Reliability Verification of Damping Capacity Assessment Through In Vitro Analysis of Implant Micromotion in Peri-implant Bone Loss Model

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Purpose: This in vitro study aimed to determine the efficacy of a damping capacity assessment in evaluating the implant stability in a simulated peri-implant bone loss model. ***Materials and Methods:*** The same type of implant was placed sequentially in 0.5-mm-depth increments in polyurethane bone of a constant density, resulting in 11 specimens with varying surrounding bone levels. The implant stability was evaluated by a damping capacity assessment consisting of six consecutive impacts in one set. The damping results, including the contact time and stability index, were measured by three repeated sets of stability tests for each specimen. All implant micromotions were recorded in real time using a laser scanning vibrometer during these stability tests. The micromotions were analyzed in terms of three parameters: maximum displacement, expected mobility, and vibration frequency. Additionally, two other stability indices were acquired three times each for reference. Pearson correlation analysis was used to confirm the correlations among all the variables; $P < .05$ was considered statistically significant. ***Results:*** As the peri-implant bone level increased, the contact time results decreased gradually from 502 to 290 μs, and the stability index increased from 55 to 78. The implant micromotions of all specimens showed a damped sine waveform graph, which can be divided into impact displacement and self-vibration patterns by the contact end points. As the implant stability increased, these contact end points converged toward the third peak, the maximum displacement and expected mobility decreased, and the vibration frequency increased (ρ = −0.85, −0.88, and 0.99, respectively). Two other stability indices reflected the implant stability due to peri-implant bone loss. The statistical analysis indicated significant correlations among all measured variables; in particular, the three stability indices exhibited high correlations with each other (ρ = 0.99, −0.99, and −1.00, respectively). ***Conclusion:*** Within the limitations of this in vitro study, the implant stability measured by a damping capacity assessment was suitable for investigating the extent of implant micromotions, which were determined by 0.5-mm horizontal changes in the peri-implant bone level.
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Keywords: damping capacity assessment, dental implant, implant stability, laser scanning vibrometer, micromotion, resonance frequency analysis

To predict the superstructure loading time or long-term success of an implant, the availability of osseointegration-related information is an essential prerequisite. However, the accurate quantification of implant stability is difficult due to the complex binding mechanism that depends on the mechanical and biologic stabilities. Several extant studies have reported discrepancies between the implant stability and the degree of osseointegration.[1–3] Nevertheless, implant stability tests are useful clinical methods that can be used to estimate the degree of osseointegration indirectly.[4–6] There is a need for various trials and continuous research related to implant stability tests for accurate osseointegration analyses.

The clinical evaluation of implant stability must be nondestructive and objective. Various methods ranging from conventional modal analysis to the recently introduced quantitative ultrasound technique have been used for such evaluations.[7] Modal analysis measures the natural frequency or displacement signal of a system in resonance initiated by external steady-state waves or a transient impulse force.[8] Many previous studies have used damping capacity assessment and resonance

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frequency analysis, both of which are included in modal analysis, to measure the implant stability.[9–12] The damping capacity assessment involves measuring the contact time between the implant and the metal tapping rod, with the result being recorded as a stability index. The tapping rod decelerates when it makes contact with the implant. The degree of deceleration is related to the damping ability of the implant and the elasticity of the tissue around it. This reflects the mechanical properties of the bone and the implant assembly. Some studies have reported limitations of damping capacity assessment, as it is affected by the implant and abutment length, implant placement site, striking position, and orientation.[9,13,14] In contrast, resonance frequency analysis relies on finding the resonant frequency of the metal peg connected to the implant; the metal peg and the implant are connected by applying magnetic pulses of a uniform amplitude until the implant resonates. This method evaluates the implant stability as a function of the stiffness of the implant-bone interface and is influenced by factors such as bone density, jaw healing time, and exposed implant height above the alveolar crest.[6] Some animal studies have shown that the resonant frequency correlates with cortical bone regions rather than the overall bone-to-implant contact ratio.[15] In other studies, the results from resonance frequency analysis have been influenced by the effective implant length and the bone quality at the implant placement site.[11,16] Several studies have compared the implant stability test results obtained using both types of modal analysis and reported their usefulness.[17–20]

