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Investigating Torque-Speed Relationship of Self-Tapping Screws

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Abstract— **Correctly torquing bone screws is important to prevent fixation failures and ensure positive patient outcomes. It has been proposed that an automatic model-based method may be able to determine the patient-specific material properties of bone, and provide objective and quantitative torquing recommendations. One major part of developing this system is the modelling of the bone-screwing process, and the self-tapping screwing process in general. In this paper, we investigate the relationship between screw insertion torque (Nm) and speed of insertion (RPM). A weak positive correlation was found below approximately 30 RPM. Further research should focus on increasing the precision of the methodology, and this testing must be extended to ex-vivo animal bone testing in addition to the polyurethane foam substitute used here.**

Clinical relevance: **To maximise the accuracy of torque recommendations, the model should account for all important factors. This study investigates and attempts to quantify the relationship between screw insertion speed and torque for later inclusion in modelling if significant.**

I. INTRODUCTION

Bone screws are commonly used in orthopaedic surgery, primarily to fix implants in bone, or for stabilising fractured bone to facilitate natural healing. Incorrect torquing of bone screws through under-/over-tightening can result in screw loosening [1] or thread stripping [2], which may cause implant failure and/or tissue damage [3]; these can be costly and risky remedy with revision surgery.

Surgeons currently torque screws in an *ad-hoc* manner. While experienced surgeons can achieve good results, the potential for error remains [4]. Wilkie *et al.* [5] proposed that an automated system for bone screw torque limitation could provide more intelligent control over bone screw torquing, leading to better patient outcomes. This system could operate by monitoring signals from the screwing process such as torque and angular displacement over time. These signals would be used to fit a model of the screwing process. The model would have unknown parameters for the bone material properties, hence fitting the model would determine these properties. The bone properties could then be combined with known information about the screw, hole, and implant geometry to estimate the optimal torque for the screw. This optimal torque could then be used through a torque indicator or limiter to allow optimal screw torquing.

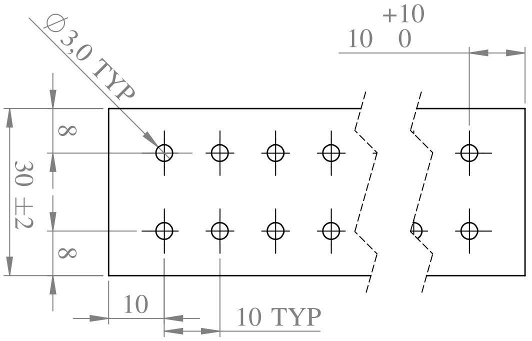

Fig. 1. Layout of holes in test sample. Holes go completely through the samples (approx. 50mm depth)

The currently proposed model-based methods for bone material property identification [6] [7] do not consider the insertion speed of the screw as a factor impacting the insertion torque. This is because evidence suggests minimal relationship between insertion speed and torque [8], however, these studies were done with aluminium, which appears to be less strain-rate dependant than bone [9] [10]. Furthermore, recent work suggests that there is indeed some difference in torques at different insertion speeds [11], however the specifics of this relationship remains unknown. In this paper, the relationship between insertion speed and torque is investigated further. Rigid polyurethane foam, a common bone substitute for biomechanical testing [12] with documented and relatively consistent material properties, was used as a substitute for real bone. A bone screw was inserted into pre-drilled holes at a variety of speeds and the torque-displacement data was recorded and analysed.

II. METHODS

A. Data Collection

The test samples were made from 0.16 g/cm^3 rigid polyurethane foam (Sikablock M160, Sika Services AG). The material was cut into pieces approximately 250 x 30 x 50 mm^3. Holes were drilled completely through the 250 x 30 mm^2 face, 8 mm from the long edges (As required by the test rig [13]), with 10 mm spacing along the long axis, and min. 10 mm space from the ends of the long axis; as in Fig 1. After drilling, the holes were inspected for defects (such as non-round holes from drill 'wandering' during initial insertion), these were marked with a cross, and not used for testing (Fig. 2). The screw used for testing was an HB 6.5 cancellous screw (Specified in ISO 5835:1991 [14]), seen in Fig. 2.

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Fig. 2. Example of test sample piece mounted in test rig, miss-drilled holes are marked with a cross. An HB 6.5 screw is pictured carefully aligned and placed against hole ready for testing.

