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A simple screwing process model for bone material identification

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Orthopaedic surgery failures due to incorrect screw torqueing are costly and dangerous. Determining bone material properties by monitoring the screwing process may lead to more accurate torque limit estimations. A model was developed relating applied torque to screw rotation. This model was tested with simulated parameter identification to ensure robustness and identifiability. A Monte-Carlo analysis with randomised signal noise (n=100) proved model identifiability and robustness, and showed close agreement of identified parameters with parent model values. Due to model simplicity and lack of experimental verification, this model will serve as a basis for future development of more advanced models.

I. Introduction

Orthopaedic surgery allows joint replacement, fractured bone immobilisation for healing, or reconstruction of severely damaged bone structures. A key part of most procedures is the use of bone screws to secure implants. Over- or under-torqueing bone screws can cause implant failure and is sometimes not recognised [1]. Bone implant failures are costly in terms of additional surgery time and associated risks to patients. These risks include tissue damage/death and insufficiently secured implants [2], which can require revision or cause lifelong impairment. Furthermore, the ageing population is likely to increase bone surgery rates. Hence, improvements to surgical efficiency and reduction of revision rates are desirable to mitigate the overall healthcare costs of Orthopaedic surgery.

The torque limits used for bone surgeries are currently educated guesses [1]. It is possible that automated estimations can reduce complications from incorrect torqueing, making the surgery safer, simpler, and faster. However, no known specific optimal torque guidelines have been published for the various bone geometries and material properties and screw design.

Bone/screw geometry and material properties govern the maximum torque for a bone screw. These also govern the dynamics of the screwing process. This paper proposes a method for torque monitoring during the screwing process, to enable identification of specific bone material properties.

II. Materials and Methods

A simple model that links torque to rotation during the screwing process was implemented in MATLAB. This model is intended for self-tapping screws used in trabecular bone. A Monte Carlo analysis was then used to determine the robustness of the identified model variables.

II.I. Torque-Rotation Model

The model relates the input turning torque (*T(t)* [Nm]) to the output rotation (*x(t)* [rad]), shown in Fig. 1. The other model parameters include the critical torque required to achieve relative rotation of the screw and bone (T_{crit} [Nm]); the rotational elasticity of the bone (b, [$N^{-1}m^{-1}$]); and a viscous friction coefficient for the screw while it is advancing into the material (c [Nms]); and a constant that relates the material failure energy density (E_{fd} [$Jrad^{-1}$]) to T_{crit} and b (α [Nm]). T_{crit} is related to the ultimate tensile stress of the bone and b is related to the shear modulus of the bone.

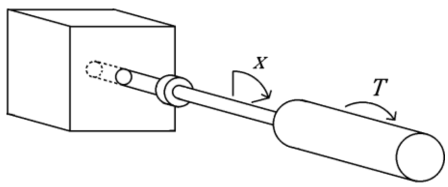

Figure 1: Modelled mechanical system of screw self-tapping into bone, with applied torque and measured rotation.

The model is based on the assumptions of purely elastic deformation for $T < T_{crit}$, and purely inelastic material failure for $T \geq T_{crit}$. Above T_{crit} the failure was modelled with a power balance between input torque minus friction times speed, $(T - T_f)\dot{x}$, with $T_f = c\dot{x}$, and material failure energy density times speed $E_{fd}\dot{x}$, with $E_{fd} = \alpha T_{crit} b$. The developed model is shown in (1). Integrating $\dot{x}$ over time then gives the output x.

$$\dot{x} = \begin{cases} b\dot{T}, & T < T_{crit} \\ \dfrac{T - \alpha T_{crit} b}{c}, & T \geq T_{crit} \end{cases} \qquad (1)$$

We implemented and simulated the model in MATLAB.

II.II. Simulation and Parameter Identification

Model parameter values were subjectively selected to demonstrate model behaviour. The rotational response to a

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ramp-step toque function shown in Fig. 2 was simulated at a 0.0001 second resolution. Samples of the rotation simulation were extracted at 0.1 second resolution to provide a noise-free data set.