Modal analyses have also been proposed as diagnostic tools for monitoring peri-implant bone loss and implant mobility.[21,22] In previous studies, the damping capacity assessment for the diagnosis of peri-implantitis and early signs of implant failure was criticized because of the lack of resolution, poor sensitivity, and susceptibility to operator variables.[17,23] A recent study suggested that resonance frequency analysis could be used as a complementary diagnostic tool; however, it should not be used as the only tool for diagnosing peri-implantitis because the implant stability was still high in the experimental peri-implantitis canine model.[24] Lachmann et al recommended that the implant stability results should not be used for the comparison of two individual implants but to monitor the state of an individual implant over time.[25]

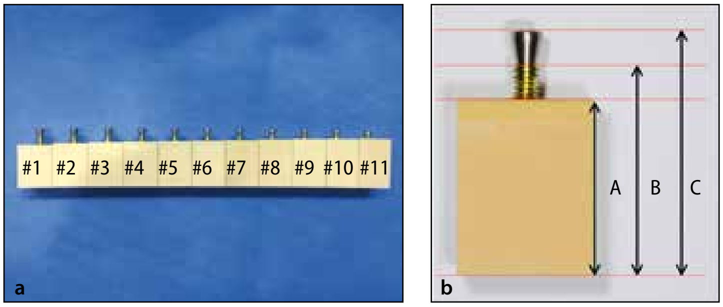
The quantitative ultrasound method relies on the dependence of ultrasonic propagation within the implant on its boundary conditions, which are precisely related to the biomechanical properties of the bone-implant interface.[26–29] This method delivers impulses through an ultrasonic contact transducer connected directly to the implant, such as the implant resonance from a metal peg. Once the superstructure is connected to the implant, it is difficult to perform a stability test using the resonance frequency analysis or the quantitative ultrasonic method. The damping capacity assessment only requires accessible striking impacts to the implant superstructure for stability measurements. The impact induces micromotions in implants with surrounding bone loss, and these motions as a kind of oscillation should be analyzed by the Doppler effect using laser vibrometry. Previous studies have used laser vibrometers to visualize the mobility of natural teeth.[30] Currently, the discrimination capabilities of laser scanning vibrometers have improved, and therefore, these devices can be used to describe even very small implant micromotions.

Recently, a stability measuring device (AnyCheck, Neobiotech) has been developed for measuring the implant stability using the same principle of damping capacity assessment. A key feature of this device is that it not only provides the damping results as a positive correlated stability index from 1 to 99, but also evaluates the implant stability with only six impacts. Although the results obtained using this device have been reported to correlate significantly with resonance frequency analysis results in one ex vivo study, the extent to which peri-implant bone loss causes a change in the implant stability results is unclear.[31] Therefore, it is necessary to analyze both the damping results and the implant micromotions during this damping capacity assessment to evaluate the implant stability and surrounding bone conditions accurately. This in vitro study aimed to determine the efficacy of a damping capacity assessment in evaluating the implant stability in a simulated peri-implant bone loss model.

MATERIALS AND METHODS

Preparation of Artificial Bones and Dental Implants

Polyurethane model bone (Sawbones, Pacific Research Laboratories) was used to reproduce the structure of the alveolar bone as closely as possible. The size of the artificial bone was 20 mm × 20 mm × 25 to 30 mm, and the height of the model bones in 11 samples was varied in increments of 0.5 mm. The upper 3-mm layer of the artificial bone had a density of 50 pounds per cubic foot (PCF) or 0.80 g/cm^3, which was used to reproduce the cortical bone, and all parts of the lower layer were made uniformly with a density of 20 PCF (0.32 g/cm^3). The dental implants (CMI IS-II Implant System, Neobiotech) were bone-level implants with a diameter of 4.0 mm and a length of 10 mm. These were titanium implants with no surface treatment and with an internal connection type. The upper 0.5 mm had a microgroove, and the body had a reversed and tapered thread design.



Specimen	A (mm)	B (mm)	C (mm)
#1	24.8	29.8	34.9
#2	25.4	29.9	34.9
#3	26.0	30.0	35.0
#4	26.4	29.9	34.9
#5	26.9	29.9	34.9
#6	27.5	30.0	35.0
#7	27.9	29.9	34.9
#8	28.5	30.0	35.0
#9	29.0	30.0	35.0
#10	29.4	29.9	34.9
#11	29.9	29.9	34.9

c

Fig 1 *(a)* Eleven specimens with varying surrounding bone levels. *(b)* Implants of the same type were placed sequentially at 0.5-mm-depth increments in a polyurethane bone of constant density. *(c)* Dimensions (in mm) of the final specimens were measured using calipers.

