Bruk Berhanu

Research Undergraduate
Laboratory for NDE and SHM Studies,
Department of Civil and
Environmental Engineering,
University of Pittsburgh,
Pittsburgh, PA, 15261
e-mail: bruk.berhanu@gmail.com

Piervincenzo Rizzo¹

Assistant Professor
Laboratory for NDE and SHM Studies,
Department of Civil and
Environmental Engineering,
University of Pittsburgh,
942 Benedum Hall, 3700 O'Hara St.,
Pittsburgh, PA, 15261
e-mail: pir3@pitt.edu

Mark Ochs

Associate Dean and Chair
Department of Oral and Maxillofacial Surgery at
the School of Dental Medicine,
University of Pittsburgh,
Pittsburgh, PA 15261
e-mail: mwo1@pitt.edu

Highly Nonlinear Solitary Waves for the Assessment of Dental Implant Mobility

In this paper we present a noninvasive technique based on the propagation of highly nonlinear solitary waves (HNSWs) to monitor the stability of dental implants. HNSWs are nondispersive mechanical waves that can form and travel in highly nonlinear systems, such as one-dimensional chains of spherical particles. The technique is based on the hypothesis that the mobility of a dental implant affects certain characteristics of the HNSWs reflected at the interface between a crystal-based transducer and the implant. To validate the research hypothesis we performed two experiments: first we observed the hydration of commercial plaster to simulate at large the osseointegration process that occurs in the oral connective tissue once a dental-endosteal threaded implant is surgically inserted; then, we monitored the decalcification of treated bovine bones immersed in an acid bath to simulate the inverse of the osseointegration process. In both series, we found a good correlation between certain characteristics of the HNSWs and the stiffness of the material under testing. [DOI: 10.1115/1.4006947]

Keywords: dental implants, osseointegration, highly nonlinear solitary waves, nondestructive testing

1 Introduction

A dental implant is an artificial titanium alloy device that is placed in contact with the jaw bones and oral connective tissues to replace functionally and esthetically the natural tooth and also to restore missing teeth in fully and partially edentulous patients. Generally, a dental implant is surgically placed in the jaw bone under the soft tissue and after three to six months of healing time, in which a stable implant-bone interface is reached, the soft tissue is opened, an abutment is connected to the implant and a crown (artificial tooth) is placed on the abutment.

Currently, there is not a universally accepted method to measure the stability of implants, i.e., to assess bone-implant interface healing. Such a method would reduce the time between the surgery and the placement of the crown, with undisputable cosmetic, economical, and clinical advantages for the patient. It also would help avoid premature restoration of the implant which can lead to failure. Several nondestructive mechanic and imaging techniques have been developed for the evaluation of orthopedic, dental prostheses, peri-implant wound healing, and the prognosis of implant therapy [1–3]. One of the most common methods is the Periotest [4–8] in which a tapper percusses the test object (tooth or implant) and the duration of contact with the test object is measured by an accelerometer located inside the tapper. The duration is then electronically converted into the Periotest value (PTV) which ranges from a -8 to $+50$. Loose implants cause a longer contact time and the PTV is correspondingly higher, while osseointegrated implants have a short contact time which results in low PTVs [9]. Despite the broad acceptance of the Periotest, its reliability in measuring implant stability has been questioned [2] since the PTV was reported to be influenced by the orientation of the excitation direction and the tapping position [10].

Another popular approach is based on the resonance frequency analysis [9,11,12]. A small L-shaped transducer screwed to the implant or the abutment is excited by a sinusoidal signal typically in the range 5–15 kHz. The dynamic response of the implant, and

particularly its resonance frequency, is measured as an indicator of the stability. The higher the resonance frequency, the more stable the implant. The measure of the first resonance peak is converted into a value called implant stability quotient (ISQ), ranging from 0 to 100. Although there is no uniform acceptance of the proper interpretation of the ISQ value, practitioners consider values below 45–50 risky for adequate stability [13]. Oh et al. [14] reported that ISQ value is proportional to bone formation. A series of stability meters based on the resonance frequency analysis is commercially available [15]. Although ISQ value might be useful for detecting tendency of implant stability, some authors questioned the diagnostic criteria for failure of the implantation [2]. Some authors argued that both PTV and ISQ value express only the displacement of the implant and cannot evaluate the surrounding periodontal tissue conditions [16]. To overcome the indicators provided by PTV and ISQ which mainly reflect the mobility and/or stability of implants, a noncontact electromagnetic vibration device was developed and tested for monitoring both tooth mobility and periodontal tissue conditions [16]. The aim was to evaluate the ability of the device to measure implant stability under various peri-implant conditions using mechanical parameters and the condition of periodontal tissues around the implant. Recently, Kim et al. [17] developed a dental implant mobility measurement system using an inductive sensor. The system includes an amplifier and an analyzer to perform power spectrum analysis. Various implant-tissue interfacial conditions were simulated in artificial implantation models of acrylic containing holes of different levels of depth and diameter.

