IJISET - International Journal of Innovative Science, Engineering & Technology, Vol. 6 Issue 9, September 2019
ISSN (Online) 2348 – 7968 | Impact Factor (2019) – 6.248
www.ijiset.com

Detection of Dental surface shift Using Laser Speckle Photography Technique

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Abstract:

The use of coherent light for imaging through highly scattering media, including biological tissues, is an active area for medical research. Scattered coherent wavelets from human tissue lead to deformation of the bio speckle fingerprint of tissue. Laser speckle phenomenon has been extensively explored; in particular, speckle analysis has been used in several optical surface roughness techniques. The technique of laser speckle formed by scattered coherent wavelets of teeth rough surface is presented to correlate between teeth surface roughness and laser bio speckle pattern contrast. Thus, eight teeth with rough surface from laser bio speckle contrast has been presented to display the tooth surface fine structure. The empirical formula between the micro-shift of the tooth due to an external load applied to it (simulating shewing process) has been studied using different Bio speckle patterns. A good correlation between experimental results obtained with speckle photography technique and most of the mechanical measuring techniques was obtained.

Keywords: Bio speckle – Tooth shift – Human teeth – Surface roughness – LASER

1. Introduction

The laser speckle imaging technique is a diagnostic technique in which the features of scattered coherent light are explored. At first, it was considered a noise, the image of the scatter pattern actually contains information on the microstructure and micro-movements of the object of a given tissue. By employing statistical analysis of the temporal and spatial fluctuations in the light scattered by microstructure dynamics. The ability of laser speckle imaging to allow the evaluation of dynamic features in tissues using a non-invasive, non-destructive cost-effective, real-time method has stimulated the academic community to focus efforts on the study of this method in the time domain (dynamic speckle analysis). However, the analysis of speckle patterns in the spatial domain also contains information on the microstructure of the surface, which can be explored by applying the proper statistical analysis. Deana *et al*. [1] describe a method to enhance the contrast between sound and decayed tooth tissue through the study of laser speckle pattern shifts in the spatial domain. Teeth's shifting is defined as the **slight movement of the teeth as a result of** genetics, age, grinding, bad habits and cavities are just some [2].

- **Genetics**: Even if you are born with straight teeth, if your genes dictate that they will shift at some point, they will," says New York orthodontist Jacqueline I. Fulop-Goodling, DMD.
- **Cavities**: When cavities are filled, the composite (plastic) can cause changes to your teeth and occasionally your bite. If decay is not treated, it can spread to the gums and bone, eating away the bone that holds the teeth in place, and loosening them.
- **Age:** New York cosmetic dentist Steven E. Roth, DMD, says that, as we age, the area between the teeth starts to wear away. "As this happens, the enamel thins out. And, because the lower teeth are inherently thinner, they wear out faster," he says. The more wear and tear on the lower teeth, the less able they are to withstand the force of the top teeth when biting down, causing shifting.
- **Grinding**: Grinding forces the lower jaw forward and puts tension on the upper teeth. The continual thrusting affects the position of the upper arch, pushing it out of alignment.
- **Tooth Loss:** "If a tooth is missing on the bottom, the tooth above it will grow downward since there is nothing there to stop it and vice versa.

In this study changes in tooth flexibility associated with preparation and subsequently cementation of laminate veneers could be numerically detected by using laser speckles photography techniques. This technique depends on mapping the optical roughness of the surface by laser speckles, so any shift of the surface can be detected due to accompanied speckles shift. The difference between two speckle pattern of consecutive images taken before and after applying the load on tooth are used to detect displacements as small as one speckle grain size (50nm)[7,8,9].

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2. Human tooth enamel structure

Tooth enamel is one of the four major tissues that make up the tooth in humans and many other animals. It makes up the normally visible part of the tooth, covering the crown. The other major tissues are dentin, cementum, and dental pulp. It is a very hard, white to off-white, highly mineralized substance that acts as a barrier to protect the tooth but can become susceptible to degradation, especially by acids from food and drink [3-4].

Enamel is the hardest substance in the human body and contains the highest percentage of minerals (96%), with water and organic material composing the rest. The primary mineral is hydroxyapatite, which is crystalline calcium phosphate. Enamel is formed on the tooth while the tooth develops within the gum before it erupts into the mouth. Once fully formed, enamel does not contain blood vessels or nerves. Remineralization of teeth can repair damage to the tooth to a certain degree but damage beyond that cannot be repaired by the body. The maintenance and repair of human tooth enamel are one of the primary concerns of dentistry. Enamel is avascular and has no nerve supply within it and is not renewed, however, it is not a static tissue as it can undergo mineralization changes.

