Force Control Algorithm for detection of Break-Through Bone Drilling

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Summary: The purpose of this study is to develop a force control algorithm that detects high force during bone drilling process where the drilling process will halt and return to a safe position when high thrust force detected. The algorithm is built using Simulink model under Matlab software. The control algorithm detects excessive force and calibrates the force in tri-axial direction as the threshold value. The system is verified through an experiment drilling cow femur bone using 5 DoF CRS Catalyst-5 robots. Preliminary drilling test is conducted to observe the maximum force the robot can hold during the drilling process.This will help to increase of safety enhancement during drilling process

Keywords: Bone Drilling, Robotic Assisted Surgery, Force Control Algorithm

1. Introduction

Bone drilling process is a common operation involved in traditional and modern surgery practice in medical applications. The operation, known as orthopaedic surgery, involves treatment of bone fracture using internal fixation method. Traditional practice uses a hand-held motor driven tool to perform the drilling process and depends only on the surgeon's experience and skills during the operation to control the penetration of the drill bit. It is not equipped with any detection method to detect the crossing of interfaces between hard and soft tissues and to discriminate the layers of tissues [1]. In today's modern surgery practice, automated machine or robot assisted surgery uses several parameters to control the operation. These parameters are forces and torques, feed rate and cutting speed. As reported by Wen-Yo Lee et al. [2], high pass filter thrust force signal is used when drilling porcine scapula neck and porcine skull to detect the interfaces between bone layers and breakthrough the penetration of the drill bit. It also includes two more signals; drilling torque trend and feed rate trend to help the breakthrough point.

A real-time breakthrough detection technique based on force derivatives was also presented by Alotta et al. [3], who carried out experiment using a Instron Testing Machine equipped with a 1 to 1kN range load cell to drill swine femurs. Marouf et al. [4] developed a breakthrough control system based on the modified Kalman filter to detect the force difference between successive samples (FDSS) which was experimented on porcine femoral shafts using a drill feed unit, a bi-directional force sensor, a quick mount drill holder and a compliant bone holder. Past researchers have also used other methods of breakthrough detection.

One researcher [5] used an electric current consumed by DC motor analyzed by fuzzy controller as the sensing signal. The voltage dropped from the DC motor indicated the force during the drilling process. Detection methods are important in orthopaedic surgery as a safety enhancement. It can help to prevent drill-bit breakage, unnecessary drill breakthrough, excessive heat generation, and mechanical damage to the bones caused by uncontrolled large forces [6].

The natural and unique properties of bone are the key to the detection method developed in modern practice. This is because at macrostructure level, the bone can be distinguished into two major types, cortical (or compact) and cancellous (or trabecular) [7]. The structure of bone is built with cortical bone wrapping around the struts of cancellous bone. The cortical bone lies on the outside surface as a protective shell for cancellous bone. Cortical bone has a much higher density with low surface area from cancellous bone, but it has a degree of porosity in the bone itself [8].

This paper presents a detection method based on PD motion control coupled with force control system in real-time drilling process. The system is build using Simulink model under the Matlab software environment. Discussions will be made on the empirical work carried out and analysis of results. However, the system is only limited to the detection of large threshold force during drilling process as the research is still on-going to attain a complete breakthrough detection system.

2. Experimental set-up

The set-up of the system to conduct the robotic bone drilling process experiment is illustrated in Figure 1. It consists of the CRS CataLyst-5 robot, C500c controller, Maxon DC motor (model RE 206508), ATI 6 DoF Force-Torque sensor and a holding device. The CRS Catalyst-5 robot uses a 5 DoF articulate joint and a linear track. Each joint of the robot has an incremental encoder to provide continuous information on motor position. C500C controller provides safety circuits, power, and motion control for the arm. It drives the motors in each joint, keeps track of motor position through feedback from the encoders, computes trajectories and stores robot applications in the memory [9].

The forces and torques sensor is mounted directly on the tool flange of the robot arm. The pressure-sensitive devices inside the force sensor will measure the applied forces and torques, and transfers this information to the controller [10]. The speed of the motor or the cutting speed (rpm) is controlled directly through the AC power supply whereas the velocity (mm/s) and the acceleration (mm/s2) of the robot movement along the linear track control the feed rate of the drilling process.

The drilling processes were performed on a fresh bovine femur. The skin and all soft tissues from the femur removed, leaving behind only the naked bone itself. The entire specimen cut into several parts to ensure rigid clamping into the holding device. An industrial titanium coated high speed steel (HSS) drill bit (4mm in diameter) was used in the drilling process. The parameters for feed rate used in the experiment were velocity (v) 0.1 mm/s and acceleration (a) 0.025 mm/s2. The drill bit cutting speed in this experiment remained constant at 3000rpm.

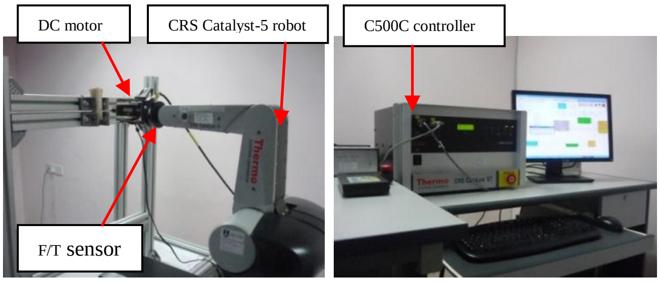

Figure 1. Experimental set-up.