Imaging techniques such as panoramic and intra-oral radiography [18] and computer tomography are widely used to assess both the quantity and quality of the jawbone [19]. They are utilized prior to surgery to estimate bone volume, density and morphology, the degree of the corticalisation, the density of mineralization, and the amount of cancellous bone [20,21]. Following the surgery, imaging methods can estimate changes in bone quantity and quality, and can determine any crestal bone loss, which may reflect the effectiveness of the osseointegration process. Conventional radiography has a limited capacity to predict less than 30–40% in the changes of bone minerals as well as trabecular bone loss. In these cases, 3D techniques such as tomography are

¹Corresponding author.

Manuscript received December 19, 2011; final manuscript received May 17, 2012; accepted manuscript posted June 7, 2012; published online November 20, 2012. Assoc. Editor: John Lambros.

preferred. However, bulkiness, cost, scatter-effect from the metallic implant and concern about radiation exposure prevent the widespread use of equipment for imaging.

In this paper, we present the results of an initial investigation where highly nonlinear solitary waves (HNSWs) are proposed as a noninvasive tool for the assessment of dental implants. HNSWs are mechanical nondispersive waves that can form and travel in highly nonlinear systems. The simplest system that can support the formation and propagation of HNSWs is a closely packed chain of elastically interacting particles (i.e., granular crystals) [22–26]. Such a medium allows the generation of these waves without the need for electronic equipment such as arbitrary function generators and piezoelectric crystals or other transduction mechanisms. Moreover, these waves are characterized by a propagation speed that can be up to one order of magnitude smaller than the sound speed of the material that composes the particles in the chain [27]. In this study, we hypothesized that the reflection of HNSWs at the interface between the nonlinear system and the implant is affected by the progression of the osseointegration process. The overarching hypothesis is that the stiffness of an implant inserted into a living bone can be assessed by observing the propagation of the solitary waves within a chain of spherical particles in contact with the prosthetic apparatus. The aim is to develop a non-invasive approach that can accurately and consistently assess the osseointegration progress and therefore enabling surgeons to determine the exact time at which healing fully occurs. The work extends to the field of biomechanics and bioengineering the application of HNSWs for the nondestructive testing (NDT) of structures. The use of HNSWs in NDT has mainly focused on the detection of impurities in the chain itself [28–33] rather than on the inspection of structures. Recently, researchers at the University of Pittsburgh and California Institute of Technology have demonstrated the feasibility of HNSWs for the NDT structural materials placed in contact with the nonlinear system [34–37].

In the present study, a HNSW transducer reported for the first time in Ref. [38] was used in two experiments. In the first experiment, hereafter plaster test, a short screw was placed inside a hardened plaster cube and stabilized with fresh joint compound. The curing of the compound, i.e., the interface between the screw and the plaster, simulated at large the osseointegration that occurs in the oral connective tissue once a dental-endosteal threaded implant is surgically inserted. In the second experiment, hereafter the bone test, we inserted medical grade dental implants inside treated bovine bone samples, which were then immersed in a solution of nitric acid. The acid induced the loss of calcium and bone softening which could be seen as reverse osseointegration. In both tests we observed how reflected solitary waves are formed at the interface between the transducer and the linear medium, i.e., the screw and the implant. We then correlated certain features of the HNSWs to either the curing time of the compound, which was responsible for the stabilization of the screw, or to the bone's calcium loss which affected the stiffness of the bone-implant system.

The paper is organized as follows: First we describe the overall concept of HNSWs as applied to the assessment of dental implants and the apparatus used to generate, detect, and digitize the solitary waves. Then, we report on the setup and results of the plaster test, while Sec. 4 presents the setup and results of the bone test. Finally, Sec. 5 summarizes the findings and outlines future issues that should be addressed prior to clinical trial.

2 Background

As stated earlier, a one-dimensional chain of n spherical particles like the one shown in Fig. 1 is the simplest nonlinear granular medium that can support the propagation of HNSWs. Conventionally, the solitary wave pulse is formed by impacting the first particle of the chain with a striker having the same mass of the beads composing the chain or alternatively by irradiating the top particle with laser pulses [39]. It has been demonstrated that when a single wave interacts with a medium (the test object)

Fig. 1 General scheme of implant and tooth assessment by means of highly nonlinear solitary waves

that is in contact with the bottom particle of the chain, one or two HNSWs are reflected back to the chain [27,36]. When the test object has a high value of the Young's Modulus only one pulse, the primary reflected solitary wave (PSW), is reflected. When the material adjacent to the granular chain is "softer," a second pulse, called secondary reflected solitary waves (SSW), can be generated in addition to the PSW. The mechanisms that determine and govern the formation of the primary and secondary reflections are detailed in Yang et al. [27], in which the formation of the secondary waves was systematically studied for the first time. Details on the governing equations that describe the propagation of HNSWs as it applies to the nondestructive assessment of linear medium are instead available in Refs. [27,34–36].