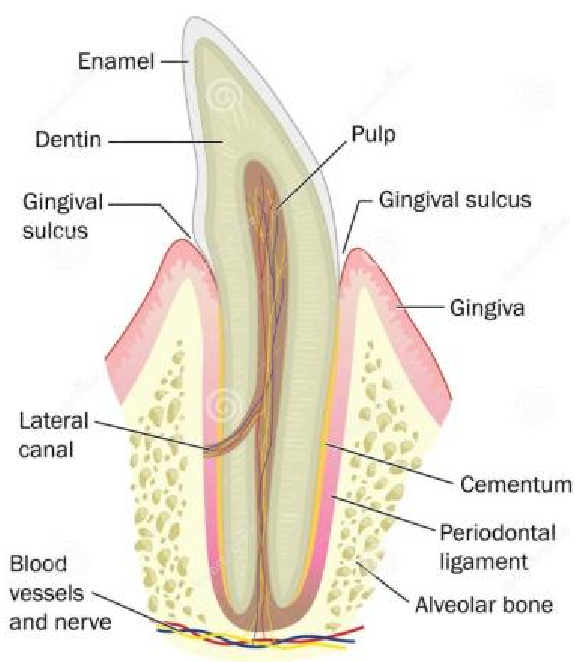

Figure (1) the basic anatomy of a human tooth

3. Speckle

According to Goodman (1984), speckle is a phenomenon that can be described only in terms of the Statistical Theory. The methods for the analysis and interpretation of the images are based on information obtained by means of first and second order statistics of brightness intensities of the captured image statistics. To simplify the analysis,

Goodman developed a statistical model of the first order, which describes the optical granules by means of the mean, variance and standard deviation of the intensities [5]. Equation (1) represents the equation of the mean intensity $< I >$:

$$< I > = \frac{\sum_{i=1}^{n} I}{n} \qquad (1)$$

Where I is the intensity and <I> the average intensity. The standard deviation of the intensity of the optical scattering is obtained by the equation (2):

$$\sigma = \sqrt{\sum_{i=1}^{n} (I_i - < I >)^2 \Big/ n-1}$$

Where n is the sample size, n = M x N pixel of an image. To enhance the difference between healthy and eroded regions, a fairly common technique of dynamic speckle was adapted to spatial speckle. The method is known as Laser Speckle Contrast Analysis (LASCA), consists of calculating the contrast of the image given by the following equation (3) [6]:

$$C = \frac{\sigma}{< I >}$$

In this work we used the statistical analysis of images containing information of optical scattering patterns of coherent light on a surface of the dental tissue. The speckle is formed by a set of clear and dark optical grains originated from the diffuse reflection and backscattering of coherent light on a particular surface [7]. The optical patter of the speckle images sifts depending upon the roughness of the surface, therefore its study in biological tissues has a potential for medical diagnosis, being thus possible to find an association between the optical scattering pattern and the demineralization process due to dental shifting.

4. Literature Review

To reach firm conclusions and provide suggestions regarding Detection of Dental surface shift, one must deeply survey and study existing techniques and their performance. This section presents an extensive survey of detecting shift methods, explains their results, and ends with a conclusion. Table 1 summarizes the most popular methods as well as their features and results. Various tools and methodologies have been proposed for Detection of Dental surface shift. Among all the surveyed methods for Detection of Dental surface shift, the laser speckles are the most widely used and efficient.

Author	Dataset	System	Measurement	Conclusion
[5] Insan Jang [2009] [5]	The sample consisted of dental casts obtained from 10 patients treated with extraction of bilateral maxillary first premolars and placement of three palatal miniscrews as anchorage for retraction of the anterior teeth.	Dental casts were measured by means of laser surface scanning system, and three-dimensional images were reconstructed.	Displacement of the central incisors was measured by the minis crew superimposition method ruga-palate-superimposition method. Correlation analysis and paired t-tests were performed to determine whether a significant difference existed between the measurements of the two superimposition methods	The maxillary dental casts can be reliably superimposed on the medial points of the third palatal rugae and the palatal vault as reference landmarks.
Julian Boldt [2011] [6]	10 teeth and 4 implants.	Two components optical systems were designed (a small 650 LED attached to tooth and CCD camera).	Tooth and implant mobility under physiological loading conditions.	1- Axial displacement of teeth shows strong time dependence with damping not observed for lateral loads. 2- Displacement under lateral loading was found to be about one order of magnitude higher than under axial load. 3- For dental implants, elastic deflection was observed in the axial and lateral direction. 4- For purely axial loading, dental implants and teeth show similar deflection under same force rise time but for lateral loading it is different.

