarov I, Delchev K, Boiadjiev T, Kastelov R, Zagurki K. Development of Hand-Held Surgical Robot ODRO-2 for Automatic Bone Drilling. J Theor Appl Mech 2017;47:12–22. https://doi.org/10.1515/jtam-2017-0017.