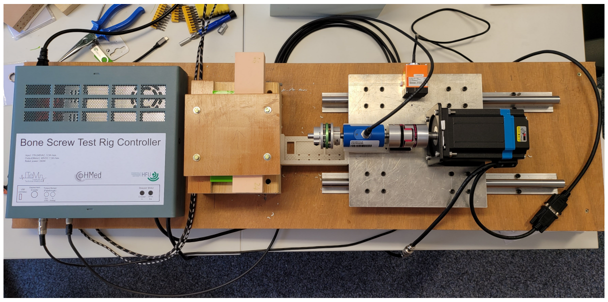

Fig. 3. Test rig used to insert screws into test samples while recording torque and rotational/angular displacement.

The screw insertion was performed with the test rig described in [13](Shown in Fig. 3). This consisted of a stepper-motor powered screwdriver with torque and rotation measurement, mounted on a sliding platform with linear displacement measurement. The platform was inclined just enough to overcome the friction of the sliding platform and make it slide unassisted towards the clamped test sample (Shown in Fig. 2).

The screws were driven into the holes at a range of speeds. First a coarse test was done from 10 to 70 RPM in 15 RPM increments, with 15 repetitions at each speed. After the rough shape of the trends was checked, another test was performed at 5 RPM to give more range. To gain more resolution at low speeds, another set of tests was done from 5 to 35 RPM in 7.5 RPM increments, with 15 repetitions at each speed, except 35 RPM, which had 10 repetitions due to limited material availability.

For the first set of tests, zero-point calibration was performed once at the start at 10RPM test, and again if the test rig needed to be restarted due to software/comm errors. For the second set, the calibration was re-run whenever the speed was changed, and if a restart was required. The first set of tests and the first 5 RPM test was carried out with a 9/64” hexagonal screw bit which tightly fit the screw; however, as the fit was very tight and not perfectly straight, there was concern that this would exacerbate screw misalignment and introduce errors, therefore the last set of tests was performed using a Torx T20 bit, which had a close fit, but allowed the screw to pivot several degrees, preventing unwanted forces.

For each test, the test sample was placed against a flat block in the clamp to ensure the front surface was perpendicular to the screwdriver shaft. The hole for testing was carefully aligned within approx. 1mm of the shaft centreline, and the test piece was lightly clamped in place. The screw was then loaded into the screw bit, and carefully placed against the hole (Fig. 2). A light push was given at the back of the motor to initially push the screw into the material, making sure it engaged, and increasing consistency as sometimes the screw hit the hole in the previous step a little harder than desired. Without touching the test rig, the ’start’ command was given, and the motor automatically inserted the screw at the constant set speed for 8 revolutions, and then reversed 9 revolutions. Each hole was used for only one insertion, however as 8 revolutions is only approximately 22 mm of the 50 mm thickness, the screws were inserted from both sides to make more efficient use of the material.

For each test, the torque, angular displacement, and linear displacement were sampled at 1000Hz. The data was sent over a USB-serial connection, and a custom program was created to save the data in labelled, timestamped, files, while also allowing USB control and configuration of the test rig.

B. Data Processing

First the data must be pre-processed. Because only the time period of screw insertion is useful, the data was trimmed to this period, and the linear displacement was initially zeroed at the start of this period.

To correct for rotational slip as the screw initially engaged in the hole, the linear encoder was used. The middle third of the insertion data was selected to avoid inconsistencies at the beginning and end of insertion; the linear displacement data from this was then fitted with a linear regression with respect to time. This was extrapolated to find the time that the displacement would be zero, assuming no slipping. The angular displacement was then zeroed at this time. This is imperfect, as the displacement will not be perfectly accurate during the initial engagement, however it will be accurate for the majority of the data recording, and is an objective way to correct for the slip given the data collection methodology above.