M. S. Adly [2013] [7]		The proposed system is a computer-based system, where digital cameras are used to provide a video sequence, of either the Sagittal, Frontal, or Transverse plane, however, if more than one plane is required in the same time we may use more than one digital camera.	Jaw Movements using a Computer Vision System.	The proposed system is considered reliable and having a reasonable accuracy. The main advantages in this system are being simple and low cost when compared with any other method having the same accuracy.
H. El-Ghandoor [2015] [8]	15 human maxillary left central incisors.	The labial surface of the teeth was illuminated by a coherent light (633 nm wavelength) from a He-Ne laser source. The room was darkened and the teeth were imaged using a CCD Camera array (Canon Power Shot SX600 HS, Japan) mounted on a tripod before and after load application.	Evaluate the effect of laminate veneer preparation and cementation on a deflection of the maxillary central incisors when subjected to average functional force.	1- Preparation of teeth for laminate veneers did not significantly affect their deflection. 2- A significant difference in mean deflection values between e-max, crea.lign, and Enamic veneered teeth was found. 3- E-max veneers and enamic veneers reduced deflection of teeth significantly while crea.lign had a non-significant effect.
Mirjam Kuhn [2016] [9]	47 pairs of lateral cephalograms.		Evaluate soft tissue profile changes after a wide range of incisor movements in the anterior and posterior directions of the incisor. Identifying baseline values more prone to substantial soft tissue profile changes were of high interest.	The major factors for predicting the soft tissue profile change during orthodontic treatment are the amount of horizontal movement of the most anterior point of the maxillary incisor, the amount of bite opening, and the initial lip thickness. Although there are significant correlations between dental movements and soft tissue changes in larger samples, predictions for individuals may be inconsistent.

Jonathan Sandler [2017] [10]	20 set of pre and past treatment study models were randomly selected from clinical trials.		Molar movement of left and right maxillary using superimposition digital study models and cephalometric radiographs.	The method described for superimposition of repeated digital models is reliable and reproducible. This could be considered for use alongside cephalometric measures in all future biomechanical orthodontic studies.

Table 1 summarizes the most popular methods for Dental surface shift detection

5. MATERIALS AND METHOD

5.1 Samples

Eight recently extracted sound human maxillary central incisors with matching dimensions were collected in a jar containing 0.5% chloramine solution. The selected teeth were mechanically cleaned by an ultrasonic scaler (Bobcat pro ultrasonic scaler, DENTSPLY professional, USA), and examined by the aid of magnifying lens under X 3.5 magnification. The defective teeth with decay, attrition, fractures or cracks were discarded.

5.2 Tooth deflection testing:

The teeth were mounted in acrylic cylindrical blocks (cold cure denture base material, Acrostone Dental Factory) parallel to their long axis, and held in a specially constructed device at 45° angle to the horizontal plane. The device allowed application of 3 Kg load at the inciso-palatal line angle. The labial surface of the teeth was illuminated by a coherent light (633 nm wavelength) from a He-Ne laser source (figure 4) The room was darkened and the teeth were imaged using a CCD Camera array (Canon Power Shot SX600 HS, Japan) mounted on a tripod before and after load application. Tooth deflection testing was done for every tooth in the study at 4 stages:

- **Stage 1:** tooth was mounted in acrylic cylindrical blocks parallel to their long axis, and held in a specially constructed device at 45° angle to the horizontal plane.
- **Stage 2:** picture was captured by the camera.
- **Stage 3:** certain load was applied on the tooth (from 100 gm. to 1 Kg step 100 gm.)
- **Stage 4:** another picture was captured again by the camera after applying the load.

The difference between the two speckle patterns of consecutive images taken before and after applying the load on the teeth was used to detect the shifts in the teeth position. These Shifts corresponded to deflection of the teeth along the measurement axis and their extent could be determined by detecting the two speckle patterns peaks of intensities using an image processing software program.

5.3 Experimental setup

Each sample was illuminated with a He-Ne laser with a wavelength of 633 nm (red) (Uniphase, USA) with 40 mW of continuous wave power. The bean was expanded by a f = 100 mm lens (K&F concept, China) achieving a circular spot size with 6 mm in diameter. The samples were than imaged using a CMOS sensor with 23.7 mm X 15.3 mm (4752 x 3168 pixels; pixel pitch = 4.99 μm) (Canon EOS Rebel T1i camera fitted with a macro 100 mm Canon lens, Japan) and stored. The photometric parameters were: exposure time = 1/200 s; f/ 29; ISO 100 and the camera was placed at an angle θ < 10° with the laser (Figure 1). No data binning was performed by the camera. [11].