In this work, we characterized the wave reflection properties measuring the time-of-flight (TOF) and the amplitude of the primary reflected solitary wave, and the amplitude of the secondary reflected solitary wave if generated. Here, the TOF denotes the transit time at a given sensor bead in the granular crystal between the incident and the reflected waves. We used the transducer shown in Fig. 2 for the automatic generation and detection of HNSWs. The transducer consisted of a Teflon tube filled with stainless steel particles. The chain embedded two sensor particles as described in Refs. [36,38], placed at the position $n = 11$ and $n = 16$ of the chain. The striker was a low-carbon steel bead lifted and released by means of an electromagnet placed on top of the tube. The electromagnet was connected in series with a switch circuit controlled by a TTL driven by a National Instrument—PXI running in LABVIEW. With the switch closed (TTL = 1), the electrical current provided by a DC power supply passes through the coil of the electromagnet to lift the striker. With the switch open (TTL = 0), the striker is released and enabled to impact the chain. A LABVIEW front panel was designed to select the TTL's width and repetition rate. This setup allowed the complete automation of the transducer, as well as the storage of the digitized waveforms.

3 Plaster Test

3.1 Experimental Setup. We cast one 75 mm (3 in) cube made of commercial gypsum plaster cement mixed with water. The water-cement ratio was equal to 0.38 according to the

Fig. 2 (a) Photo of the actuator used to generate and detect HNSWs. (b) Actuator's design. Dimensions expressed in mm. The figure is reproduced from Ref. [38].

manufacturer's recommendation. After the plaster fully cured, a 4 mm diameter, 20 mm deep hole was bored into one face of the cube, and a 10 mm long steel screw was inserted and stabilized with fresh commercial joint compound. The compound represented at large the interface element between the implant and the bone tissue that heals during the osseointegration process. Figure 3 shows the test specimen after the experiment was completed.

Immediately after placing the screw, the HNSW transducer was placed above the cube to allow contact between the bottom particle of the chain and the head of the screw. Ten measurements were taken every 15 min for 8 h, which could be considered the curing time of the joint compound.

3.2 Results and Discussion. Figure 4(a) shows the voltage output measured by both instrumented beads at the baseline, i.e., right after placing the transducer in contact with the test object. Three pulses are visible for each sensor. The first impulse, whose amplitude can be designed as A_1 , corresponds to the arrival of the incident solitary wave generated by the striker's impact. The sub-

sequent pulses represent the PSW and SSW reflected from the interface with the linear media, and herein indicated as A_2 and A_3 , respectively. Interestingly, the force profile shows the presence of a third reflected pulse tailing the SSW about 100 μ s later. The origin of this third impulse is unclear. We speculate that it might be generated by reflections at the interface between the fresh compound and the hardened cement. As the amplitude of this reflected pulse was smaller than the PSW and SSW and disappeared after 2 h, we ignored its presence in the analysis. Figure 4(b) shows the voltage output measured after 400 min, i.e., when the fresh compound fully cured. The absence of the SSW is evident as well as the change in the amplitude of the primary pulse.

To quantify the effect of the joint compound curing on the characteristics of the HNSWs propagating within the actuator, the wave's time of flight, amplitude, and speed were monitored over time. Figure 5(a) shows the values of A_1 as measured by the top sensor bead in the chain (11th particles away from the point of impact of the striker) as a function of the monitoring time. The dots represent the average value of the ten measurements taken every 15 min normalized with respect to the averaged amplitude at the baseline. The vertical bar represents the 2σ confidence interval, with σ equal to the standard deviation. As this amplitude is only affected by the impact velocity, its value was expected to be constant. The values' distribution is regular remaining within $\pm 10\%$ from the baseline. Moreover, the overall average amplitude is $3.621V \pm 4.64\%$. This confirms the good reproducibility of the impact. We believe that lower standard deviations can be attained by reducing the friction along the inner wall of the tube and preventing any rotation of the particles, in particular of the instrumented bead. In fact, during the bone test, we observed that the PZT rotated away from the perpendicular direction of wave propagation. To confirm this hypothesis we report in Fig. 5(b) the amplitude A_1 measured from the bottom sensor bead ($n = 16$). The data exhibit similar trend but the standard deviation related to the average value of 3.496V was equal to 2.97%. Compared to the standard deviation (4.64%) associated with the top sensor's data, the value of 2.97% suggests that the effect of rotation of the sensor bead occurred closer to the point of impact.