To get a simple value to compare for each test, parameter identification was used to estimate the material strength (in MPa) from each dataset. The model used for identification was based on [15], and used only the cutting torque and friction torque terms. This model is summarized in (1). Where G_1 and G_2 are geometric parameters based on the size/shape of the hole and screw. $\psi(\phi)$ and $\zeta(\phi)$ are discontinuous functions correcting for the screw taper partially engaging (as the screw first enters the material) and breaking-through (if the screw exits the opposite side of the material; not important here), respectively. α is the angular length of the thread-cutting section of the screw. μ is the friction coefficient between the screw and the hole, and σ_{uts} is the ultimate strength of the hole material. The τ_{cutting} term increases as the screw engages,

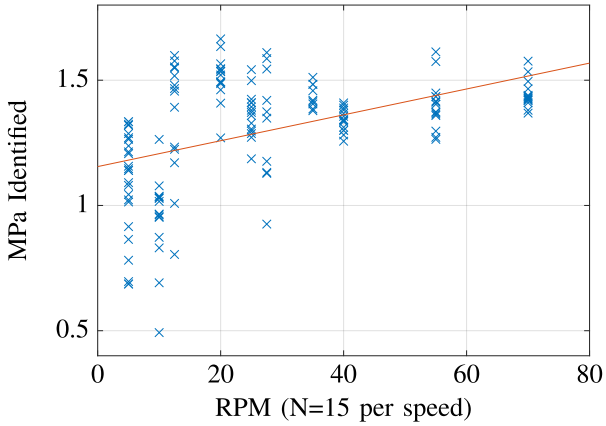

Fig. 4. Relationship between insertion speed and identified strength, with linear fit.

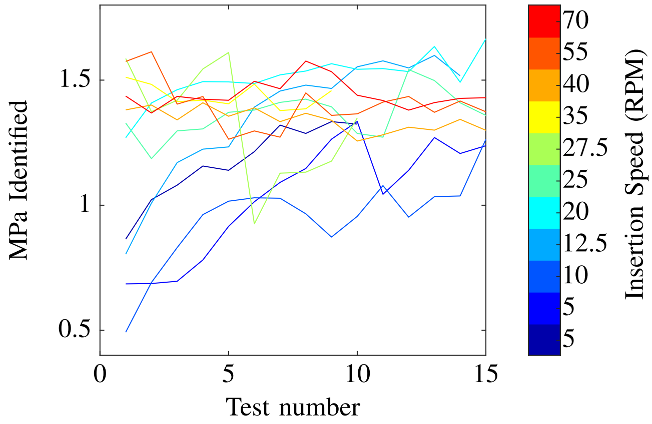

Fig. 5. Trend in identified strength values for each set of tests. Using color-bar as legend to show insertion speed of each set.

and then remains constant, while the τ_{friction} term increases linearly as the screw is inserted deeper. As the shape of the screw thread [14] does not fit the triangular shape used in the model [15], it was approximated by setting the thread angle, 2β, in [15] to $\alpha + \beta$ from [14] (30°); the major diameter was used as-is.

$$\begin{aligned}\tau_{\text{total}}(\phi) &= \tau_{\text{cutting}} + \tau_{\text{friction}} \\ &= \sigma_{\text{uts}} G_1 \left(\frac{\psi(\phi) - \zeta(\phi)}{\alpha}\right) + \sigma_{\text{uts}} G_2 \mu \left(\phi - \frac{\alpha}{2}\right)\end{aligned} \tag{1}$$

A simple linear least squares regression was used on the preprocessed datasets to fit the model and identify the σ_{uts} values (all other variables are known). As the τ_{total} is directly proportional to σ_{uts}, it is used to represent the insertion torque in the analysis later; this also accounts for experimental variation in insertion depths, and the variation in torque throughout the insertion.

III. RESULTS

The initial relationship between insertion speed and identified strength is shown in Fig. 4, with $r^2 = 0.22$. The identified values as a function of test number for each speed were plotted in Fig. 5, the two sets of 5RPM tests are shown as separate lines. As there were significant non-random variations visible in the first tests, the relationship plot was recreated with only the last 5 (presumably stabilised) tests from each speed in Fig. 6 with $r^2 = 0.06$.

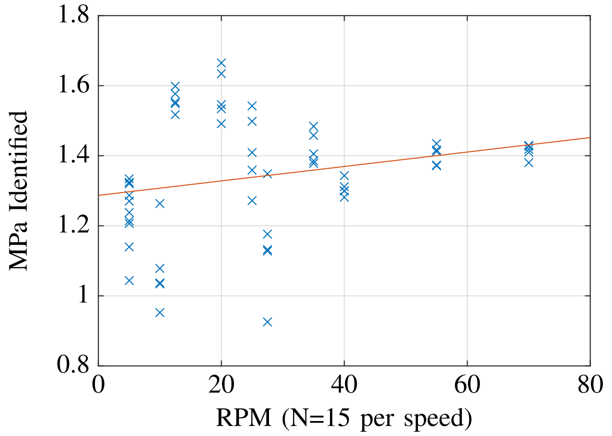

Fig. 6. Relationship between insertion speed and identified strength, with linear fit, for last 5 tests at each speed.

