Acoustic Characterization of Intramedullary Screw Fixation in Bone

Bianca Winter[1], Robert A. Kaufmann[2], Martin Schneider[1], Berndt Zeitler[1] and Steffi Reinhold[1]
[1] *University of Applied Sciences Stuttgart, 70174 Stuttgart, Germany, Email: berndt.zeitler@hft-stuttgart.de*
[2] *University of Pittsburgh, Email: kaufmannra@upmc.edu*

Introduction

Total elbow arthroplasty currently achieves fixation through the use of polymethyl methacrylate (PMMA) which fills the void between the implant and bone and quickly dries in an exothermic reaction. It does not promote osseointegration, which is defined as "the formation of a direct interface between an implant and bone, without intervening soft tissue" [1]. The bond between the PMMA and bone can weaken and lead to loosening and implant failure with up to 50% aseptic loosening rates in young patients [2].

The overall research explores a novel method of fixation that may promote osseointegration through the use of an intramedullary screw incorporated into the implant components. As the screw is advanced, it pulls the implant into a cavity created by drilling and broaching the bone. A snug fit is desired and serves to increase implant stability and allow for bone integration [1], [3].
Secure fixation affords the opportunity to create cross-linkages between the implant and bone and inhibit detrimental micro-motion and shear force creation [4], [5]. Screw fixation in long bones has been used since 1990 through the OPRA System (Integrum AB, Sweden), which is a bone anchoring method for prosthesis fixation. A clinical investigation of 51 subjects with an above knee amputation were treated with OPRA with a cumulative survival rate of 92% at 2 years follow-up [4].

A novel total elbow arthroplasty has been designed that employs intramedullary screws to achieve secure fixation between the implant and bone [6]. Figure 1 illustrates a schematic of the novel implant being screwed into the upper arm bone.
As the screw is advanced, the implant is pulled into bone with relatively little torque. Once contact between the implant and bone is experienced, the pressure between these two as well as the torque required for seating the implant further increases. The goal of this tightening effort is to create a stable and durable connection. It is crucial that the screw is neither tightened so much that screw stripping or a fracture occurs or so little that a loose implant to bone fixation occurs.

The necessary torque that is required for secure fixation remains unknown and, yet, there appears to be a successful range as both high and low torque environments may be conducive to osseointegration.
Higher torque values lead to increased primary stability but may have adverse effects on bone adjacent to the screw threads [7], [8]. High torque creates micro fractures at the implant interface during implantation leading to bone debris inside the screw threads, which may have osteogenic effects [7], [8], [9]. High torque can also lead to a fracture, which is a very damaging complication as it dissipates the hoops stresses within the cortical bone and renders the circumference of the cortical bone unable to allow purchase of the intramedullary screw [10].

Low insertion torque leads to less initial stability but can result in considerable de novo bone formation. This bone neoformation enabled implants to catch up from a stability perspective when compared to high torque applied implants [11].

There exist no standardized method for correlating torque with implant stability. Prior efforts have relied on subjective "two-finger tightness", which heavily depend on the surgeon's tactile sensitivity and experience and are both inaccurate and unreliable [12]. Therefore, an objective method for determining the torque required for a secure fixation is sought.

The aim of the present study is to investigate whether acoustic measurement methods can be used to assess the screw connection in the bone. Acoustic failure prediction of bone has been described and occurs due to the changed acoustic propagation due to the internal stress of screw tightening leading to micro-structure deformity [13].

For this purpose, experimental investigations were carried out on a porcine bone using this novel elbow implant [6]. Within the study, the resonance frequencies of the drive-point mobility, meaning the ratio of the velocity of the bone relative to the applied force on the bone, was determined as a function of the tightening torque of the screw, in order to be able to determine criteria of the connection.