2. Detection force control

This section will present the detection algorithm of high force during the drilling process. The detection algorithm in the Force Control subsystem is design based on conditionally executed system as in Figure 2. It is built with two Enabled Subsystems, a relational operator, a merge block, an output port and four input port signal together with a constant block from the Matlab Simulink library. It is implemented using WinCon software to generate a real-time code.

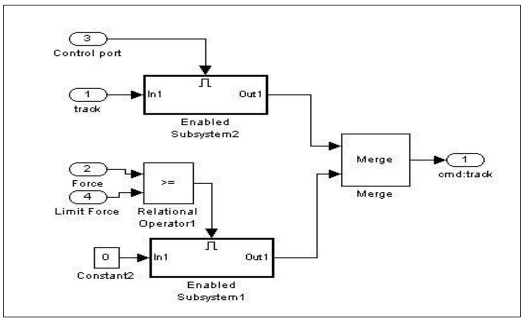

Figure 2. Block diagram for detection system.

Figure 3 shows the process cycle for the drilling operation. It begins with the setting up of the drilling parameters: velocity (v), acceleration (a), cutting speed and the desired robot position (x_d) in the track position. Then the operation mode needs to change during the drilling processes to activate the detection algorithm system. The drilling thrust forces are measured during the drilling processes where the measured forces are in the tri-axial direction denoted as F_x, F_y and F_z. Only force in the z direction (F_z) is used to compare with the value of the threshold force (F_t) in the algorithm. In Equation (1) the x_n denotes the current position of the robot and x_i is the initial position before the drilling processes.

$$x_n = \begin{cases} x_i, & F_z \geq F_t \\ x_{d,} & F_z \langle F_t \end{cases} \qquad (1)$$

From the equation, it shows that when F_z is greater or equal to the threshold value, the current position of the robot (x_n) will be equal to its initial position (x_i). Whereas if it is less than the threshold value, the current position of robot (x_i) will be equal to the desired robot position (x_d). When the robot moves back to its initial position, the drilling parameters will change back before continuing with the drilling processes. The process cycle end if no other drilling processes take place.

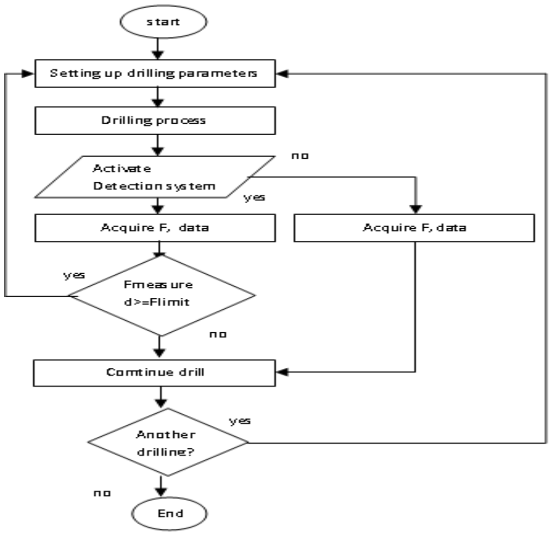

Figure 3. Flow chart for detection system.

3. Results and discussion

The results from the experimental drilling process are explained in this section. Two results presented in this paper are based on the measured forces in three different directions and measured track position (drilling depth). The data plotted in graphical form against real time reading. Before carrying out the drilling process with the detection algorithm system, preliminary drilling test conducted to determine the threshold force in the z-direction to observe the maximum force that the CRS robot can withstand.

Figure 4 shows the forces profile for the preliminary drilling test. The figure also shows that from 0 until 20 seconds, the drilling tool bit is in the stage where no contact made with the bone yet. Between the time intervals 20 to 160 seconds, the drilling tool bit starts to penetrate the bone. The drilling process of the cancellous bone can be observed and the force in the z-direction is increasing gradually. At 160 seconds, the force in the z-direction reached a maximum value of 78 Newton (N) before there is a sharp drop in value. During this state, after the sharp drop, no drilling tool bit penetration occurred on the bone and it remained at current position. Therefore, no further drilling process takes places after 160 seconds. From the result, it indicates that the CRS robot cannot withstand force in the z-direction higher than 70N approximately. Therefore, the limit force or the threshold force in the detection algorithm will be set to approximately 70N.

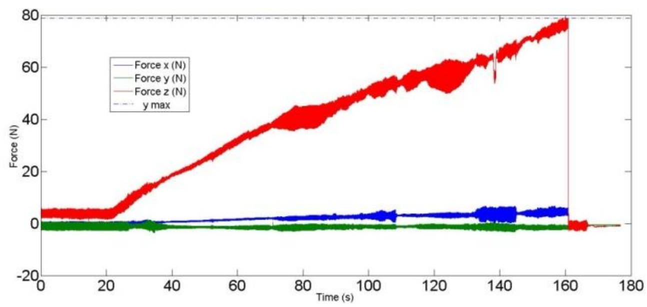

Figure 4. Measured forces profile for preliminary test.