IV. DISCUSSION

From the initial data in Fig. 4, there appears to initially be a slight increase in torque as speed increased. After about 20-30 RPM, there is not so much obvious variation. This suggests that there is some effect up to this speed, and then minimal change thereafter. However, because of the high variation present, the trends in identified strength over the individual tests at each speed were plotted in Fig. 5. This shows that there was some systematic errors in the experiment, as increasing trends can be seen, especially at lower speeds. It is thought that this could be due to either increasing temperature of the screw throughout the testing, or surface contamination(e.g. skin oil) of the screw which is slowly rubbed off. Notably these effect the initial tests, particularly on the low speeds. To try and counteract this, a modified dataset was made with the last 5 samples at each speed, as shown in Fig. 6. In this case the variation is lower, but still significant, suggesting that there may still be more experimental issues; however, the r^2 value decreased, which also suggests that the previous trend could be partially due to experimental errors; this would disagree with [11], although that testing was much more limited in scope, and the same potential errors may have also been present there, however they would not be visible due to the limited dataset in that paper. Another explanation is that in this study we are assuming a linear fit, which may be inappropriate, and could be the reason for the very poor r^2; a more appropriate curve, for example, a logistic curve, may improve the fit, however this is difficult to check with the relatively low number of data points in this paper, so more granular speed resolution may be useful in future studies.

Nevertheless, there are a few simple things that can be improved or investigated in subsequent studies. In this study only a single material was tested, however different materials/conditions may have different responses to speed. Future work may address this by testing with different densities of PU foam, or with ex-vivo animal bone. Controlling for surface contaminants which may have affected consistency can be done by washing the screw between tests, and controlling for temperature can be achieved by doing the same with a consistent water temperature to remove heat build-up from previous tests; it may also be desirable to test these individually to determine which factors are most relevant. If temperature has a larger effect, this may not be so significant in clinical settings since the screws are only inserted once, minimising heat build-up, and the vascularity of bone will help transfer the heat away as it is generated; however if surface contamination has a large effect, then in-depth investigation may be required, as the fluids present in-vivo could have major clinical implications, which would be difficult to simulate with dry PU foam or ex-vivo/frozen animal bone.

Another simple improvement is in regards to the screw engagement/linear displacement offset. In this testing, the screw was placed up against the hole with some force, and this was used as the zero-point for displacement; however in reality, pushing the screw against/into the hole already starts the insertion, so the zero point will be incorrect. Additionally, as mentioned in the method, the slipping of the screw as the insertion begins is difficult to quantify. And, with the setup used here, the shaft couplers introduce some axial compressibility, which prevent the displacement sensor from being used at the primary independent variable in the parameter identification, even though it can help account for both slip and zero-point offset. These can be remedied by adjusting the shaft coupler so that the shaft ends press against each-other, and the coupler cannot compress, making it more akin to a rigid coupler, but still allowing some rotational misalignment. Then the displacement zero point can be accurately determined by placing the screw tip inline with the surface of the material and zeroing the displacement at that point.

Another possible error source is that as the test rig controller warms up after being turned on, the ADC readings may drift until the temperature stabilises; so it is important to check the that the torque reads as zero before starting each test, and re-calibrate as necessary. The torque sensor used has a range of 20 Nm, and 0.5% accuracy (of total range), which is about 0.1 Nm, and as the maximum torque measured here is about 0.4 Nm, there may be some errors introduced by the sensor selection. Future work can address this with a lower range sensor (e.g. 5 Nm).

Some aspects may be much harder to control. For example, variations in the holes could arise from sample preparation (e.g. drill bit warming up/wearing down). Humidity may affect the permeable PU foam. Room temperature may vary during the day, or between days for larger studies. The PU foam may have significant inhomogeneity. And, random noise can be present from numerous sources. However, these should not be blamed until all controllable sources or error have been addressed.