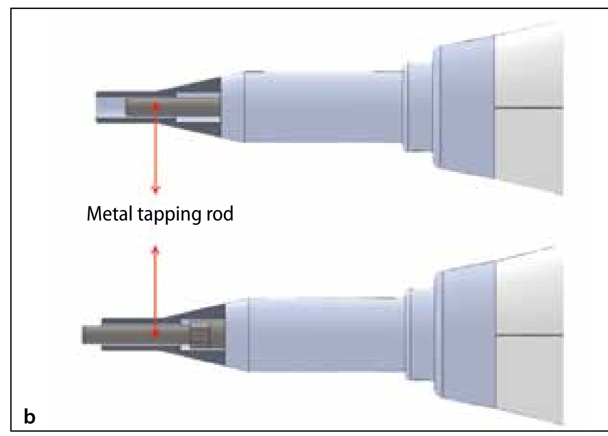


Fig 2 *(a)* Implant stability measuring device using a damping capacity assessment. *(b)* This device measures a contact time with a target from the reciprocating metal tapping rod.

Specimen Preparation

All specimens were designed to exhibit different stability according to the horizontal alveolar bone loss. Implant placement was performed according to the manufacturer's recommendation. However, initial drilling used a computer numerical control machine to ensure accurate depth and position in a constant axial direction, whereas final drilling was completed manually using a tap drill to precisely adjust the implant depth. The height of the artificial bone was increased by 0.5 mm, and the implant insertion depth was also increased by 0.5 mm (Fig 1). After the implants were placed, the healing abutment was connected to the implant with a manual force of up to 10 Ncm using a torque ratchet. All healing abutments had a diameter of 4.8 mm and a height of 5.0 mm. As a result, each specimen exhibited different stability according to the horizontal alveolar bone loss.

Implant Stability Measurement

The implant stability test was performed using a damping capacity assessment device. This device measured the contact time with a target from the reciprocating metal tapping rod and displayed the result as a stability index called the AnyCheck value (Fig 2). The device and the specimen were fixed with an X–Y table and metal vice, respectively. The metal tapping rod and the long axis of the implant were set perpendicular to each other. A slight gap was created between the healing abutment and the metal tapping rod using a 0.1-mm spacer. To minimize other movements, the operator buttons were kept completely separate from this device. One test set consisted of six consecutive impacts and was repeated three times per specimen. The damping results, including the contact time and stability index, were identified by this device.

To validate the results of the damping capacity assessment, all micromotions of a healing abutment connected to the implant were recorded using a laser scanning vibrometer (ESV-200, EM4SYS) during this stability test (Fig 3). The laser head was positioned opposite the impact point of the healing abutment. The laser scanning vibrometer operates in a noncontact measurement mode. When the laser beam strikes the target, the Doppler signal generated by the vibration is measured by the optical interferometer of the laser scanning vibrometer. This vibration is then determined from the frequency shift detected by the interferometer. After the data filtering and quantifying procedures, the implant micromotions were analyzed in the graph based on three parameters: maximum displacement, expected mobility, and vibration frequency.

