The Role of Functional Parameters for Topographical Characterization of Bone-Anchored Implants

Anna Arvidsson, MSc, PhD;* Bashar A. Sater, MSc;* Ann Wennerberg, DDS, PhD*†

ABSTRACT

Background: The surface topographical characterization of bone-anchored implants has been recommended to be based on amplitude, spatial, and hybrid parameters. There are also functional parameters that have the potential to describe characteristics important for a specific application.

Purpose: The aim of the present study was to evaluate if parameters that have been described as functional in engineering applications are also relevant in the topographical characterization of bone-anchored implants.

Materials and Methods: The surface topography of threaded titanium implants with different surface roughness (S_a, S_{ds}, and S_{dr}) was analyzed with an optical interferometer, and five candidating functional parameters (S_{bi}, S_{ci}, S_{vi}, S_m, and S_c) were calculated. Examples of the same parameters for five commercially available dental implants were also calculated.

Results: The highest core fluid retention index (S_{ci}) was displayed by the turned implants, followed by fixtures blasted with 250- and 25-µm particles, respectively. Fixtures blasted with 75-µm Al_2O_3 particles displayed the lowest S_{ci} value. This is the inverse order of the bone biological ranking based on earlier in vivo studies with the experimental surfaces included in the present study.

Conclusion: A low core fluid retention index (S_{ci}) seems favorable for bone-anchored implants. Therefore, it is suggested to include S_{ci} to the set of topographical parameters for bone-anchored implants to possibly predict the biological outcome.

KEY WORDS: bone-anchored implants, functional parameters, surface topography

Dental and orthopedic implants are two examples of bone-anchored implants that need sufficient bone anchorage to establish clinical success. Bone anchorage has been reported to be affected by six factors: implant material, implant design, surface quality, status of the bone, surgical technique, and implant loading conditions.[1] The surface quality factor is composed of many different properties such as surface chemistry, surface energy, surface charge, wear and friction properties, and surface topography.

The influence of implant surface roughness on bone biological response has been investigated in vivo at different structure scales. For example, Gotfredsen and colleagues compared turned titanium implants with TiO_2-blasted implants.[2] The rougher implants (blasted) displayed higher removal torque values than the smoother implants (turned), and their histomorphometrical evaluation showed more bone in contact with the implant surface for the blasted than the turned as-machined. A study by Feighan and colleagues also concluded prevalence regarding the amount of bone for rougher blasted implant surfaces than as-machined turned ones.[3] In another study, Predecki and colleagues found that the average height of implant structures (R_a) should be larger than 0.5 for fixation of bone. They suggested that the surface roughness was needed for the vascularization and ingrowth of new bone.[4] Later, surface structure with an average height of approximately 1.5 µm was reported as optimal for bone anchorage when comparing blasted titanium implants with different surface roughnesses.[5–8]

Thus, since the surface roughness of bone-anchored implants has been shown to influence the bone

*Department of Biomaterials, Göteborg University, PO Box 412, 405 30 Göteborg, Sweden; †Department of Prosthetic Dentistry/Dental Technology, Göteborg University, PO Box 450, 405 30 Göteborg, Sweden

Reprint requests: Anna Arvidsson, Department of Biomaterials, Göteborg University, PO Box 412, 405 30 Göteborg, Sweden; e-mail: anna.arvidsson@biomaterials.gu.se

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response, an adequate characterization of implant surface structures is important. An ultimate surface topography characterization is represented by visual images and topographical parameter values.[9] There is a wide range of parameters describing the three-dimensional surface topography. Since it is difficult to interpret and utilize many parameters, fewer parameters with higher relevance are preferred. However, the relevance of specific parameters varies between different applications. Previously, guidelines for topographical characterization of dental implants have been presented, and it was recommended that surface topography at least should be described by one amplitude parameter, one spatial parameter, and one hybrid parameter.[10] Amplitude parameters describe the height variation of structures, spatial parameters the lateral variation, while hybrid parameters reflect a combination of amplitude and spatial variation, for example, the slope of peaks.[9]

However, amplitude, spatial, and hybrid parameters give general description of surface topography, and sometimes it is more effective with functional parameters that describe characteristics important for a specific application.[9] Surfaces may be associated with requirements concerning wear, bearing, lubrication, and sealing tightness. For example, the bearing properties of surfaces are not enhanced by narrow and spiky structures.