V. CONCLUSIONS

The relationship between self tapping screw insertion speed and insertion torque was investigated. There is some evidence for a positive correlation at low speeds, however the variance in the data limits the predictive ability of this analysis. A number of suggestions have been made to improve future studies, and hopefully find conclusive evidence for the existence or non-existence of a quantitative relationship. Additionally, ex-vivo animal bone testing must be performed to test the applicability to real bone, although this will not be a perfect representation of in-vivo human application.

REFERENCES

[1] M. Evans, M. Spencer, Q. Wang, S. H. White, and J. L. Cunningham, "Design and testing of external fixator bone screws," *Journal of Biomedical Engineering*, vol. 12, no. 6, pp. 457–462, Nov. 1990.

[2] A. Feroz Dinah, S. C. Mears, T. A. Knight, S. P. Soin, J. T. Campbell, and S. M. Belkoff, "Inadvertent Screw Stripping During Ankle Fracture Fixation in Elderly Bone," *Geriatr Orthop Surg Rehabil*, vol. 2, no. 3, pp. 86–89, May 2011.

[3] N. J. Hallab and J. J. Jacobs, "Biologic effects of implant debris," *Bull NYU Hosp Jt Dis*, vol. 67, no. 2, pp. 182–188, 2009.

[4] M. J. Stoesz, P. A. Gustafson, B. V. Patel, J. R. Jastifer, and J. L. Chess, "Surgeon Perception of Cancellous Screw Fixation," *Journal of Orthopaedic Trauma*, vol. 28, no. 1, p. e1, Jan. 2014.

[5] J. Wilkie, P. D. Docherty, and K. Möller, "A simple screwing process model for bone material identification," *Proceedings on Automation in Medical Engineering*, vol. 1, no. 1, pp. 038–038, Feb. 2020.

[6] ——, "Developments in Modelling Bone Screwing," *Current Directions in Biomedical Engineering*, vol. 6, no. 3, pp. 111–114, Sep. 2020.

[7] J. Wilkie, P. D. Docherty, T. Stieglitz, and K. Möller, "Geometric Generalization of Self Tapping Screw Insertion Model," in *2021 43rd Annual IEEE Conference of the IEEE Engineering in Medicine and Biology Society, In Press*, Guadalajara, Mexico, 2021.

[8] R. Chumakov, "Optimal control of screwing speed in assembly with thread-forming screws," *Int J Adv Manuf Technol*, vol. 36, no. 3, pp. 395–400, Mar. 2008.

[9] Y. Chen, A. H. Clausen, O. S. Hopperstad, and M. Langseth, "Stress–strain behaviour of aluminium alloys at a wide range of strain rates," *International Journal of Solids and Structures*, vol. 46, no. 21, pp. 3825–3835, Oct. 2009.

[10] F. Linde, P. Nørgaard, I. Hvid, A. Odgaard, and K. Søballe, "Mechanical properties of trabecular bone. Dependency on strain rate," *Journal of Biomechanics*, vol. 24, no. 9, pp. 803–809, Jan. 1991.

[11] J. A. Wilkie, P. D. Docherty, and K. Möller, "Speed-torque relationship for self-tapping bone screw insertion," in *15th Interdisciplinary Symposium Automation in Medical Engineering (AUTOMED 2021).*, Basel, Switzerland, 2021.

[12] K. L. Calvert, K. P. Trumble, T. J. Webster, and L. A. Kirkpatrick, "Characterization of commercial rigid polyurethane foams used as bone analogs for implant testing," *J Mater Sci Mater Med*, vol. 21, no. 5, pp. 1453–1461, May 2010.

[13] J. A. Wilkie and K. Möller, "Test rig for bone screw insertion modelling," in *15th Interdisciplinary Symposium Automation in Medical Engineering (AUTOMED 2021).*, Basel, Switzerland, 2021.

[14] International Organization for Standardization, "ISO 5835:1991(en), Implants for surgery — Metal bone screws with hexagonal drive connection, spherical under-surface of head, asymmetrical thread — Dimensions," https://www.iso.org/obp/ui/#iso:std:iso:5835:ed-1:v1:en, 1991.

[15] L. D. Seneviratne, F. A. Ngemoh, S. W. E. Earles, and K. A. Althoefer, "Theoretical modelling of the self-tapping screw fastening process," *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, vol. 215, no. 2, pp. 135–154, Feb. 2001.