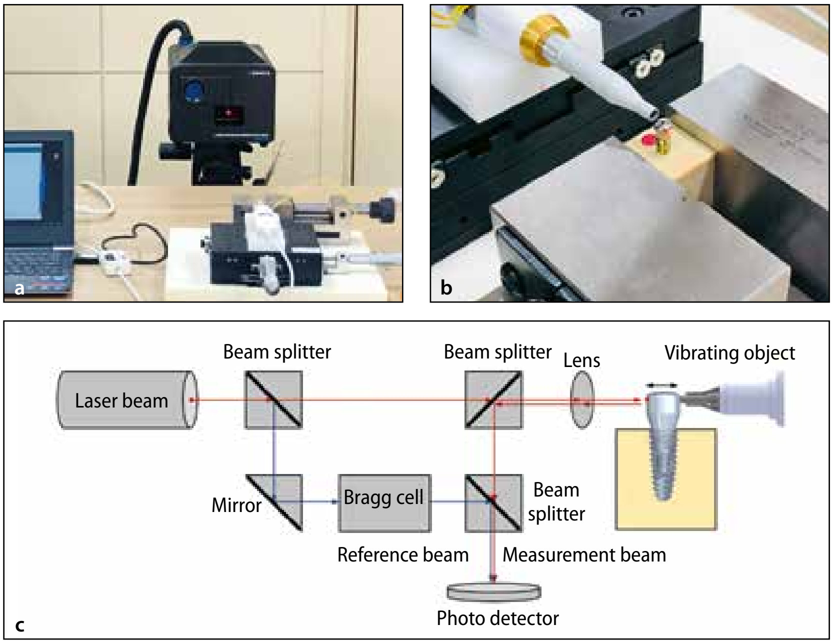


Fig 3 *(a)* All micromotions of a healing abutment connected to the implant were recorded using a laser scanning vibrometer. *(b)* The laser head was positioned opposite the impact point of the healing abutment. *(c)* A schematic of the laser scanning vibrometer operation.

Comparison with Other Stability Indices

To verify the reliability of implant stability, two additional stability indices were acquired three times each per specimen. One is a stability index called implant stability quotient (ISQ) that is obtained from the resonance frequency analysis (Osstell ISQ, Integration Diagnostics), and the other is a Periotest value acquired from another damping capacity assessment device (Periotest M, Medizintechnik Gulden).

Statistical Analysis

The damping results and implant micromotions were acquired from three repeated stability tests that consisted of six consecutive impacts. The contact time of each specimen was calculated as the mean of 18 damping results. The maximum displacement and expected mobility were calculated as the mean of the five greatest values among the 18 results, and the vibration frequency was analyzed using one representative graph selected randomly from the 18 results. All stability indices were calculated as the mean of the three repeated test results.

Pearson correlation analysis was performed to investigate the correlation between all variables. The normality of the quantitative variables was verified by means of the Shapiro-Wilk test. The simple linear correlation between quantitative variables was evaluated using Pearson coefficient (ρ). All statistical analyses were performed using R (version 3.6.1, R Foundation for Statistical Computing). A P value of $< .05$ was considered statistically significant.

RESULTS

Damping Results and Other Stability Indices

As the peri-implant bone level increased, the contact time decreased gradually from 502 to 290 µs, and the AnyCheck value corresponding to the contact time increased from 55 to 78 (Table 1). The ISQ value increased from 56 to 82, and the Periotest value decreased from +4.5 to –6.0. All stability indices reflected the assumed implant stability of the specimen.

Implant Micromotions

Initial vibration anomalies were observed in the velocity graph (Fig 4, upper graph). The displacement graph, calculated by the integral of the velocity graph, showed typical damped sine waveforms with one large peak followed by several smaller peaks. The corresponding graphs of displacement vs time showed an amplitude envelope that exponentially decreased in size.

To analyze the implant micromotions, three parameters—maximum displacement, expected mobility, and vibration frequency—were identified and measured using the displacement graph. The maximum displacement is represented by the first positive peak amplitude (peak 1), the expected mobility represents 1.2 times the amplitude (expected from the exponential decay curve) from the second negative peak to the third positive peak (peaks 2 and 3), and the vibration frequency represents the mean frequency of the 10 peaks (peaks 3 to 13) after the third peak (Fig 4, lower graph). As the peri-implant bone level increased, the maximum displacement decreased from 702.53 to 178.82 µm, and expected mobility decreased from

Table 1 All Damping Results Including Contact Time and Corresponding Stability Index