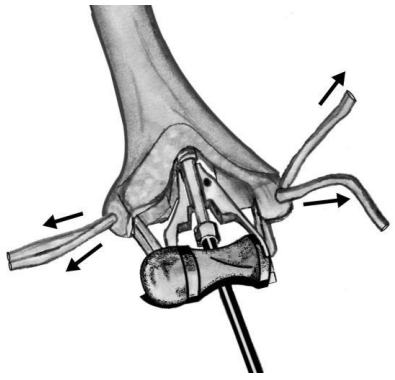

Figure 1: Schematic illustration of the implant being screwed into the upper arm bone [6].

Investigation

A right upper front leg of a pig served as the test object (Figure 2). The bone is approximately 17 cm long (approx. 30 cm in humans), with about 9 to 10 cm making up the shaft. The shaft is 2.5 cm wide and 3.5 cm thick (slightly thinner in humans) and is essentially hollow on the inside, containing spongy bone (spongiosa), which is very porous, soft, and lightweight. The central part of the bone and shaft is the narrowest point, while the bone becomes thicker toward the ends.

It was first investigated in its original, unmodified state. Subsequently, the original elbow joint was drilled and broached to create a big notch (or cavity) for the elbow implant. Subsequently a hole was drilled using increasing size drill bits until resistance was met. The drill hole was then tapped and acoustic measurements were taken. The implant was advanced by tightening the $7/16''$ (= 11,11 mm) screw and acoustic measurements were carried out with the implant in place and the screw tightened to varying degrees. Figure 2 shows the bone, with the notch and the inserted implant and screw.

The tightening was performed using a torque wrench in steps of 0.1 Nm, ranging from 0.3 to 1.7 Nm.

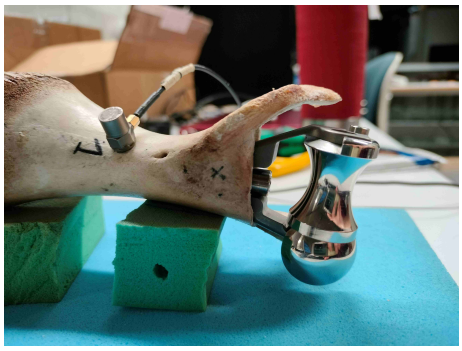

Figure 2: The bone, with notch, implant and screw on the right, as well as accelerometer to measure the velocity in the middle.

Using an accelerometer, the velocity was measured on the shaft at the centre of the bone. The mobility was obtained by calculating the ratio of velocity divided by the averaged force from both of the two impulse hammer excitation points in front of and behind the accelerometer. The bone was supported on Sylomer and was thereby freely suspended within the considered frequency range ($\geq$ 100 Hz).

Results

Initially, the mobility of the original bone showed resonance frequencies of the bending waves at 1540 Hz and 1850 Hz. After creating the cavity for the implant, these frequencies increased to 1740 Hz and 2400 Hz (Figure 4). This increase of the resonance frequency is attributed to the now shorter and lighter bone. An additional resonance appeared at 900 Hz, which probably pertains to a wave type other than a bending wave, due to the new shape and notch and will not be part of the current study.

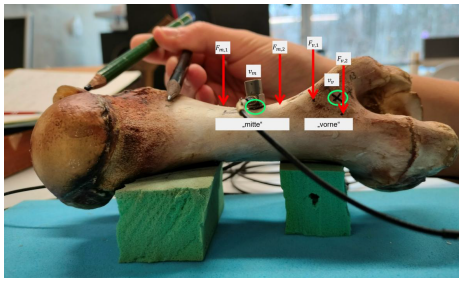

Figure 3: Measurement setup with the unmodified bone placed on Sylomer, the accelerometer (green), and the excitation points (red) positioned at the centre (purple box). The elbow joint is visible on the right side of the image.