Figure 5(c) shows the amplitude of the primary reflected wave measured by both sensor beads and normalized with respect to the baseline's average value. As the compound cured, the PSW amplitude increased. The trend is such that by the end of the second hour, A_2 increased exponentially by 80% after which exhibited a linear plateau. At the end of the monitoring period, the increase was two-fold. This behavior resembles the well-known trend that cementitious materials (cement pastes and concretes) exhibit over

Fig. 3 Plaster test. Photo of the sample. Note that the clearer surface around the screw is joint compound that bled out the bore after inserting the screw.

Fig. 4 Plaster test. (a) Solitary waves measured from both instrumented beads at the baseline, i.e., curing time = 0; (b) solitary waves measured from both instrumented beads at curing time = 400 min.

time, i.e., the increase of strength at a fast rate during early curing². The experimental data are fit with a polynomial curve. The amplitude measured by the top sensor presents a plateau between 175 min and 250 min that is not observed in the bottom sensor. It is speculated that small rotations due to the impact of the striker might have caused a misalignment of the PZT embedded in the transducer. Nonetheless, the overall monotonic behavior of the PSW ratio is visible.

Figure 5(d) shows the amplitude of the secondary reflection with respect to the monitoring time measured by the top sensor. The behavior is complementary to that observed in Fig. 5(c). For instance, by observing the measurements at 125 min the amplitude of the SSW decreased 80% while the amplitude of the PSW increased by 80%. The amplitude's slope of the SSW became almost null after 3 h, after which the amplitude decreased by approximately 10% only. Although not shown here, the values measured by the bottom sensor particle were very similar. The behavior of the secondary wave can be explained by referring to the work of Yang et al. [27]. When the linear medium is softer, the bottom particle of the chain penetrates deeper into the medium resulting in the loss of contact of the last bead with the rest of the chain. In this case, the last bead experiences a delay time until it bounces back under the resistance of the elastic medium. The rebounding particle induces a second impact to the chain, the secondary wave. This suggests that a change in the stability of the

screw can be captured by measuring the strength of the solitary wave. It should be noted that the values in Fig. 5 were chosen normalized with respect to the baseline value, i.e., at 0 h, to better assess the relative variation of the HNSW's characteristics with respect to the baseline.

The analysis of the TOF and wave speed is presented in Fig. 6. The time of flight of the primary reflected waves is shown in Fig. 6(a). As the joint compound cured, the TOF decreased of about 5%, indicating a stiffer material. The monotonic trend allows for the relation between this HNSW feature and the stiffness of the screw-compound-plaster system. Figure 6(b) shows the wave speed of the incident pulse and of the primary reflected wave whereas Fig. 6(c) shows the ratio between the two speeds. Although a clear trend is not as visible as for the amplitude ratios, Fig. 6(c) shows that as curing progressed, the speed of the PSW became closer to the speed of the incident pulse.

4 Bone Test

4.1 Experimental Setup. A flat-shaped bovine costal bone (posterior thoracic rib) containing both an outer cortical and a central cancellous portion was prepared. The geometry of the sample is schematized in Fig. 7. The through thickness length of the specimen was approximately 16 mm, while its length and width were equal to approximately 36 mm. The sample was immersed into isotonic saline (0.9% sodium chloride) for 24 h in order to balance tonicity, simulate normal physiologic osmosis, and to avoid the development of dehydration.

²See, for instance, Chap. 5 of Ref. [40].

Fig. 5 Plaster test. (a) Normalized amplitude of the incident impulse measured by the top particle. (b) Normalized amplitude of the incident impulse measured by the bottom particle. (c) Normalized amplitude of the primary reflected wave measured by the top particle (the empty squares represent the data from the bottom sensor). The solid diamonds represent the data from the top sensor. (d) Normalized amplitude of the secondary reflected wave measured by the top particle.

A NobelReplace Tapered Groovy implant with a textured collar and internal trichannel prosthetic connection was used. The implant was 4.3 mm in diameter and 13 mm long and was placed into the test sample by utilizing a OsseoSet™100 drilling unit with a Branemark System® Surgery Kit. The placement protocol can be summarized as follows. After the sample was sufficiently hydrated, a pilot hole approximately 1 mm in diameter and 3–4 mm deep was drilled into the center of the installation site, ensuring a centimeter radius clearance of bone tissue on all sides of the hole. After the initial hole was drilled, a drill bit was used to deepen the pilot hole to approximately 10 mm, slightly less than the length of the implant. A “narrow platform” drill bit was then used to widen the hole to the approximate diameter of the implant, after which a “regular platform” bit was used to deepen the hole to 13 mm, which represented the length of the implant we used. The “narrow” and “regular” platform names represent the size of implant that is to be installed, with “narrow platform” representing the 10 mm length and “regular platform” representing the 13 mm length. “Regular platform” implants were used because they are the most common implant used in this type of procedure. After

the correctly-sized hole was created in the bone sample, a threaded screw tap was used to create threads on the inner bone surface that would form the implant-bone interface. Using the threads created previously, the 13 mm professional grade titanium dental implant was then screwed into the site, at first using a measured torque of 50 N-m, and then by hand tightening until the top of the implant surface was approximately 1 mm above the bone surface. During the preparation of the osteotomy site operation, external pulse irrigation was applied to avoid detrimental heating of the bone and to remove bone debris that formed while drilling.