Specimen	Test set	AnyCheck value	Contact time (μ) 1	2	3	4	5	6	Set mean	Total mean	SD
#1	1	55	502	501	501	502	501	502	502	499	2.60
	2	55	500	502	496	497	497	496	498		
	3	55	500	496	495	497	498	496	497		
#2	1	60	422	423	425	424	423	425	424	423	1.63
	2	60	424	424	423	424	421	422	423		
	3	60	427	420	424	422	422	423	423		
#3	1	62	399	401	400	398	401	396	399	400	2.15
	2	62	399	399	401	400	398	394	399		
	3	62	402	400	401	402	398	402	401		
#4	1	64	382	385	384	379	383	386	383	384	1.65
	2	64	383	383	383	383	385	386	384		
	3	64	383	384	383	385	382	384	384		
#5	1	66	361	360	361	361	361	358	360	360	1.37
	2	66	362	360	360	361	360	362	361		
	3	66	362	361	359	361	357	359	360		
#6	1	68	346	347	347	348	347	346	347	347	0.83
	2	68	346	347	347	345	346	348	347		
	3	68	348	346	347	346	347	347	347		
#7	1	70	333	332	333	332	333	331	332	333	0.70
	2	70	334	333	332	333	332	333	333		
	3	70	332	333	333	332	333	332	333		
#8	1	72	317	317	320	319	320	319	319	319	1.33
	2	72	321	320	320	320	318	319	320		
	3	72	320	321	321	320	320	317	320		
#9	1	73	313	313	312	311	312	311	312	312	0.73
	2	74	312	312	312	312	311	312	312		
	3	73	313	312	313	311	313	312	312		
#10	1	75	305	306	306	305	306	306	306	306	0.50
	2	75	305	306	306	306	306	305	306		
	3	75	305	306	306	306	305	305	306		
#11	1	78	290	292	292	291	292	292	292	292	0.87
	2	77	293	291	291	293	292	293	292		
	3	77	292	293	291	292	292	293	292		

140.83 to 56.73 µm; the vibration frequency increased from 5.68 to 12.50 kHz. Table 2 lists the representative mean values for all the variables analyzed in this study.

Trends According to Implant Stability

As the implant stability increased, the contact time, maximum displacement, and expected mobility decreased. Although the absolute contact time decreased, the relative position of the contact end point in the displacement graph converged toward the third peak as the implant stability increased (Fig 5). After the third peak, the interference with a metal tapping rod disappeared completely for all the specimens, and the implant remained self-vibrating. The vibrating frequency increased with the implant stability. The tendency of all variables can be analyzed using trend lines with R^2 values closest to 1. In this study, the contact time and maximum displacement were analyzed using power trend lines, the expected mobility was analyzed using an exponential trend line, and the vibration frequency was analyzed using a linear trend line. In addition, three different stability indices were analyzed using linear trend lines, and these indices were found to be similar to each other (Fig 6).

Pearson Correlation Result

The statistical analyses of correlations indicated the existence of significant correlations among all variables. Among the variables related to the damping tests, a very strong positive correlation was seen between the vibration frequency and AnyCheck value (ρ = 0.99, $P < .001$), maximum displacement and contact time (ρ = 0.93, $P < .001$), and expected mobility and contact time (ρ = 0.86, $P < .001$); further, a significant positive

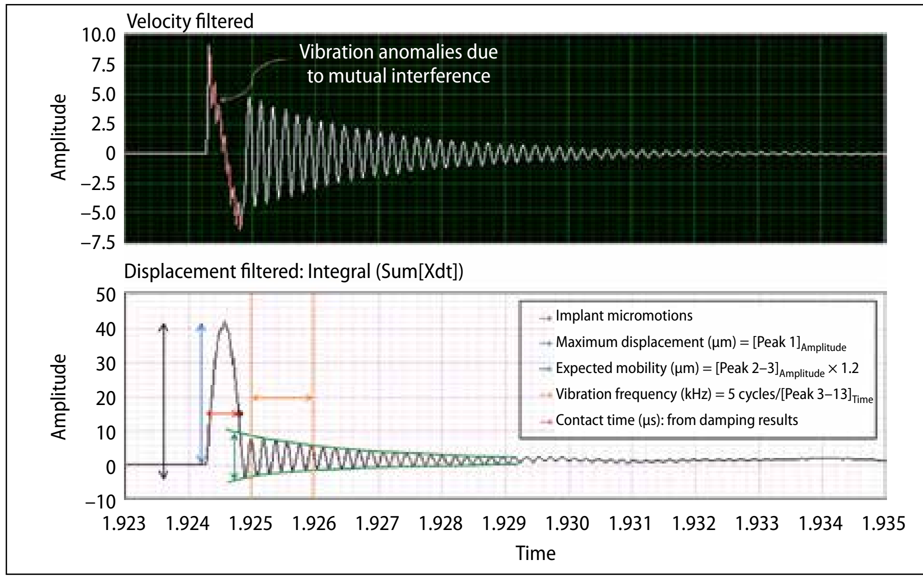


Fig 4 Graphs of velocity *(upper)* and displacement *(lower)* for the implant micromotions showed a damped sine waveform pattern. Initial vibration anomalies were marked in the velocity graph. Contact time from damping results and three parameters of implant micromotions were defined in the displacement graph.