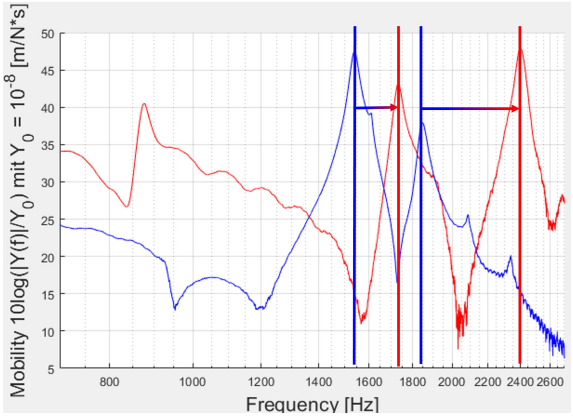

Figure 4: Mobility over frequency for the pure bone (blue) with resonance frequencies at 1540 Hz and 1850 Hz and the bone with notch (red) with increased resonance frequencies at 1740 Hz and 2400 Hz.

Figure 5 presents the mobility with the implant in place. Note that it varies quite strongly, because bone is very difficult to excite exactly in the same position and the surface contact is very different along the bone - even in spots very close to each other. Each colour represents a different tightening torque, whereby the red cure is without the implant.

In Figure 6, individual curves from Figure 5 are plotted over a smaller frequency range to provide a clearer and more accessible overview. It is evident that the resonance frequencies shift, however, the exact amount is not clearly discernible. To better illustrate this, the frequency of the first resonance (around 1740 Hz) is plotted against the applied torque in Figure 7.

When examining the progression of the first resonance frequency in Figure 7, a distinction between two different torque regions becomes apparent: loose and tight torque ranges. From 0 up to approximately 0.7 Nm, the torque is still considered loose. In this region, the resonance frequency decreases as the torque increases. A definitive explanation for this behaviour could not be determined within the scope of this study. Possible theories include that the added mass at the one side of the bone converts the boundary conditions from free-free, were multiples of half a wavelength describe the mode shape, to more free-fixed boundary condition, were odd multiples of

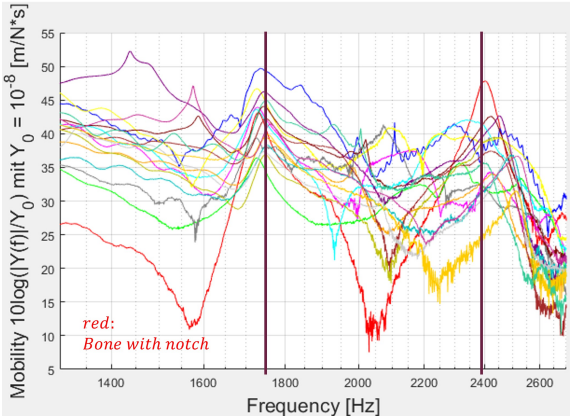

Figure 5: Mobility over frequency for the bone with varying screw tightness (one colour per torque level; red curve represents the bone without implant). Two prominent resonance frequencies are visible at approximately 1700 Hz and 2400 Hz. The individual curves and resonance peaks vary depending on the strength of the screw connection.

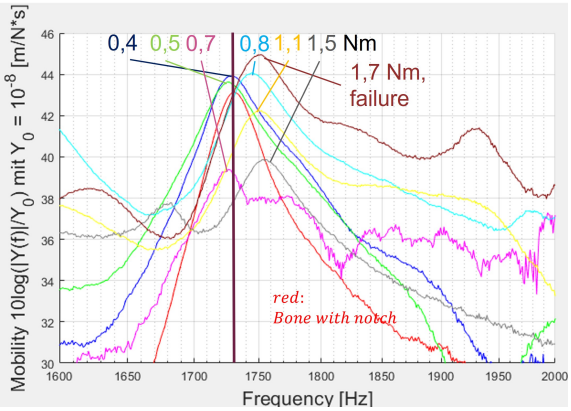

Figure 6: Mobility over frequency for the bone with varying screw tightness with less curves and smaller frequency range (one colour per torque level; red curve represents the bone without implant). One prominent resonance frequencies is visible at approximately 1700 Hz. The individual curves and resonance peaks vary depending on the strength of the screw connection.

the quarter wavelength describe the mode shape. Thereby the wavelength increases and the resonance frequency is shifted to lower frequencies. This trend could also be reproduced in simplified FEM simulations.