To induce degradation, the sample was immersed in a solution of nitric acid ([w/w] = 67–70%). The HNSW transducer was then placed on the bone specimen allowing the contact between the implant and the bottom particle of the chain. Ten measurements were taken every 15 min for about 13 h. Degradation of the implant was considered negligible because of its material composition and its nonreactive nature with nitric acid. Photos of the experimental setup are presented in Fig. 8.

Simultaneously, the loss of calcium was quantified using an atomic absorption spectrometer. Every two hours, 5 ml of solution were diluted 1000× in deionized water and analyzed using a spectrometer. In order to calculate the percentage of calcium lost during the monitoring period, the calcium content of the pristine bone was inferred by measuring the final concentration of calcium in the solution after the sample fully dissolved in the acid.

4.2 Results. Figure 9 shows the voltage output recorded by the top sensor measured at the baseline, i.e., at the beginning of the experiment, and after 8 h. Remarkably, only the primary reflected wave is generated clearly at the interface and the formation of the SSW did not occur even when the sample was heavily degraded. As damage progressed, there seemed to be a reduction of its amplitude.

To quantify the effect of bone degradation on the characteristics of the HNSWs, Fig. 10 is reported. Figure 10(a) shows the amplitude of the incident HNSW as a function of the monitoring time, normalized with respect to the averaged value taken at the baseline. Overall, 540 pulses were generated during the experiment. The overall values are confined within an interval of $\pm 10\%$ which is higher than what observed in Fig. 5(a).

Figure 10(b) presents the amplitude ratio A_2/A_1 as a function of the monitoring time. The values are normalized with respect to the averaged data taken at the baseline. A linear decrease is clearly visible, and by the end of the monitoring period, the ratio decreased by approximately 90%. The few data visible between 100 and 200 min that lay below the interpolation line are the effect of an accidental misalignment of the sensor bead that underestimates the stress component along the direction of propagation. Finally, Fig. 10(c) shows the time of flight associated with the primary solitary waves as a function of the monitoring time. The values are normalized with respect to the averaged data taken at the baseline. Interestingly, this parameter does not change significantly although it is known [27,38,39] that the wave-speed V_s is proportional to the dynamic contact force F_m , which is measured by the voltage output, according to:

$$V_s \propto F^{1/6} \quad (1)$$

Overall, Fig. 10 shows few outliers with large standard deviations at 120 min and 240 min, for instance. These were the results of isolated occurrences in the setup. For example at 120 min, we observed a gap between the top sensor particle and the particle immediately below.

In order to establish a correlation between the characteristics of the solitary waves and the level of bone degradation, the calcium loss was measured using an atomic absorption spectrometer (AAS). This loss was back calculated after determining the calcium content of the nitric acid solution after the bone sample had

Fig. 6 Plaster test. (a) Normalized time of flight of the TOF as measured by the top sensor. (b) Wave speed of the incident pulse (empty circles) and of the PSW (filled diamonds). (c) Speed ratio PSW over incident pulse.

Fig. 7 Diagram of the bone specimen

Fig. 8 Front and top view of the experimental setup

Fig. 9 Bone test. Solitary waves measured from the top instrumented bead at the baseline and after 8 h.

thoroughly degraded. Figure 11 compares the variation of the normalized reflected amplitude to the loss of calcium content. The graph refers to the first 4 h of the experiment when the measurements with the spectrometer were taken. Across this interval, the sample lost about 60% of its calcium content while the feature related to the propagation of the solitary wave decreased by 50%. Although the calcium loss appears to be linear, the same cannot be said from the solitary wave data and more investigation is therefore needed to relate the wave's feature to the bone

Fig. 10 Bone test. (a) Normalized amplitude of the incident impulse measured by the top particle. (b) Normalized amplitude of the primary reflected wave measured by the top particle. (c) Normalized TOF measured by the top particle.

Fig. 11 Bone test. Values of the normalized amplitude of the reflected solitary wave (dots) superimposed to the calcium content of the sample (continuous line).

characteristics. We speculate that the amplitude of the reflected feature is related to some other clinical factors of the implant-bone system. It is known that clinical factors that affect the surrounding of an implant are bone loss, trabecular/cortical bone ratio, trabecular bone modulus, and type of loading [41].