Table 2 Representative Mean Values of All Variables Used in This Study

Specimens		Implant micromotions			Damping results		Other indices	
No.	Peri-implant bone loss (mm)	Maximum displacement (μm)	Expected mobility (μm)	Vibration frequency (kHz)	Contact time (μs)	AnyCheck value	ISQ value	Periotest value
#1	5.0	702.53	140.83	5.68	499	55	56	+4.40
#2	4.5	372.01	87.85	6.33	423	60	61	+2.23
#3	4.0	387.11	111.77	6.94	400	62	64	+0.97
#4	3.5	323.53	103.04	7.58	384	64	67	−0.37
#5	3.0	178.05	118.77	8.20	360	66	69	−1.27
#6	2.5	274.49	87.11	8.93	347	68	70	−2.17
#7	2.0	247.2	65.95	10.00	333	70	74	−3.37
#8	1.5	198.51	73.22	10.87	319	72	75	−3.70
#9	1.0	224.97	69.28	11.36	312	73.3	80	−4.77
#10	0.5	211.87	59.39	11.90	306	75	80	−5.23
#11	0	178.82	56.73	12.50	292	77.3	82	−5.97

ISQ = implant stability quotient.

correlation was seen between maximum displacement and expected mobility (ρ = 0.73, *P* = .01). A strong negative correlation was seen between the contact time and AnyCheck value (ρ = −0.98, *P* < .001), vibration frequency and contact time (ρ = −0.94, *P* < .001), expected mobility and AnyCheck value (ρ = −0.88, *P* < .001), and expected mobility and vibration frequency (ρ = −0.87, *P* < .001); further, a significant negative correlation was seen between the maximum displacement and AnyCheck value (ρ = −0.85, *P* = .001) and maximum displacement and vibration frequency (ρ = −0.76, *P* = .006). A near-perfect correlation was seen between the stability indices of the three measuring devices: AnyCheck value and Periotest value (ρ = −1.00, *P* < .001), AnyCheck

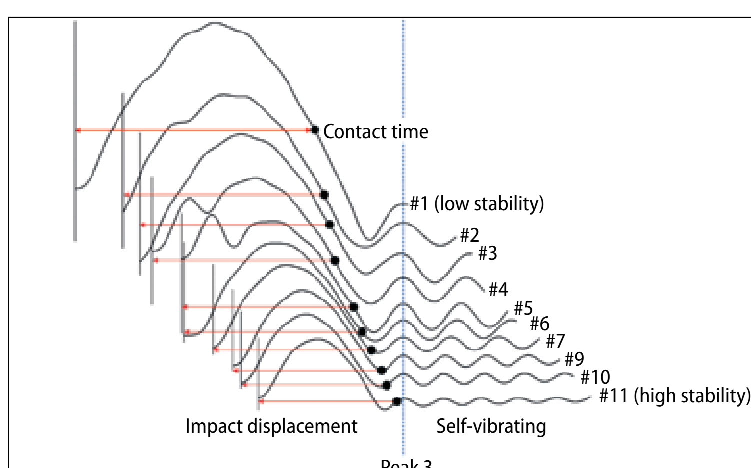


Fig 5 Displacement-time graph changes with the implant stability. As the implant stability increased, the absolute value of the contact time decreased, and the relative position of the contact end point (black node) converged toward the third peak. The result obtained for sample #8 contained a large error and was therefore excluded from this figure.

