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Original article

Measuring system for an attitude angle of a denture using an Inertial Measurement Unit

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ABSTRACT

Purpose: The aim of this study was to assemble and verify a measuring system for 3-D movements (attitude angle) of the denture during function.

Methods: For the calibration test, the sensor was fixed at the center of the rotary table. Operation and stopping of the rotary table were repeated 8 times, and the direction of rotation was reversed in the middle. The amount of rotation was 1.2 and 2.4°. As a pilot clinical trial, the attitude angles of three upper complete dentures during tapping were measured by this system.

Results: The attitude angles calculated by this system reduced by 3–4%. Pitch and roll of Subject III were significantly larger than Subjects I and II ($P < 0.001$), but yaw of Subject: III was significantly smaller than Subject: II ($P < 0.01$) during tapping. Pitch and yaw of "good" was significantly smaller than "average" in the stability of the dentures ($P < 0.001$). But roll of "average" was significantly smaller than "good" ($P < 0.05$). Pitch and yaw of "B" was significantly smaller than "C" in the type of maxillary ridge ($P < 0.001$). But roll of "C" was significantly smaller than "B" ($P < 0.05$).

Conclusions: The measurement accuracy of this system was equivalent to that of 3-D motion capture system by four infrared TV cameras. The measuring system using the IMU is reliable and easy to analyze the attitude angle of the denture during function. It may serve a diagnostic appliance to evaluate the quality of the denture.

1. Introduction

The number of edentulous people will decline significantly in the United States. Slade et al. reported that the predicted 8.6 million edentulous people in 2050 will be only 30% less than the estimated 12.2 million edentulous people observed in the 2009-2012 survey [1]. However, several million people are still wearing conventional dentures. When the denture movement during function is large, oral functions such as chewing and pronunciation cannot be recuperated properly [2,3]. Especially the complete denture displaces instantly by large force like occlusal force, because it has not rigid support such as teeth and implants and rests only on the mucosa rich in compressibility. Therefore, it is useful to develop a measuring system for the denture movement of which clinical application is possible. We can also diagnose the quality of occlusal adjustment in dentures using it.

In previous studies about measuring denture movements, methods using X-ray [4–7] have problems that can be measured only by 2-dimensional and have a risk of radiation exposure. Methods using magnet such as the mandibular kinesiograph [8–10] have problems that are easily affected by measuring environment and can measure only one point. A 3-D motion capture system with four infrared TV cameras was used for the first time in order to measure the denture movement with 6 degrees of freedom [11,12]. This system is not affected by foreign environment and can accurately measure multipoint. But this measuring apparatuses are large and expensive, so they are not yet used in dental clinics. Therefore, the amount of the denture movement is perceived visually and tactually in the clinic.

For measuring the complete denture movements, we cannot use a strain-gage-type and the inductance-type displacement converter due to difficulty securing immovable point. In this case, we can measure with an Inertial Measuring Unit (IMU), without securing immovable point. Furthermore, it leads to reduce the measuring cost and the size of the measurement device. The

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purpose of this study is to assemble and verify a measuring system for an attitude angle of the denture.

2. Materials and methods

2.1. Measuring system

The system of measuring denture movement consisted of an IMU (MPU-9250, InvenSense Inc., California, UAS), a control unit, and a bluetooth module. The IMU contains a 3-axis gyroscope, a 3-axis accelerometer, and 3-axis digital compass. The IMU was embedded with self-curing acrylic resin (UNIFAST III, GC Corporation, Tokyo, Japan) (Fig. 1). The size of the sensor is $13 \times 11 \times 4$ mm. The weight is 0.9 g. 3-axis digital compass was not used in this study. Because the conversion speed of the digital compass is 3 times slower than that of the gyroscope and accelerometer. In order to calculate the offset of the circle in three dimensions, it is necessary to calibrate the offset amount as a sphere. This operation is very complicated. The resolution (word length of Analog to Digital Converter) of accelerometer and gyroscope is 16 bit.