At around 0.7 Nm, the resonance frequency increases sharply, even exceeding that of the notched bone. This marks the beginning of the tight torque region. Here, the resonance frequency continues to rise with increasing torque. Here the assumption is that the screw that is within the bone increases the tension or effective bending stiffness of the bone, thereby giving it a higher resonance frequency as if tightening the string of a guitar.

Within the tight torque range, two distinct drops in the resonance frequency can be observed. The first occurs at 1.4 Nm, corresponding to the point at which the connection was subjectively described as firm. This drop could indicate a first weakening the bone-thread, resulting in

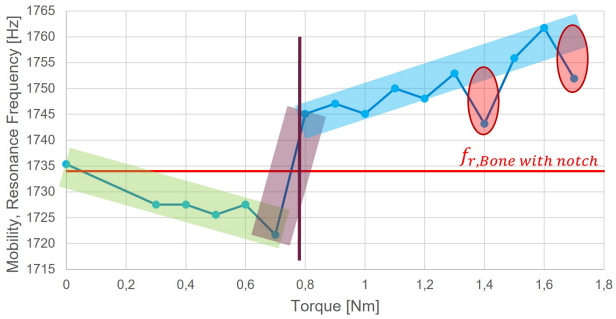

Figure 7: First resonance frequency over corresponding torque. Green: Loose torques – resonance frequency decreases. Purple: Transition (around 0.7 Nm) – strong increase in frequency. Blue: Tight torques – slight increase in resonance frequency. Red: sudden drop in high torque region possibly suggesting initial bone thread failure.

the reduction of effective bending stiffness. The second drop appears at the end of the measurement series, at 1.7 Nm, where the bone was visibly fractured (a fragment broke off), thereby causing the effective bending stiffness to reduce even more, leading to a lower frequency. This second drop is associated with a failure of the bone.

Conclusion

This study demonstrated that acoustic measurement methods can be employed to assess the screw connection of an implant within a porcine bone. A clear relationship between the screw's tightening torque and the bone's bending wave resonance frequencies was observed.

Two distinct ranges of torque when tightening the screw/implant are observed:

- At low torques, the resonance frequency decreases, due to the added mass.
- At high torques, the resonance frequency increases, due to the increased effective bending stiffness.
- A transition occurs, where the resonance sharply increases and even surpasses that of bone with a notch.

At the end of the high torque region, the resonance frequency drops several times, which suggest the failure/breaking of the bone to a different extents.

The findings suggest that it is possible to assess the tightness of the screw connection using acoustic measurement methods, more specifically with drive-point mobility measurements on the bone. The resonance frequencies of the bone changes as a function of the torque that was applied to advance and then secure the implant to the bone.

Study Limitations

In this study, the firm connection states were based solely on the intuition of the scientist (BW) that was performing the experiment and represent a source of error. Future implantation studies may generate torque recom-

mendations that are based on biomechanical stability assessment and obviate the need for subjective torque application.

Outlook

Future investigations will include the performance of multiple trials on the same bone performed by different scientists to identify inter and intra observer measurement reliability and repeatability.

Furthermore, similar measurements on different specimens will be carried out to allow the evaluation of variations that may occur due to bone geometry (length or wall thickness) and bone density.

The hope is that these two (low and high) torque ranges when tightening the screw appear in the further tests, implying that a guiding relative increase in resonance frequency could be identified in the high torque region, above the steep transition, that helps to decide when a firm connection is achieved.

Literatur

[1] Jayesh RS, Dhinakarsamy V. Osseointegration. J Pharm Bioallied Sci. 2015 Apr;7(Suppl 1):S226-9. doi: 10.4103/0975-7406.155917. PMID: 26015719; PMCID: PMC4439679.