The bone formation processes around bone-anchored implants are not fully understood, but it can be hypothesized that the volume of fluid that a surface can retain has an impact on the proceeding bone healing, since a fluid phase is built up around the implant during a few days after insertion, as shown by in vivo bone remodeling studies.[11–13] With time, the initial fluid phase decreases and is replaced by tissue.[11–13] It can also be hypothesized that the fluid space closest to the implant is crucial for the availability of nutrition to the cells involved in bone healing. Therefore, the aim of the present study was to evaluate if parameters that have been described as functional in engineering applications are also relevant in topographical characterization of bone-anchored implants.

MATERIALS AND METHODS

Specimens

Threaded fixtures (Nobel Pharma AB, Göteborg, Sweden) were prepared with the following experimental surface treatments:

1. Turned ($n = 1$)
2. Blasted with TiO_2 particles with a size of 25 µm ($n = 3$)
3. Blasted with Al_2O_3 particles with a size of 25 µm ($n = 3$)
4. Blasted with Al_2O_3 particles with a size of 75 µm ($n = 2$)
5. Blasted with Al_2O_3 particles with a size of 250 µm ($n = 1$)

The fixtures originate from earlier in vivo studies;[5–8] therefore, the number of specimens in the present study varies with the availability of specimens. Before topographical analysis, the specimens were ultrasonically cleaned in diluted Extran MA01 (VWR International AB, Stockholm, Sweden) and absolute ethanol, respectively, and dried at 60°C for 24 hours.

Furthermore, the surface topography of five commercially available fixtures was investigated:

1. Astra Tech Fixture MicroThread™ (Ø: 4 mm, L: 15 mm, reference 24344, Astra Tech Dental AB, Mölndal, Sweden) ($n = 1$)
2. TiUnite™ (Ø: 4 mm, L: 8.5 mm, reference 27086, Nobel Biocare AB, Göteborg, Sweden): Threads at the middle of the fixture were analyzed. There is a roughness gradient along the vertical axis of TiUnite and the middle part was expected to reflect the "average roughness." ($n = 1$)
3. Osseotite® (Ø: 3.75 mm, L: 8.5 mm, reference 0ss385, 3i, Palm Beach Gardens, FL, USA): Threads at the apical part of the fixture were analyzed, since the blank threads at the upper part of the implant could not be accessed due to analytical technique reasons. ($n = 1$)
4. Straumann SLA® (Ø: 3.3 mm, L: 12 mm, reference 043.1435, Straumann, Basel, Switzerland) ($n = 1$)
5. Friadent XiVe® S Cellplus (Ø: 5.5 mm, L: 13 mm, reference 26-146399, Friadent, Mannheim, Germany) ($n = 1$)

Topographical Analysis

The surface topography was assessed with an optical interferometer (MicroXAM™, PhaseShift, Tucson, AZ, USA). With a 50× objective and a zoom factor of 0.625, an area of 200 × 260 µm^2 was measured. Before calculating the topographical parameters using the software of the instrument, errors of form and waviness were removed with a digital Gaussian filter, since this type of