After completing the preliminary test, the drilling process continues using the detection algorithm system. The result is shown in Figure 5. The figure also shows that from the time interval 0 to 80 seconds, it indicates the state of drilling cancellous bone and the value of the forces in the z-direction is increasing. At the time of 80 seconds, it shows that the measured force in the z-direction value is 70.4N, which it already greater than the threshold force value of 70N. At this state, the CRS robot will stop the drilling process and return to the safe position. As shown in the same figure, the value of the force in the z-direction decreases further after 80 seconds.

The movement of the CRS robot in the linear track is also recorded in Figure 6. In the figure it shows that between the time interval 0 to 80 seconds, the CRS robot moves from position 630 millimetres (mm) to 638 mm. After the detection algorithm, high force in the z-direction detected at time 80 seconds and the CRS robot will move backward to a safe position.

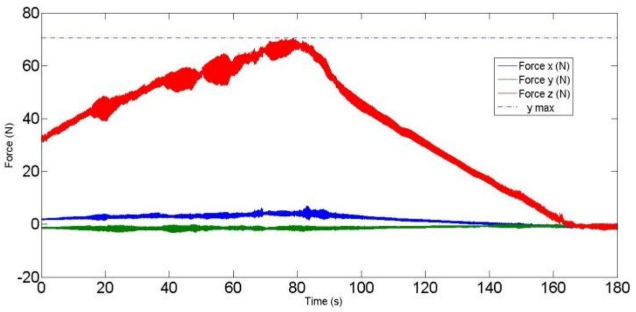

Figure 5. Measured forces profile for detection algorithm.

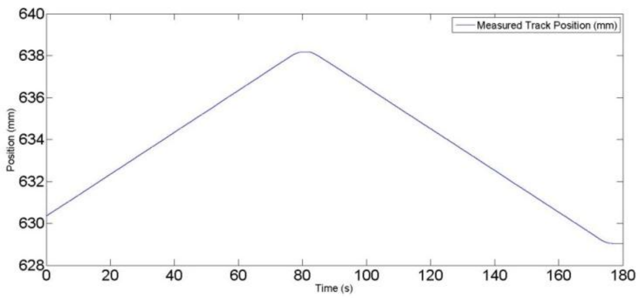

Figure 6. Measured track position.

3. Conclusion

Many research works had done implementing various detection methods for bone drilling processes using different parameters as the threshold value for the detection algorithm. In this research, the values of the tri-axial forces are measured. However, only the value of the force in the z-direction used as the threshold value in the detection algorithm and achieved through experimental investigations using femur bone of a cow as the drilling specimen. Drilling operation conducted using CRS Catalyst-5 robot controlled by a force-torque sensor architecture system with a built in detection algorithm in the force-torque sensor architecture system. The experimental results showed that when the force in the z-direction surpasses the threshold value, the CRS Catalyst-5 robot stops drilling and moves to a safe position.

The detection method is important because it helps to increase the safety during the drilling process and prevent any drill bit breakage, unnecessary drill bit insertion and any mechanical damage to the bone or CRS Catalyst-5 robot itself. In future, it is necessary to improve the research by designing a new algorithm that is able to detect the breakthrough of the drill bit during the drilling process. In addition, the possibility of using a surgical drill bit to attain a more accurate result for drilling bone demands further research work.

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References

[1] B. Allotta, G. Giacalone, L. Rinalidi, 1997, A hand-held drilling tool for orthopedic surgery, IEEE/ASME Transaction on Mechatronics, 2:218-229.
[2] W.Y. Lee, C.L. Shih, 2006, Control and breakthrough detection of a three-axis robotic bone drilling system, Journal Mechatronics, 16:73-84.
[3] B.Alotta et al., 1996, Study on mechatronic tool for drilling in the osteosynthesis of long bone:Tool/bone interactions, modelling and experiments , Mechatronics, 6/4:447-459.
[4] F. R. Ong and K. Bouazza-Marouf, 1999, The detection of drill bit break-through for the enhancement of safety in mechatronic assisted orthopaedic drilling, Mechatron, 9:565–588.
[5] Y.L. Hsu, S.T. Lee, H.W. Lin, 2001, A modular mechatronic system for automatic bone drilling, Biomedical Engineering, Applications, Basis and and Communications, 13/4:168-184
[6] O.Burak Ozdoganlar JuEun Lee, B. Arda, 2012, Modeling and experimentation of bone drilling forces, Journal of Biomechanics.
[7] Jae-Young Rho et al., 1998, Mechanical properties and the hierarchical structure of bone, Medical Engineering & Physics, 20:92-102.
[8] Stuart H Ralston, 2005, Structure and metabolism of bone, medicine, 33/12:58-60.
[9] Thermo Electron Corp., CRS CataLyst-5 Robot System, 2004, User Guide, Canada.
[10] Thermo Electron Corp., Force Sensor, 2004, User Guide, Canada.