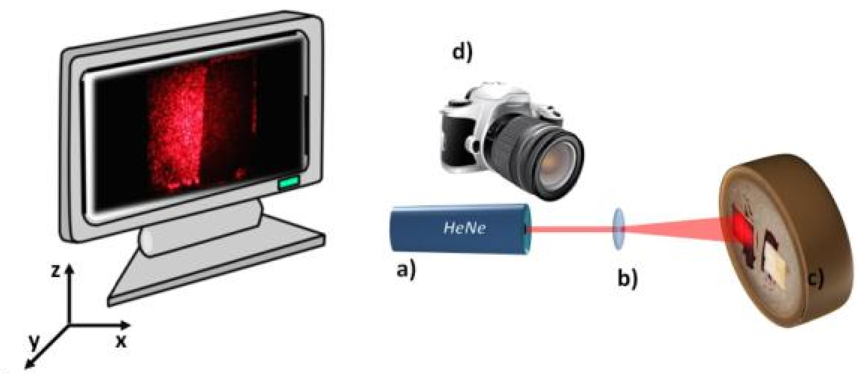

Figure (2) Schematic diagram of the experimental setup: (a) Laser HeNe wavelength 633nm; (b) focusing lens with f = 10cm; (c) samples; (d) camera Canon T1. [12]

There are two types of speckles (Objective and subjective speckles) [12-13]. A speckle pattern can be formed either at reflection of coherent light from a rough surface or in transmission by allowing coherent light to pass through a transparent medium having a randomly fluctuating refractive index distribution. The speckle pattern is characterized by a random intensity distribution that may be described by statistical means. The speckle spots are clearly visible when such an object is viewed under illumination by laser light. Figure (3) illustrates two possible ways of the speckle-pattern formation when laser lights reflected from a rough surface [14].

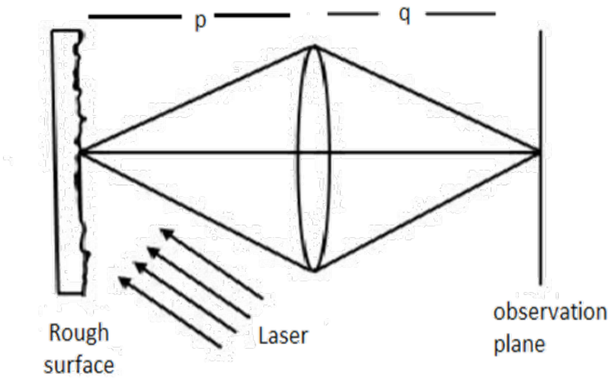

Figure (3): scheme speckle pattern formation under illumination of a rough surface by laser light

If the speckle pattern is formed by collecting the scattered radiation by a lens as shown in figure (3), a subjective speckle pattern is formed. The average size of the speckle grains is then related to the numerical aperture ratio F of the lens, and to the magnification M, as shown in equation (1).

$$\sigma_{sp} = 1.22\,\lambda\,(1+M)\frac{f}{D} \tag{1}$$

With f is the focal length of the lens and D is the lens diameter. The subjective speckle pattern may be treated as the image of a speckle pattern at different scale in the plane of the scattering surface. For these speckles the averaged size is given by:

$$\sigma_{sp} = 1.22\,\lambda\,\frac{(1+M)}{M}\,F = \sigma_{sp} = 1.22\,\lambda\,\frac{(1+M)}{M}\,\frac{f}{D} \tag{2}$$

For both objective and subjective speckle formations, it is possible to obtain a speckle size comparable with the wavelength of the light forming the speckle pattern.

6. Experimental results

Eight recently extracted sound human maxillary central incisors with matching dimensions were used. The teeth were mounted in acrylic cylindrical blocks (cold cure denture base material, Acrostone Dental Factory) parallel to their long axis, and held in a specially constructed device at 45° angle to the horizontal plane. The device shown in figure (4) allowed application of 3 Kg load at the incisor-palatal line angle.

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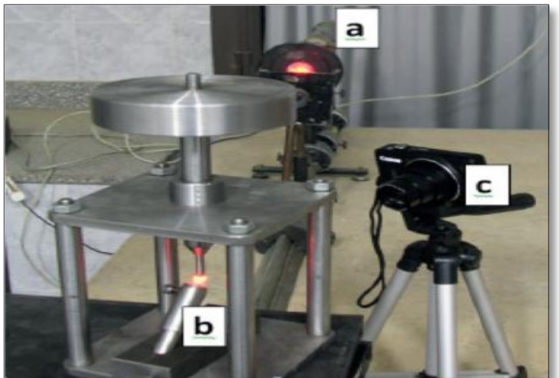