TABLE 1 Description of Topographical Parameters Included in the Present Study

Type of Parameter	Parameter	Description	Unit
Functional	S_{bi}	The surface bearing index, that is, the ratio of the root mean square (RMS) deviation over the surface height at 5% bearing area. Larger values indicate a large relative bearing area and thus a good bearing property. Usually, engineering surfaces have values $0.3 < S_{bi} > 2$.[9]	—
	S_{ci}	The core fluid retention index, that is, the ratio of the void volume of the unit sampling area at the core zone (5–80% bearing area) over the RMS deviation. A larger S_{ci} indicates a good fluid retention in the core zone, and values range typically from 0 to slightly more than 2.	—
	S_{vi}	The valley fluid retention index, that is, the ratio of the void volume of the unit sampling area at the valley zone (80–100%) over the RMS deviation. A larger S_{vi} indicates a good fluid retention in the valley zone, and values generally range from 0 to 0.3.	—
	S_m	The material volume of the surface, that is, the material volume as the material portion enclosed in the 10% bearing area and normalized to unity.	µm
	S_c	The core void volume of the surface, that is, a core void volume is enclosed from 10 to 80% of surface bearing area and normalized to the unit sampling area.	µm
Amplitude	S_a	The arithmetic mean height deviation from a mean plane.	µm
Spatial	S_{ds}	The density of summits, that is, the number of summits of a unit sampling area.	$/\mu m^2$
Hybrid	S_{dr}	The developed interfacial area ratio, that is, the ratio of the increment of the interfacial area of a surface over the sampling area.	%

Mathematical formulas for the parameters can be found in the literature.[9]

filter is ideally suited for smoothening of surfaces rich in features.[9] The size of the filter was $50 \times 50\,\mu m$,[2] as recommended previously.[10] Each specimen was measured at three top areas, three flank areas, and three valley areas of the threads.

Topographical Parameters

Five candidating functional parameters for bone-anchored implants (S_{bi}, S_{ci}, S_{vi}, S_m, and S_c), as well as one amplitude parameter (S_a), one spatial parameter (S_{ds}), and one hybrid parameter (S_{dr}), were included in the present study (Table 1). The S_{bi}, S_{ci}, S_{vi}, S_m and S_c originate from splitting the surface into three height zones (peak zone, core zone, and valley zone) and then making volume calculations based on the zones. The height distribution is graphically presented in the bearing area curve, which is a cumulative form of the height distribution, that is, the probability function.[14] The bearing ratio shows what fraction of the surface that is above a certain height, and in the bearing area ration curve the normalized height is found at the vertical axis and the bearing area ratio (0–100%) at the horizontal axis. The peak zone, the core zone, and the valley zone are obtained by drawing two horizontal lines in the bearing area ratio curve intersecting at 5 and 80% of the bearing area, respectively.

RESULTS

Visual images of fixtures with different surface treatments are shown in Figure 1, A–E. The turned fixture contained oriented structures from the turning process (see Figure 1A), and for the blasted fixtures the size of dominating structures increased with increasing size of blasting particles (see Figure 1, B–E).

The relative surface bearing indexes (S_{bi}) of the experimental fixtures varied from 0.61 (blasted implants with 25-µm particles) to 0.69 (turned implants) (Table 2). The turned implants also displayed the highest core fluid retention index (S_{ci}), and fixtures blasted with 75-µm Al_2O_3 particles had the lowest S_{ci} value. Concerning the valley fluid retention index (S_{vi}) and the material and core void volume (S_m and S_c, respectively), the turned fixtures displayed the lowest values and the fixtures blasted with 250-µm Al_2O_3 particles the highest (see Table 2).

Topographical differences were indicated for the five commercial dental implants included in the present