5 Discussion and Conclusions

In this paper, we propose a novel nondestructive testing method based on the propagation of highly nonlinear solitary waves (HNSWs) to monitor the stability of dental implants. A cost-

effective actuator/sensor made of a chain of spherical particles (i.e., a granular crystal) and an electromagnet, and remotely controlled via software used for the generation and detection of the waves.

The method was first tested on a cement-compound-screw system to evaluate the effect of compound hydration on some selected HNSWs' features. We chose to observe this system as the hydration of compound simulates at large the osseointegration process that occurs in the jaw after an implant is surgically placed. We found that a single pulse perpendicularly incident to the actuator/screw interface results in two reflected pulses, categorized into primary solitary wave (PSW) and secondary solitary wave (SSW). The amplitudes and the time-of-flight (TOF) of these two reflected waves are dependent on the hydration. Specifically, we found that by the time the compound had fully cured, the amplitude of the PSW had a two-fold increase and the SSW amplitude was 90% smaller. During the same monitoring period, the TOF of the PSW decreased of about 8% monotonically.

The method was then tested on a real implant placed in an *in vitro* sample cut from costal bovine bone. The inverse of the osseointegration process, which follows the surgical placement, was simulated by immersing for several hours the samples into a solution of nitric acid. Only the PSW was generated at the interface and the features based on its characteristics showed a trend opposite to that found in the plaster test. This was expected because, as the test progressed, the mechanical properties of the sample deteriorated. The amplitude of the reflected waves decreased linearly whereas the TOF remained constant. The data were also compared to the loss of calcium caused by the solution of nitric acid and there appeared an overall correlation between the amplitude of the reflection and the change in the bone's calcium content. It should be remarked that the reflected wave always retained a compact support without significant dispersion. As such, HNSWs can be used as information carriers in the assessment of dental implants.

There is an apparent analogy between the HNSW-based method and the use of guided ultrasonic waves propagating; for example, along a rod in contact with the implant. Although there is no reported study of this kind, at least to the best of the authors' knowledge, we argue that in any GUW-method only the reflection coefficient would be eventually affected while no phase shift will be observed unless mode conversion occurs at the interface. The present approach can virtually exploit three parameters: the time of flight (TOF), the amplitudes, and not discussed in the paper the duration at half-width. Moreover the HNSW-based method does not require the use of electronics for the generation of high-voltage input signals, contrary to piezoelectric transducers. Finally, guided waves will be dispersive while the solitary waves maintain a compact support.

In order to demonstrate the advantages of the proposed method over the commercial systems discussed in the introduction, more tests are necessary and comparative analyses need to be carried out. With respect to the resonant frequency and the Periotest method that include the computation of one parameter only, i.e., the resonant frequency and the contact duration, respectively, the new technology can virtually exploit more parameters. Moreover the HNSW-based method does not require the use of electronics for the generation of sine waves. However, we acknowledge that the method presented in this paper can be implemented in clinical trial only once the size of the HNSW transducer is reduced and the effect of the particle size on the sensitivity of the proposed technology is systematically investigated. The use of one sensor particle instead of two would allow shortening the number of particles in the chain. In this case, however, the speed cannot be computed and therefore used to assess the stability of the implant.

Acknowledgment

The authors acknowledge the support of the University of Pittsburgh' Clinical and Translational Science Institute engineering to

clinical collaborative research pilot program, through grants National Institutes of Health through Grant Numbers UL1 RR024153 and UL1TR000005. Mr. Berhanu performed this research supported in part from grants from the Office of the Provost, University of Pittsburgh. The authors would like to acknowledge the help of Mr. Aydin Tabrizi, Dr. Xianglei Ni, and Dr. Jason Monnell for their assistance in the setup of some of the experiments presented here. The authors have no conflict of interests to disclose.