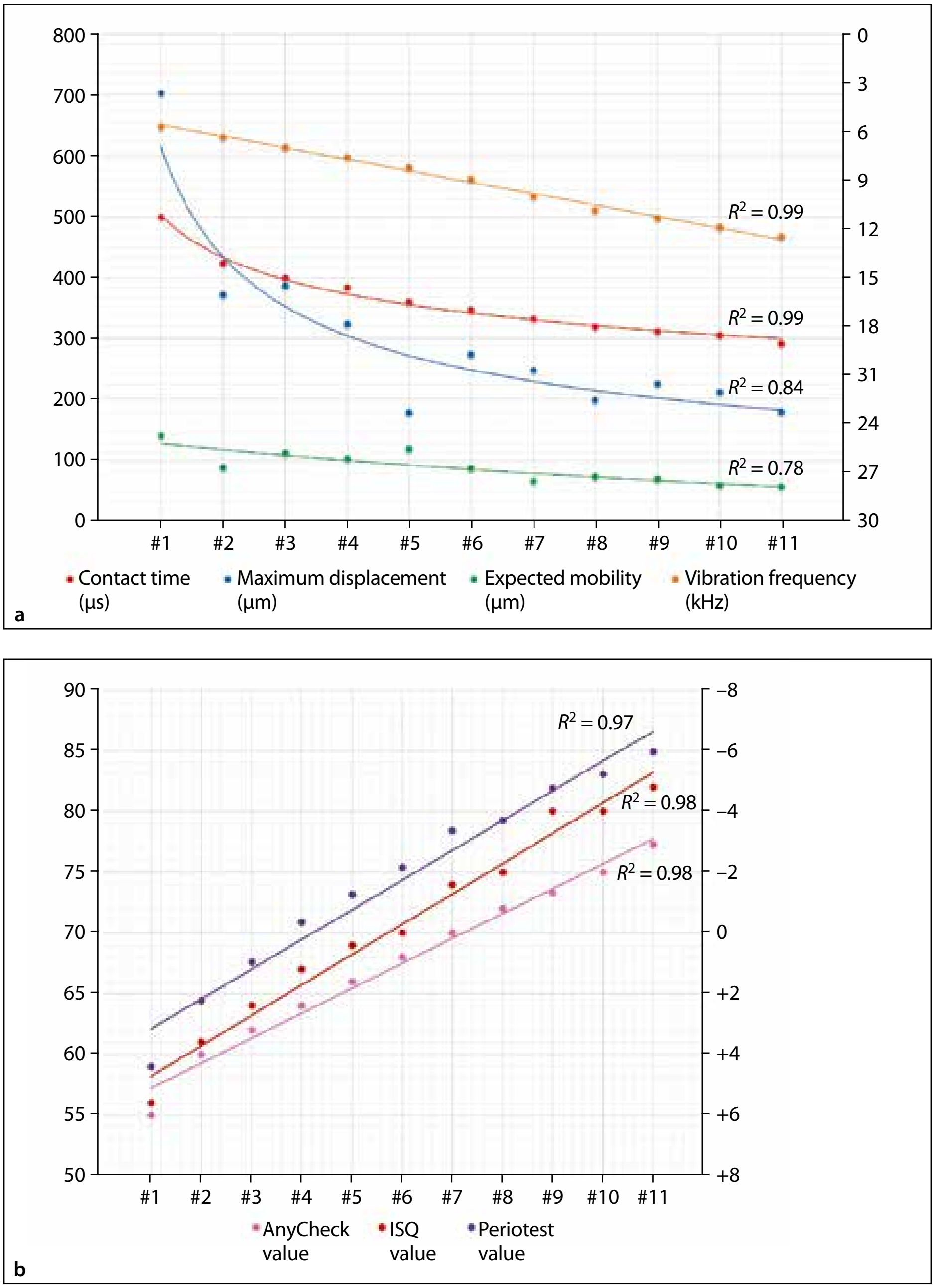


Fig 6 Trend lines with R^2 values closest to 1 for *(a)* the contact time and maximum displacement analyzed using power trend lines, expected mobility analyzed using an exponential trend line, and vibration frequency analyzed using a linear trend line; and *(b)* three stability indices analyzed using linear trend lines.

value and ISQ value ($\rho = 0.99$, $P < .001$), and ISQ value and Periotest value ($\rho = -0.99$, $P < .001$).

DISCUSSION

In this in vitro study of a damping capacity assessment, the interactions among the metal rod, implant, and supporting bone were observed. As the implant started to move due to the impact force from the metal rod, the supporting bone resisted it, causing the implant to oscillate. During this process, the behavior of the oscillating implant and the metal rod interfered with each other, and the oscillating implant lost energy during each cycle. In the velocity-time graph, the initial vibration anomalies were due to these mutual interferences, and the amplitude of the implant velocity decreased with time. The displacement-time graph, calculated by integrating the velocity-time graph, showed the damped sine wave form. The first largest peak corresponded to the moment when the metal rod came into direct contact with the implant, whereas the following small peaks corresponded to the periods when the implant vibrated itself after the impact. The natural transition of both segments implied that all impact forces were well absorbed by the implant and the supporting bone. As a result, implant micromotions should be divided into the impact displacement and the self-vibrating behavior.