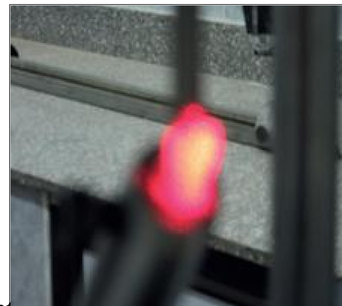

Figure (4) Assembled system showing (a) Laser source, (b) mounted tooth in loading device and (c) digital camera photographing the labial surface

The labial surface of the teeth was illuminated by a coherent light (633 nm wavelength) from a HeNe laser source. The room was darkened and the teeth were imaged using a CCD Camera array (Canon Power Shot SX600 HS, Japan) mounted on a tripod before and after applying different loads (from 100 gm. to 3 Kg step 100 gm.). The difference between the two speckle patterns of consecutive images taken before and after applying the load on the teeth was used to detect the shifts in the teeth position. These Shifts corresponded to deflection of the teeth along the measurement axis and their extent could be determined by detecting the two speckle patterns peaks of intensities using an image processing software program.

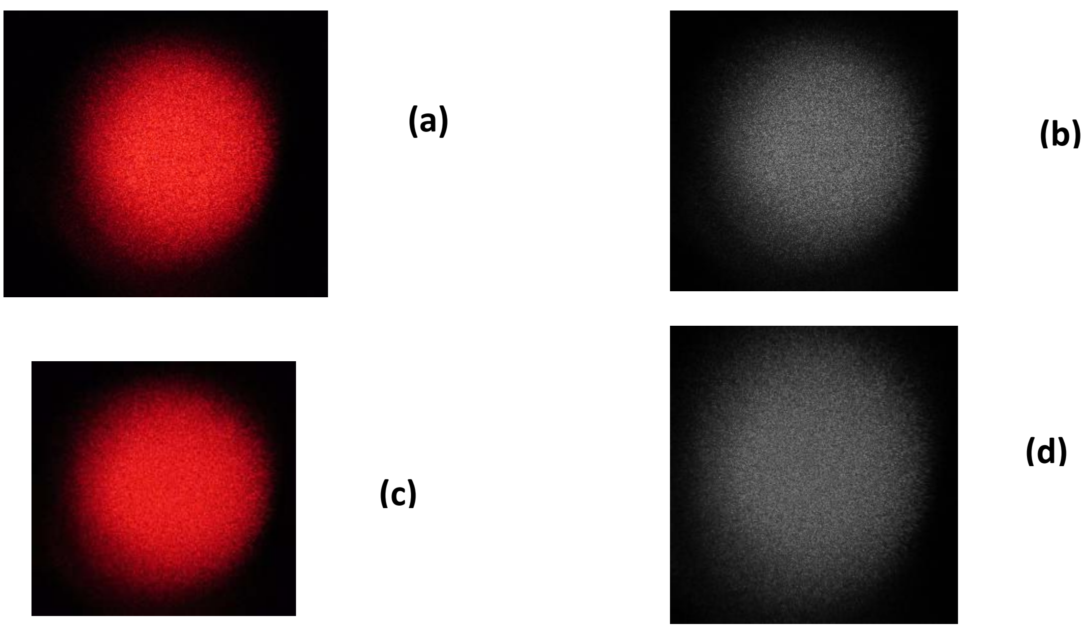

Figure (5) Photography of laser speckles before (a, b) and after load application (c, d)

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Laser speckle photography (LSP) technique was selected in this study because it can accurately determine the amount of deflection of teeth. It is based on natural phenomena that when a coherent light ray is allowed to be incident on an optically rough object it will scatter randomly through all directions. Interference of these scattered rays leads to the formation of a bright spot (constructive interference), and dark spots (destructive interference), these are called Laser Speckles.

This technique is used for measuring many variables such as displacement, velocity and refractive index profile. The general procedure consists of exposing a high-resolution photographic plate to two displaced speckle patterns, one before and one after a change is introduced to the diffuse object. In this study, The difference between the two speckle patterns of consecutive images taken before and after applying the load on the teeth was used to detect the shifts in the teeth position. These Shifts corresponded to deflection of the teeth along the measurement axis and their extent could be determined by detecting the two speckle patterns peaks of intensities using an image processing software program (fig 6).