References

- [1] Pastrav, L. C., Jaecques, S. V., Jonkers, I., Perre, G. V., and Mulier, M., 2009, "In Vivo Evaluation of a Vibration Analysis Technique for the Per-Operative Monitoring of the Fixation of Hip Prostheses," *J. Orthop. Surg. Res.*, **4**, p. 10.
- [2] Atsumi, M., Park, S. H., and Wang, H. L., 2007, "Methods to Assess Implant Stability: Current Status," *Int. J. Oral Maxillofac. Implants*, **22**, pp. 743–754.
- [3] Chang, P.-C., Lang, N. P., and Giannobile W. V., 2009, "Evaluation of Functional Dynamics During Osseointegration and Regeneration Associated With Oral Implants," *Clin. Oral Implants Res.*, **21**, pp. 1–12.
- [4] Schulte, W., D'Hoedt, B., Lukas, D., Muhlbradt, L., Scholz, F., Bretsch, J., Frey, D., Gudat, H., Konig, M., and Markl, M., 1983, "Periotest: A New Measurement Process for Periodontal Function," *Zahnarzt Mitt*, **73**, pp. 1229–1230.
- [5] Schulte, W., D'Hoedt, B., Lukas, D., Muhlbradt, L., Scholz, F., Bretsch, J., Frey, D., Gudat, H., Konig, M., and Markl, M., 1983, "Periotest: A New Measurement Process for Periodontal Function," *Zahnarzt Mitt*, **73**, pp. 1233–1236.
- [6] Schulte, W., D'Hoedt, B., Lukas, D., Muhlbradt, L., Scholz, F., Bretsch, J., Frey, D., Gudat, H., Konig, M., and Markl, M., 1983, "Periotest: A New Measurement Process for Periodontal Function," *Zahnarzt Mitt*, **73**, pp. 1239–1240.
- [7] Schulte, W., and Lukas, D., 1992, "The Periotest Method," *Int. Dent. J.*, **42**, pp. 433–440.
- [8] Schulte, W., and Lukas, D., 1993, "Periotest to Monitor Osseointegration and to Check the Occlusion in Oral Implantology," *J. Oral Implantol.*, **19**, pp. 23–32.
- [9] Meredith, M., 1998, "A Review of Nondestructive Test Methods and Their Application to Measure the Stability and Osseointegration of Bone Anchored Endosseous Implants," *Crit. Rev. Biomed. Eng.*, **26**, pp. 275–291.
- [10] Derhami, K., Wolfaardt, J. F., Faulkner, G., and Grace, M., 1995, "Assessment of the Periotest Device in Baseline Mobility Measurements of Craniofacial Implants," *Int. J. Oral Maxillofac. Implants*, **10**(2), pp. 221–229.
- [11] Meredith, N., Alleyne, D., and Cawley, P., 1996, "Quantitative Determination of the Stability of the Implant-Tissue Interface Using Resonance Frequency Analysis," *Clin. Oral Implants Res.*, **7**, pp. 261–267.
- [12] Meredith, N., Book, K., Friberg, B., Jemt, T., and Sennnerby, L., 1997, "Resonance Frequency Measurements of Implant Stability In Vivo. A Cross-Sectional and Longitudinal Study of Resonance Frequency Measurements on Implants in the Edentulous and Partially Dentate Maxilla," *Clin. Oral Impl. Res.*, **8**, pp. 226–233.
- [13] Watzek, G., 2004, *Implants in Qualitatively Compromised Bone*, Vol. 1, Quintessence Publishing Co., Surrey, UK, p. 181.
- [14] Oh, J. S., Kim, S. G., Lim, S. C., and Ong, J. L., 2009, "A Comparative Study of Two Noninvasive Techniques to Evaluate Implant Stability: Periotest and Osstell Mentor," *Oral Surg. Oral Med. Oral Pathol. Oral Radiol. Endod.*, **107**(4), pp. 513–518.
- [15] Osstell, 2012, "Osstell Scientific," accessed August 2, 2012, <http://www.osstell.com/>
- [16] Hayashi, M., Kobayashi, C., Ogata, H., Yamaoka, M., and Ogiso, B., 2010, "A No-Contact Vibration Device for Measuring Implant Stability," *Clin. Oral Implants Res.*, **21**(9), pp. 931–936.
- [17] Kim, D.-S., Lee, W.-J., Choi, S.-C., Lee, S.-S., Heo, M.-S., Heo, K.-H., and Yi, W.-J., 2011, "Development of a Dental Implant Mobility Measurement System Using an Inductive Sensor," *Proceedings of the 33rd Annual International Conference of the IEEE EMBS*, Boston, MA, August 30–September 3, pp. 361–364.
- [18] Mupparapu, M., and Singer, S. R., 2004, "Implant Imaging for the Dentist," *J. Can. Dent. Assoc.*, **70**(1), p. 32.
- [19] Wodarski, J., 2005, "Assessment of the Changes Occurring in the Bone Cement-Implant Border Zones Using the Computer Image Analysis," *Bio-Algorithms Med-Syst.*, **1**(1/2), pp. 317–320.