Normally distributed noise with a standard deviation of 2 was applied to the noise free data to provide an identification set. In total 100 identification sets were determined with unique noise. The model was identified for each data set to provide an indication of the effect of noise on the model parameter values.

A type of simulated annealing [3] was used to perform the parameter identification. The code tracked a single best guess, but allowed the current guesses to move to against the object criteria up to 10 times before resetting it to the stored best guess. This iterated 2000 times, with the standard deviation of the added randomness starting at 1/10 of the parameter values of the current guess, and reducing to 1/200 of the current guess near the end. Each identification data set used the same initial conditions.

III. Results and Discussion

Fig. 1 shows the relationship between input torque and output rotation for the model. Table 1 presents the results of the Monte-Carlo analysis.

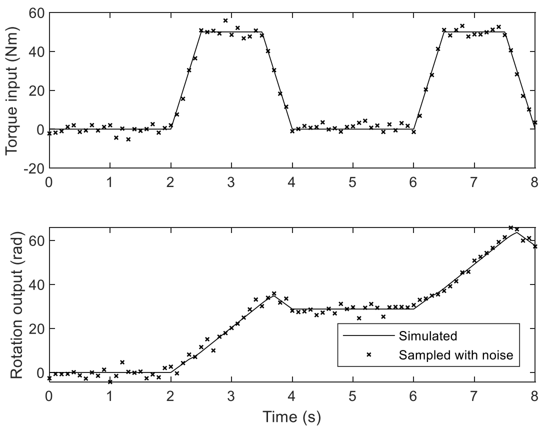

Figure 2: Simulation input and output. Noise $\sigma = 2$. Output decreases at ~3.75s and ~7.75s due to elastic relaxation.

Table 1: Known and identified parameters statistics (n=100) (initial guess: T_{crit} =13.3, b=0.1, c=1]).

	T_{crit}	b	c
Known value	30.0	0.200	2.00
Average identified	31.5	0.195	1.97
Standard deviation	4.1	0.031	0.075
Coefficient of variation	13.6	15.3	3.7

The Monte-Carlo analysis shows that the simulated annealing consistently converged to reasonable parameter values and was not particularly dependant on noise. Hence, it may be concluded that the developed model is robust and identifiable in the domain of likely parameter values.

There are limitations to this simple model. Notably, we assumed that the bone is homogeneous (and the parameters are independent of screw location). We also modelled the friction on the advancing screw as purely viscous. However, there are likely to be components of viscous and coulomb friction. Friction is also likely to increase as the screw advances into the bone. The elasticity and the displacement as force increases will be dependent on both the bone rigidity, and the screw /screwdriver rigidity; this could be problematic if displacement is measured at the handle of a screwdriver, but could be resolved by measuring the displacement at the tip of the screwdriver instead. Analysis of the effects of these assumptions will be part of future research comparing this model to more complex models and experiments, and attempting to mitigate discrepancies. The parameters used here were chosen without an experimental justification; future work will base these on experimental data and literature (e.g. T_{crit} could be determined by increasing torque until a screw rotates).

The eventual aim is to develop a method for optimising torque recommendations during orthopaedic surgery. This will require a more sophisticated model derived from *ex vivo* animal experimentation. However, this research shows the preliminary feasibility of using models for obtaining bone material properties that are critical for successful model-based decision support in orthopaedic surgery. Existing screwing models in literature will also help guide future modelling efforts [4][5].

Table 1 shows that the model values obtained were close to the parent values used to simulate the model and that the noise did not cause significant divergence from the true underlying behaviour. The coefficient of variations shown are within the tolerance required to benefit decision support to the surgeon. However, this divergence is likely to increase if additional identified model parameters are required to capture the complex behaviour of bone.

IV. Conclusion

This paper proposed a model for the torque-rotation relationship of bone, and determined that the model was identifiable, and robust. Future work will utilise and develop this model to capture the complex non-linear behaviour of human bone.

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AUTHORS INFORMATION

Conflict of interest: The authors declare no conflict of interest.

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