[2] Callaghan JJ, Forest EE, Olejniczak JP, Goetz DD, Johnston RC. Charnley total hip arthroplasty in patients less than fty years old. A twenty to twenty-ve-year follow-up note. J Bone Joint Surg Am. 1998;80(5):704e714.

[3] Thesleff, Alexander, et al. "Biomechanical characterisation of bone-anchored implant systems for amputation limb prostheses: a systematic review.Änals of biomedical engineering 46.3 (2018): 377-391.

[4] Brånemark, R., Berlin, Ö., Hagberg, K., Bergh, P., Gunterberg, B., and Rydevik, B. (2014). A novel osseointegrated, percutaneous prosthetic system for treatment of patients with transfemoral amputation: A prospective study of 51 patients. Bone Joint J, 96-B(1), 106–113

[5] Turkyilmaz, I., Aksoy, U. and McGlumphy, E.A. (2008) Two alternative surgical techniques for enhancing primary implant stability in the posterior maxilla: a clinical study including bone density, insertion torque, and resonance frequency analysis data. Clinical Implant Dentistry and Related Research 10: 231–237.

[6] C. H. Bettwitt et al., Elbow Uncemented Hemiarthroplasty: Surgical Technique. Department of Orthopaedic Surgery, University of Pittsburgh, published by Elsevier Inc., 10. August 2023

[7] Tabassum, A., Walboomers, X.F., Wolke, J.G.C., Meijer, G.J. and Jansen, J.A. (2010a) Bone particles and the undersized surgical technique. Journal of Dental Research 89: 581–586.

[8] Duyck J, Roesems R, Cardoso MV, Ogawa T, De Villa Camargos G, Vandamme K.(2015) Clin Effect of insertion torque on titanium implant osseointegration: an animal experimental study. Oral Implants Res. 2015 Feb;26(2):191-6.

[9] Dhore, C.R., Snel, S.J., Jacques, S.V.N., Naert, I.E.,Walboomers, X.F. and Jansen, J.A. (2008) In vitro osteogenic potential of bone debris resulting from placement of titanium screw-type implants. Clinical Oral Implants Research 19: 606–611.

[10] Bidgoli M, Soheilifar S, Faradmal J, Soheilifar S. (2015) High Insertion Torque and Peri-Implant Bone Loss: Is There a Relationship? J Long Term Eff Med Implants. 2015;25(3):209-13.

[11] Campos, F.E., Gomes, J.B., Marin, C., Teixeira, H.S., Suzuki, M., Witek, L., Zanetta-Barbosa, D. and Coelho, P.G. (2012) Effect of drilling dimension on implant placement torque and early osseointegration stages: an experimental study in dogs. Journal of Oral and Maxillofacial Surgery Official Journal of the American Association of Oral and Maxillofacial Surgeons 70: 43–50.

[12] Acker WB 2nd, Tai BL, Belmont B, Shih AJ, Irwin TA, Holmes JR. Two-Finger Tightness: What Is It? Measuring Torque and Reproducibility in a Simulated Model. J Orthop Trauma. 2016 May;30(5):273-7. doi: 10.1097/BOT.0000000000000506. PMID: 26655518.

[13] García-Vilana, S.; Sánchez-Molina, D.; Abdi, H. AcousticEmission in Bone Biomechanics: A Comprehensive Review of Mechanical Properties and Predictive Damage Modeling. Sensors 2025, 25, 598.https://doi.org/10.3390/s25030598

[14] M. Möser et al. (TU Berlin). Körperschall, Physikalische Grundlagen und technische Anwendungen, 3. aktualisierte Auflage. Springer-Verlag Berlin Heidelberg, 2009.

[15] M. Möser et al. (TU Berlin). Technische Akustik. 10. Auflage. Springer-Verlag Berlin Heidelberg, 2015.