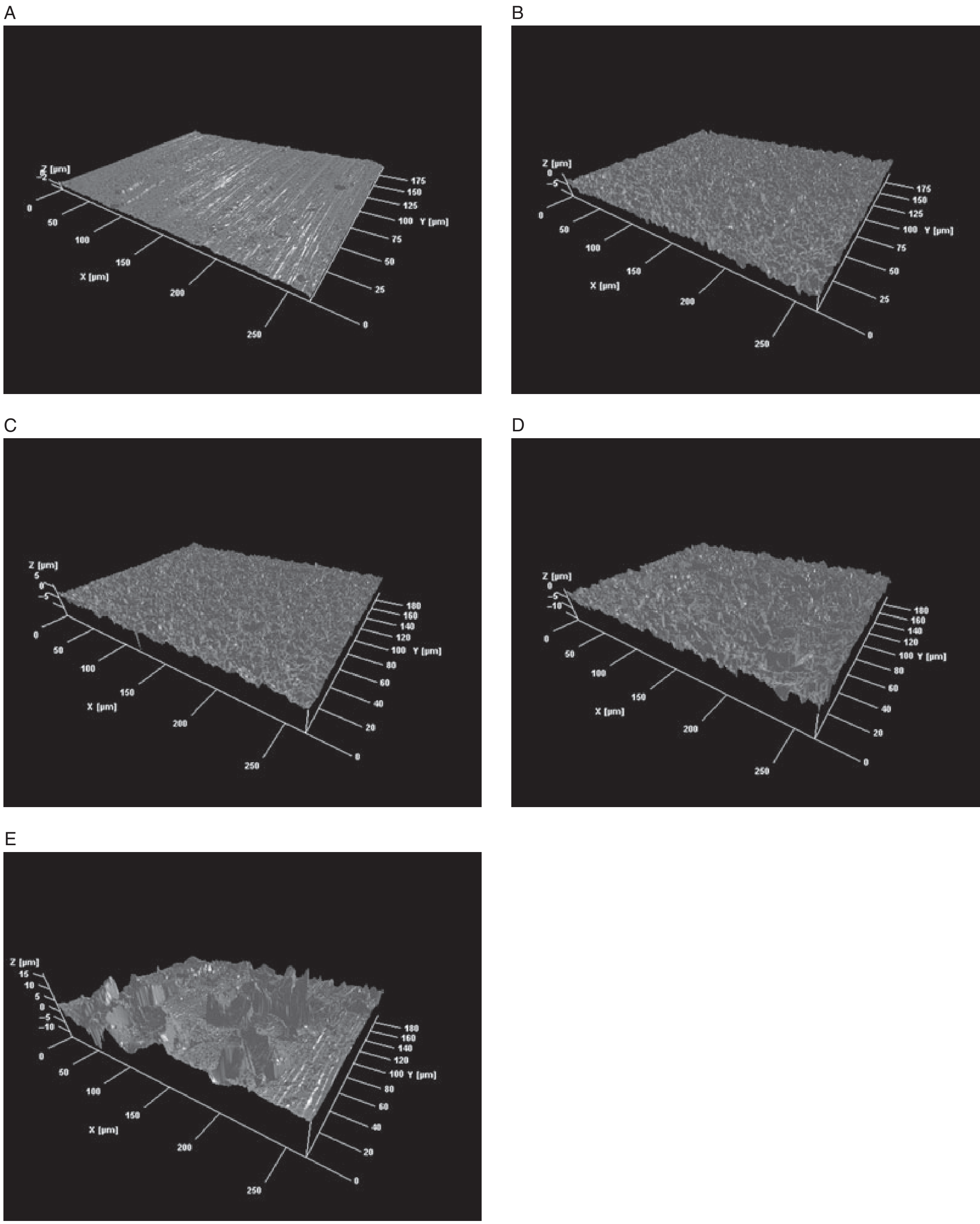

Figure 1 Topographical images of flank thread areas of (A) a turned fixture, (B) a fixture blasted with 25-µm TiO_2 particles, (C) a fixture blasted with 25-µm Al_2O_3 particles, (D) a fixture blasted with 75-µm Al_2O_3 particles, and (E) a fixture blasted with 250-µm Al_2O_3 particles.