- [20] Turkyilmaz, I., Tozum, T. F., Tumer, C., and Ozbek, E. N., 2006, "Assessment of Correlation Between Computerized Tomography Values of the Bone, and Maximum Torque and Resonance Frequency Values at Dental Implant Placement," *J. Oral Rehabil.*, **33**, pp. 881–888.
- [21] Berndt, D., Luckow, M., Lambrecht, J. T., Beckmann, F., and Müller, B., 2008, "Quality Assessment of Clinical Computed Tomography," *Proc. SPIE*, **7078**, pp. 70780N1–N10.
- [22] Nesterenko, V. F., 1984, "Propagation of Nonlinear Compression Pulses in Granular Media," *J. Appl. Mech. Tech. Phys.*, **24**, pp. 733–743.
- [23] Nesterenko, V. F., 2001, *Dynamics of Heterogeneous Materials*, Springer-Verlag, New York.
- [24] Coste, C., Falcon, E., and Fauve, S., 1997, "Solitary Waves in a Chain of Beads Under Hertz Contact," *Phys. Rev. E*, **56**, pp. 6104–6117.
- [25] Daraio, C., Nesterenko, V. F., Herbold, E. B., and Jin, S., 2005, "Strongly Nonlinear Waves in a Chain of Teflon Beads," *Phys. Rev. E*, **72**, p. 016603.
- [26] Job, S., Melo, F., Sokolow, A., and Sen, S., 2007, "Solitary Wave Trains in Granular Chains: Experiments, Theory and Simulations," *Granular Matter*, **10**, pp. 3–20.
- [27] Yang, J., Silvestro, C., Khatri, D., De Nardo, L., and Daraio, C., 2011, "Interaction of Highly Nonlinear Solitary Waves With Linear Elastic Media," *Phys. Rev. E*, **83**, p. 046606.
- [28] Sen, S., Manciu, M., and Wright, J. D., 1998, "Soliton Like Pulses in Perturbed and Driven Hertzian Chains and Their Possible Applications in Detecting Buried Impurities," *Phys. Rev. E*, **57**, pp. 2386–2397.
- [29] Manciu, M., Sen, S., and Hurd, A. J., 1999, "The Propagation and Backscattering of Soliton-Like Pulses in a Chain of Quartz Beads and Related Problems. (I). Propagation," *Physica A*, **274**, pp. 588–606.
- [30] Manciu, M., Sen, S., and Hurd, A. J., 1999, "The Propagation and Backscattering of Soliton-Like Pulses in a Chain of Quartz Beads and Related Problems. (II). Backscattering," *Physica A*, **274**, pp. 607–618.
- [31] Hong, J., and Xu, A., 2002, "Nondestructive Identification of Impurities in Granular Medium," *Appl. Phys. Lett.*, **81**, pp. 4868–4870.
- [32] Porter, M. A., Daraio, C., Herbold, E. B., Szelengowicz, I., and Kevrekidis, P. G., 2008, "Highly Nonlinear Solitary Waves in Periodic Dimer Granular Chains," *Phys. Rev. E*, **77**, p. 015601.
- [33] Starosvetsky, Y., Jayaprakash, K. R., and Vakakis, A. F., 2012, "Scattering of Solitary Waves and Excitation of Transient Breathers in Granular Media by Light Intruders and No Precompression," *J. Appl. Mech.*, **79**(1), p. 011001.
- [34] Ni, X., and Rizzo, P., 2012, "Highly Nonlinear Solitary Waves for the Inspection of Adhesive Joints," *Exp. Mech.* (accepted).
- [35] Ni, X., and Rizzo, P., 2011, "Use of Highly Nonlinear Solitary Waves in NDT," *Mater. Eval.* (accepted).
- [36] Ni, X., Rizzo, P., Yang, J., Kathri, D., and Daraio, C., 2011, "Monitoring the Hydration of Cement Using Highly Nonlinear Solitary Waves," *NDT&E International* (in press).
- [37] Ni, X., Nassiri, S., Rizzo, P., and Vandenbossche, J., 2011, "Highly Nonlinear Solitary Waves-Based Sensor for Monitoring Concrete," *Proc. SPIE*, **7981**, p. 79812L.
- [38] Ni, X., Rizzo, P., and Daraio, C., 2011, "Actuators for the Generation of Highly Nonlinear Solitary Waves," *Rev. Sci. Instr.*, **82**(3), p. 034902.
- [39] Ni, X., Rizzo, P., and Daraio, C., 2011, "Laser-Based Excitation of Nonlinear Solitary Waves in a Chain of Beads," *Phys. Rev. E*, **84**, p. 026601.
- [40] Carino, N. J., 2004, "The Maturity Method," *Handbook of Nondestructive Testing*, V. M. Malhotra and N. J. Carino, eds., CRC Press, Boca Raton, FL, Chap. 5.
- [41] Shunmugasamy, V. C., Gupta, N., Pessoa, R. S., Janal, M. N., and Coelho, P. G., 2011, "Influence of Clinically Relevant Factors on the Immediate Biomechanical Surrounding for a Series of Dental Implant Designs," *J. Biomech. Eng.*, **133**(3), p. 031005.