First, two concepts were applied to analyze the impact displacement zone. One is the maximum displacement (1st peak), and the other is the expected mobility (2nd–3rd peak × 1.2). Because the maximum displacement was directly related to the impact, it was expected to be affected not only by the bone quality but also by external factors related to the impact forces. By contrast, the expected mobility was influenced by internal factors related to the implant or implant-bone interface. Although the maximum displacement and the expected mobility were both found to have a significant correlation with the contact time or vibration frequency, the results of this study showed that the maximum displacement was strongly correlated with the contact time ($\rho = 0.93$) and the expected mobility was strongly correlated with the vibration frequency ($\rho = -0.87$). These results can also be estimated from the shape of the trend lines. It should be noted that the maximum displacement and contact time are close to the logarithmic curve; however, the expected mobility and vibration frequency are close to the straight line. Therefore, the maximum displacement could be related to the damping capacity assessment and the expected mobility to the resonance frequency analysis. This suggests that both modal analyses could be associated with the lateral displacement of the implants. Other in vitro experiments revealed correlations among the bone density, ISQ, and lateral displacement measurements.[32] They concluded that the resonance frequency analysis reflected the micromobility of a dental implant; it, in turn, was determined by the bone density at the implant site.

Second, the self-vibrating zone was analyzed by measuring the frequency of 10 peaks from the 3rd peak because the 3rd peaks in all specimens were assumed to be completely unaffected by the impact. In the damping capacity assessment, the self-vibrating zone represents the damped natural frequency, which is the natural frequency that actually resonates in the underdamped vibration state. From a mechanical standpoint, an implant that is free to vibrate at one end and fixed at the other is a simple cantilever beam.[33] Therefore, it is necessary to understand the resonance of the cantilever beam and its mass model to evaluate the implant stability. Resonance is a phenomenon that occurs when the frequency at which a force is periodically applied is equal or nearly equal to one of the natural frequencies—those at which the mass-beam system resonates without interference—of the system on which it acts. An external force, such as a one-time impulse or vibration, can also cause resonance. By applying this principle, stability measurement using the resonance involves evaluating how strongly the implant is fixed based on the resonance frequency. However, the transient impact-based damping capacity assessment estimates the implant stability using the contact time with the metal rod and not the resonance.[34] A significant correlation between the contact time and the self-vibrating frequency in this study implies that the damping results are comparable to the resonance in terms of reliability. According to Sennerby and Meredith, the resonance frequency analysis technique is a bending test for the implant-bone complex wherein a transducer applies an extremely small bending force.[6] The damping capacity assessment uses a slightly larger bending force generated by an electronically controlled metal rod. The difference between the two approaches is that the former estimated the resonance frequency from the vibration caused by the magnetic pulse, whereas the latter estimated it from the damping results correlated with the vibration frequency. However, both methods are thought to be related to the natural frequency of the implant itself. Many previous studies have revealed a correlation between both methods.[35–37] Kwon et al reported that a linear equation describing the correlation between implant damping and resonant frequency can be formulated mathematically.[38] However, most of the aforementioned results were confirmed by performing an in vitro or ex vivo investigation. If the model were so complicated that it closely mimicked human bodies such as blood supplies or complex bone structures, there would have been many embedded uncertainties.[39]

Finally, the changes of 0.5 mm or more at the peri-implant bone level in all specimens were found to be a significant difference in both implant micromotions and damping results. Further, the implant stability index tends to be similar to the other indices from the two different modal analyses. This suggests that the damping capacity assessment and tracing of implant micromotions may be helpful in diagnosing peri-implant bone loss. The resonance frequency analysis has some disadvantages in measuring the implant stability in long-term follow-up periods because of the removal of implant superstructures and the requirement of a disposable and distinctive transducer. If considerable data about the relationship between the damping results and the implant micromotions are accumulated by artificial intelligence, the damping capacity assessment will be particularly useful in the maintenance phase because it can be applied to measurements of the implant prosthesis. Nevertheless, it is more important to confirm the initial bone resorption with less than 0.5-mm change in the clinical field. Further related studies regarding the multiple factors involved in clinical stability measurements using a damping capacity assessment are needed.

CONCLUSIONS

Within the limitations of this in vitro study, the implant stability measured by a damping capacity assessment was suitable for investigating the extent of implant micromotions, which were determined by 0.5-mm horizontal changes in the peri-implant bone level.

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