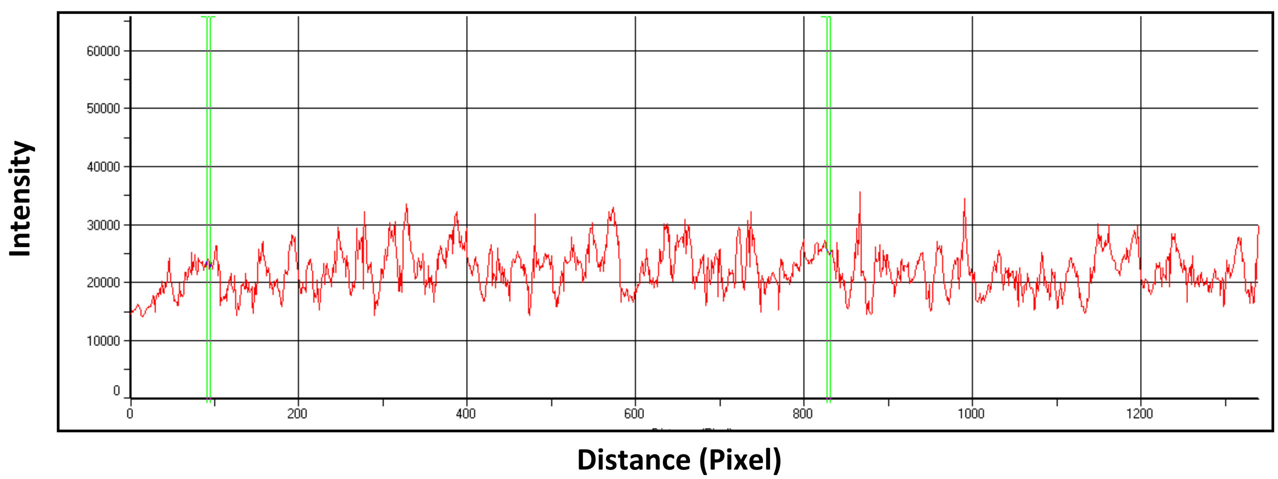

Figure (6) Speckle peaks (line profile) of intensities as detected by special image processing software program

After graphing the line profile, we export the peaks in an excel sheet to obtain the value of the maximum and minimum intensities. Then we calculate the contrast as shown in equation (3).

$$Contrast = \frac{Imax - Imin}{Imax} \quad (3)$$

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For each of the 8 teeth we recorded the maximum and minimum intensity and the calculated the contrast and shift using equation (3). Tables (2-9) shows the recorded data for Intensities, contrast and shift.

	Tooth 1			
	I max	**I min**	**Contrast**	**Shift**
No load	2463	1103	0.381380	6.000005
Disk	2516	906	0.470485	8.000007
100 gm	2325	929	0.429010	11.00001
200 gm	2108	810	0.444825	15.00001
300 gm	2258	961	0.402920	17.00001
400 gm	2159	937	0.394703	21.00002
500 gm	2238	863	0.443405	26.00002
600 gm	2681	810	0.535950	28.00002
700 gm	2028	858	0.405405	30.00002
800 gm	2159	929	0.398316	34.00002
900 gm	1911	683	0.473400	36.00003
1 kg	2155	820	0.448739	38.00001

	Tooth 2			
	I max	**I min**	**Contrast**	**Shift**
No load	2973	593	0.667414	4.000003
Disk	2744	1197	0.392540	6.000005
100 gm	2502	650	0.587563	20.00002
200 gm	2337	650	0.564781	22.00002
300 gm	2241	650	0.550329	23.00003
400 gm	2339	650	0.565072	32.00004
500 gm	2418	650	0.576271	33.00004
600 gm	2263	650	0.553725	34.00004
700 gm	2227	517	0.623178	36.00003
800 gm	2917	621	0.648954	38.00003
900 gm	2746	725	0.582253	40.00003
1 kg	2733	722	0.582055	42.00003

	Tooth 3			
	I max	**I min**	**Contrast**	**Shift**
No load	1938	640	0.503491	2.000002
Disk	2597	461	0.698496	5.000006
100 gm	2637	602	0.628280	7.000008
200 gm	2547	650	0.593369	8.000009
300 gm	2574	650	0.596774	10.00001
400 gm	2269	650	0.554642	12.00001
500 gm	2989	640	0.647286	18.00002
600 gm	2044	650	0.517446	20.00002
700 gm	2322	650	0.562584	22.00002
800 gm	2701	650	0.612056	23.00003
900 gm	2610	650	0.601227	25.00003
1 kg	2711	650	0.613210	27.00001

	Tooth 4			
	I max	**I min**	**Contrast**	**Shift**
No load	2963	1027	0.485213	5.000003
Disk	2479	649	0.585038	2.000001
100 gm	2661	734	0.567599	3.000002
200 gm	2479	593	0.613932	6.000004
300 gm	2479	659	0.579987	11.00001
400 gm	2479	536	0.644444	14.00001
500 gm	2479	649	0.585038	15.00001
600 gm	2479	489	0.670485	17.00001
700 gm	2479	621	0.599355	18.00001
800 gm	2479	385	0.731145	23.00001
900 gm	2479	423	0.708477	26.00002
1 kg	2479	498	0.665435	29.00002