TABLE 2 Surface Topography of Titanium Implants with Different Surface Treatments

Implant	*n*	Surface Topographical Parameters							
		S_{bi}	S_{ci}	S_{vi}	S_m	S_c	S_a	S_{ds}	S_{dr}
Turned	9	0.69	1.55	0.12	0.02	0.44	0.30	0.08	4.49
		(0.35)	(0.14)	(0.02)	(0.00)	(0.07)	(0.05)	(0.05)	(1.26)
25-µm TiO_2	27	0.61	1.38	0.14	0.05	1.08	0.78	0.09	31.5
		(0.16)	(0.10)	(0.02)	(0.01)	(0.23)	(0.20)	(0.02)	(7.0)
25-µm Al_2O_3	27	0.61	1.42	0.13	0.04	0.94	0.65	0.10	28.7
		(0.21)	(0.09)	(0.01)	(0.01)	(0.09)	(0.08)	(0.02)	(4.7)
75-µm Al_2O_3	18	0.64	1.36	0.14	0.06	1.44	1.04	0.08	46.7
		(0.13)	(0.08)	(0.01)	(0.01)	(0.17)	(0.14)	(0.01)	(10.3)
250-µm Al_2O_3	9	0.63	1.44	0.16	0.16	2.71	1.84	0.06	63.4
		(0.08)	(0.14)	(0.02)	(0.05)	(0.65)	(0.43)	(0.01)	(21.8)

Values are means of top, valley, and flank areas. SDs within parentheses.

study (Table 3). For example, TiUnite displayed the highest S_{ci} mean value and Astra Tech the lowest. Concerning the S_c parameter, Friadent showed the highest value and Osseotite the lowest. In terms of amplitude (S_a) and hybrid (S_{dr}) parameters, Friadent was the roughest, and Astra Tech and Osseotite were the smoothest.

DISCUSSION

In the present study, five candidating functional parameters for bone-anchored implants were investigated for implants with different surface roughness. The magnitude of the core fluid retention index (S_{ci}) was found to be inversely related to the bone biological ranking based on earlier in vivo studies with the same experimental fixtures.

In 1993, Stout and colleagues presented a set of 14 parameters, the so-called Birmingham 14, for characterizing a surface in three dimensions.[9] The set includes three index parameters (S_{ci}, S_{vi}, and S_{bi}) that are associated with the bearing area ratio curve and normalized with the root mean square (RMS) deviation (S_q). As discussed by Stout and colleagues, the functional properties are more easily understood as indexes than the absolute physical quantities, that is, the meaning of a large or small value of an index is easier to realize in manufacturing processes.[9] Thus, the index parameters can be used to qualitatively identify the shape features and discriminate different types of three-dimensional surface topography.[15] However, since the values of index parameters are similar to each other whether different roughness levels are considered, it is difficult to interpret

TABLE 3 Surface Topography of Five Commercially Available Dental Implants

Implant	Surface Topographical Parameters							
	S_{bi}	S_{ci}	S_{vi}	S_m	S_c	S_a	S_{ds}	S_{dr}
Astra Tech	0.83	1.47	0.13	0.05	1.04	0.66	0.09	23
	(0.38)	(0.34)	(0.03)	(0.04)	(0.56)	(0.23)	(0.05)	(7)
TiUnite	0.53	1.86	0.08	0.09	2.18	1.18	0.06	84
	(0.03)	(0.07)	(0.01)	(0.02)	(0.39)	(0.20)	(0.01)	(36)
Osseotite	0.69	1.54	0.11	0.04	0.77	0.50	0.08	18
	(0.29)	(0.20)	(0.03)	(0.03)	(0.30)	(0.16)	(0.05)	(4)
Straumann	0.60	1.56	0.12	0.12	2.50	1.62	0.08	69
	(0.06)	(0.04)	(0.01)	(0.02)	(0.34)	(0.21)	(0.01)	(8)
Friadent	0.60	1.57	0.11	0.15	2.72	1.75	0.07	145
	(0.06)	(0.12)	(0.01)	(0.03)	(0.40)	(0.25)	(0.01)	(81)

Values are means of nine measurements. SDs within parentheses.