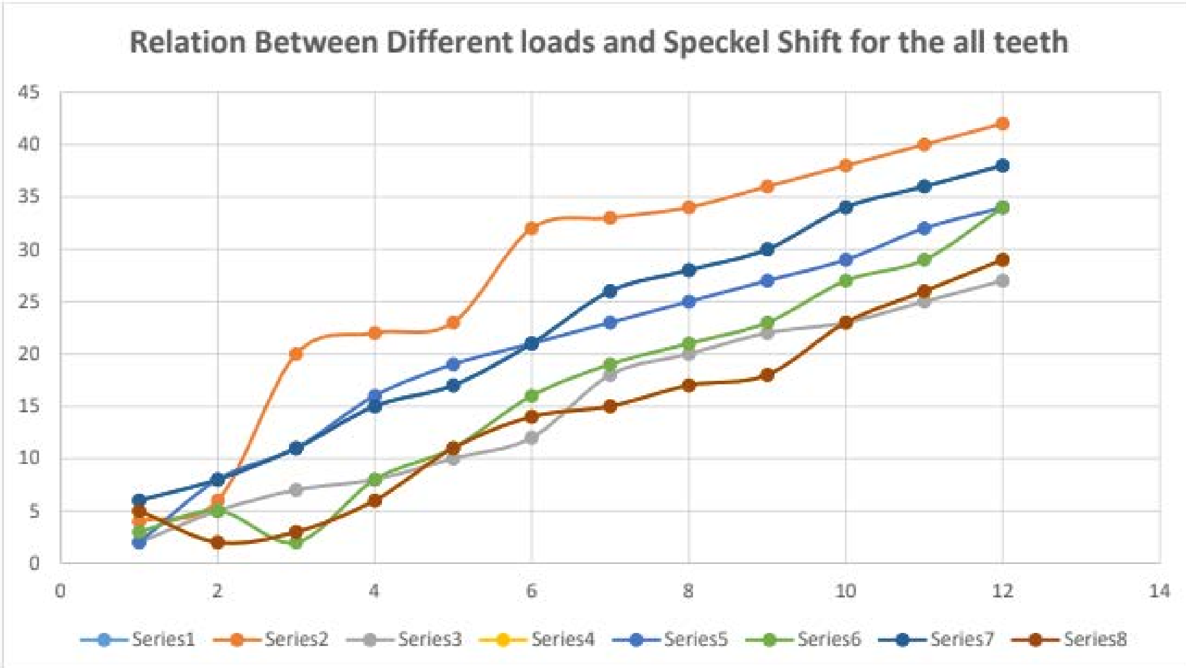
	Tooth 5			
	I max	**I min**	**Contrast**	**Shift**
No load	2479	295	0.787311	2.000001
Disk	2479	251	0.816117	8.000005
100 gm	1210	387	0.515341	11.00001
200 gm	1210	374	0.527778	16.00002
300 gm	1210	387	0.515341	19.00002
400 gm	1210	355	0.546326	21.00002
500 gm	1210	326	0.575521	23.00002
600 gm	1210	359	0.542384	25.00002
700 gm	1210	342	0.559278	27.00003
800 gm	2479	197	0.852765	29.00002
900 gm	2479	283	0.795076	32.00002
1 kg	2479	261	0.809489	34.00002

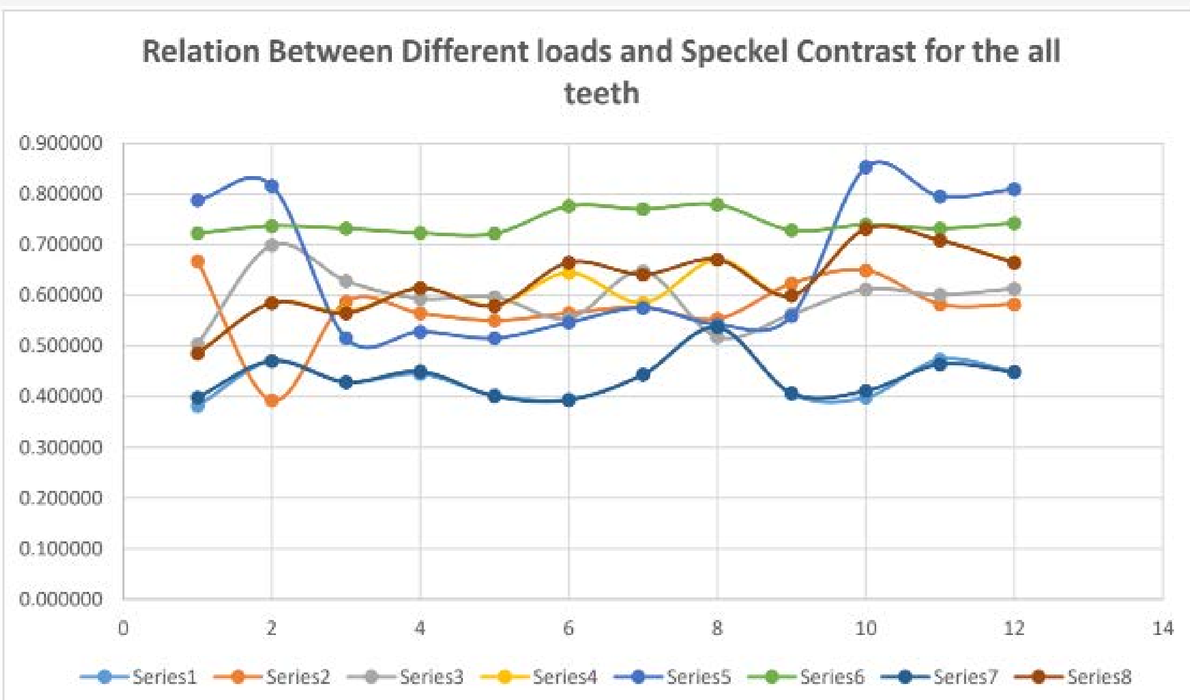
	Tooth 6			
	I max	**I min**	**Contrast**	**Shift**
No load	2401	387	0.722382	3.000004
Disk	2401	364	0.736709	5.000003
100 gm	2401	372	0.731699	2.000001
200 gm	2401	386	0.723000	8.000005
300 gm	2401	388	0.721764	11.00002
400 gm	2401	303	0.775888	16.00002
500 gm	2454	319	0.769924	19.00002
600 gm	2454	305	0.778905	21.00002
700 gm	2454	386	0.728169	23.00002
800 gm	2401	360	0.739225	27.00003
900 gm	2434	377	0.731768	29.00002
1 kg	2401	355	0.742380	34.00002

	Tooth 7			
	I max	**I min**	**Contrast**	**Shift**
No load	2565	1103	0.398582	6.000005
Disk	2516	906	0.470485	8.000007
100 gm	2322	929	0.428484	11.00001
200 gm	2108	800	0.449794	15.00001
300 gm	2258	966	0.400744	17.00001
400 gm	2159	940	0.393353	21.00002
500 gm	2240	863	0.443764	26.00002
600 gm	2688	810	0.536878	28.00002
700 gm	2028	855	0.406868	30.00002
800 gm	2159	900	0.411572	34.00002
900 gm	1911	700	0.463807	36.00003
1 kg	2155	820	0.448739	38.00001

	Tooth 8			
	I max	**I min**	**Contrast**	**Shift**
No load	2963	1027	0.485213	5.000003
Disk	2479	650	0.584532	2.000001
100 gm	2661	740	0.564834	3.000002
200 gm	2479	593	0.613932	6.000004
300 gm	2479	660	0.579484	11.00001
400 gm	2661	536	0.664686	14.00001
500 gm	2966	649	0.640941	15.00001
600 gm	2479	489	0.670485	17.00001
700 gm	2479	621	0.599355	18.00001
800 gm	2479	385	0.731145	23.00001
900 gm	2479	423	0.708477	26.00002
1 kg	2479	501	0.663758	29.00002

Tables (2-9) max, min intensities, contrast, and shift at different loads


Relation Between Different loads and Speckel Shift for the all teeth
45
40
35
30
25
20
15
10
5
0
0
2
4
6
8
10
12
14
Series1
Series2
Series3
Series4
Series5
Series6
Series7
Series8


Relation Between Different loads and Speckel Contrast for the all teeth
0.900000
0.800000
0.700000
0.600000
0.500000
0.400000
0.300000
0.200000
0.100000
0.000000
0
2
4
6
8
10
12
14
Series1
Series2
Series3
Series4
Series5
Series6
Series7
Series8

Conclusion

Among the different devices and methods aiming at extracting tooth surface properties in vitro, only in the last few years some new optical methods have been proposed dealing with mid-cost systems. Conventional approaches have been usually relied on high cost complex system such as mechanical or optical profile meters. While laser speckle is the new sensitive technique will be used to investigate fine characteristics of human tooth.

This technique is novel, simple, non-contact, and not expensive method to detect tooth shifting. Moreover, it is also an accurate method for detecting tooth shift in the range of microns.

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