the load bearing capability and lubrication retention properties of the engineering surfaces as no scalar information is given by the parameter.[15] This drawback is overcome with the volume parameters (S_m and S_c) that are naturally geometrically descriptors of surface topography. In the present study, three index parameters (S_{bi}, S_{ci}, and S_{vi}), as well as two scale-dependent volume parameters (S_m and S_c), were included. The lowest mean values of both the two scale-dependent parameters and S_{vi} were presented by the turned surface, which is the smoothest in terms of S_a and S_{dr}. The largest mean values of S_m, S_c, and S_{vi} were found for the surface blasted with 250-μm particles, which is the roughest surface in terms of S_a and S_{dr}. Thus, the magnitude of S_m, S_c, and S_{vi} was found to follow the surface roughness, that is, a larger S_a value gave larger S_m, S_c, and S_{vi} values. This result was also the case for the scale-dependent parameters S_m and S_c of the commercial implants. The Friadent implant was the roughest in terms of S_a and S_{dr} and demonstrated the largest S_m and S_c mean values. The finding is not unexpected since the functional parameters depend only on amplitude variation, and enough information to reconstruct them is probably combined in the RMS deviation, skewness, and kurtosis (ie, sharpness of surface height distribution).[16] However, values of the relative surface bearing index (S_{bi}) and core fluid retention index (S_{ci}) did not follow the roughness scale, since the turned implants displayed the largest S_{bi} and fixtures blasted with Al_2O_3 particles with a size of 75 μm the lowest S_{ci} mean values. Among the commercial implants, the smallest S_{ci} mean value was found for the Astra Tech fixture.

However, the surface chemistry of the commercial implants differs, and to evaluate the influence of topographical difference on the bone biological response, the surface chemistry of the implants must be similar. This is the case for the experimental Al_2O_3-blasted fixtures included in the present study.[7] They have been compared in in vivo studies, and the number of topography measurements of each type of surface in this study varies with the availability of specimens from earlier studies. However, the values of amplitude (S_a), spatial (S_{ds}), and hybrid (S_{dr}) parameters determined in the present study are in accordance with earlier published values.[5–7] The bone response in vivo was earlier studied with the rabbit bone model. After a healing period of 4–12 weeks, the bone response was evaluated either by a removal torque test or by taking biopsies for preparation of histological sections and analysis of bone-to-metal contact. Blasted implants demonstrated a higher removal torque and percentage of bone-to-metal contact compared with turned as-machined.[5,6,8] Furthermore, after 4 weeks there was a significantly higher bone-to-metal contact for implants blasted with 25-μm particles compared to the 250-μm blasted ones.[17] Implants blasted with different materials (Al_2O_3 or TiO_2) of the same particle size (25 μm) demonstrated similar result,[8] while a higher removal torque and more bone-to-metal contact was found for the implants blasted with 75-μm particles compared with the 25-μm blasted.[7] Thus, surface roughness obtained by blasting the implants with 75-μm particles was found as optimal for bone response.

The highest core fluid retention index (S_{ci}) was displayed by the turned implants, followed by fixtures blasted with 250- and 25-μm particles, respectively. Fixtures blasted with 75-μm Al_2O_3 particles displayed the lowest S_{ci} value. This is the inverse order of the bone biological ranking based on earlier in vivo studies previously described. Thus, the results indicate that a small fluid retention of surface structures in the core zone is relevant for bone response. The core zone is the vertical part from 5 to 80% of the bearing area (see Table 1) and when a surface changes from unworn to worn, this index decreases.[9] Furthermore, different manufacturing processes result in different S_{ci} values. For example, a bored surface has an S_{ci} value of approximately 2.2 compared to approximately 0.4 of a honed surface.[9]

The results of the present study indicate that a low core fluid retention index (S_{ci}) value is favorable for the biological outcome of bone-anchored implants. Thus, it is suggested that topographical characterization of bone-anchored implants includes the S_{ci} parameter to the set of amplitude, spatial, and hybrid parameters.

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