The attitude angle of the denture was calculated according to the following procedures. First, the waveform analysis of the sensor output was performed, and offset correction value variation was calculated. The sensor output was corrected by offset correction value in order to prevent the occurrence of an integration error. Next, the attitude angle (angle of inclination) from the initial state was calculated by acceleration vector of the accelerometer output and integrating angular velocity of the gyroscope output. The initial attitude angle was calculated by acceleration output. This original software was programmed on the platform of LabVIEW (LabVIEW2010 ver10.02f, National Instruments Corporation, Texas, USA).

2.2. Sensor characteristic

First, drift and noise of the sensor output were measured to check the characteristic of the sensor in a stationary state for 10 min. Next, for the IMU calibration test, the IMU was fixed at the center of the rotary table (dia. 24 cm) with double-sided adhesive tape. The edge of the rotary table was measured with a laser displacement meter (HL-G105-S-J, Panasonic Corporation, Osaka, Japan). The resolution is ± 1.5 μm. The linearity is ± 0.1%F.S. The measurement error is ± 20 μm. When converted into the angle, the measurement error is $\pm 0.01°$. Operation and stopping of the rotary table were repeated 8 times, and the direction of rotation was reversed in the middle. The amount of rotation was 1.2 and 2.4°. The IMU data and the output of the laser displacement meter were measured at the same time. The rotation angle of the IMU was calculated by acceleration vector and integrating angular velocity. The relation between two rotation angles were analyzed.

2.3. Subjects

As a pilot trial, three complete denture wearers (from 69 to 79 years old) participated in this study. Before deciding whether or not to participate, the subjects received an explanation of this study (Tokyo Medical and Dental University no. 1268), and we obtained informed consent from all subjects. They were free from any signs or symptoms of craniomandibular dysfunction. The included subjects have been edentulous for over 5 years. Because of loose and uncomfortable, their dentures were fabricated by the dentist who possessed five years or more of clinical experience at the Special Care Clinic, Tokyo Medical and Dental University. All dentures were made under identical conditions. We used veracia SA posterior (SHOFU Inc., Kyoto, Japan) for molar artificial teeth. The type of occlusion with the dentures was lingualised occlusion. The classification of maxillary edentulous ridge of the Subjects I and II was type B [13]. The Subject III was type C. When try to move the denture in the horizontal direction with the finger, the stability of the denture was judged as good (hardly moving) or average (slight movement, less than about 2 mm) or poor (more). The perceived stability of the maxillary denture of Subjects I and II was good. The stability of Subject III was average. All subjects wore the new dentures for at least 1 month. Measurement data of a lower denture is convolution of jaw movement and denture movement. Complete separation is difficult with present system. In addition, it is difficult to make a verification experiment system on how much it was deconvoluted. For that reason, we measured the attitude angle of upper denture in this study. The IMU sensor was attached to the central incisors of the upper denture with the wax (NP-0010, ONO SOKKI Inc., Yokohama, Japan) in this study. The subjects were instructed to tap for 10 s. The classification of the maxillary edentulous ridges, the assessment of the stability, and measuring the denture movements were performed by one tester. R (R version 3.3.3 (2017-03-06) – “Another Canoe” Copyright (C) 2017 The R Foundation for Statistical Computing Platform: x86_64-w64-mingw32/x64 (64-bit)) was used for the statistical analyses. One way ANOVA was used to test for significant differences in the attitude angle among the subjects. We used the Tukey contrasts as multiple comparisons. Differences in the attitude angle between “good” and “average” in stability of the denture and differences in the attitude angle between “B” and “C” in type of the ridge were tested using t-tests. P-values of <0.05 were considered significant.

3. Results

3.1. Sensor characteristic

Zero drift and noise of the sensor output were measured to examine the characteristic of the sensor in a stationary state for 10 min. Average values per one second were calculated. Time series graphs of those values are shown in Fig. 2. The standard

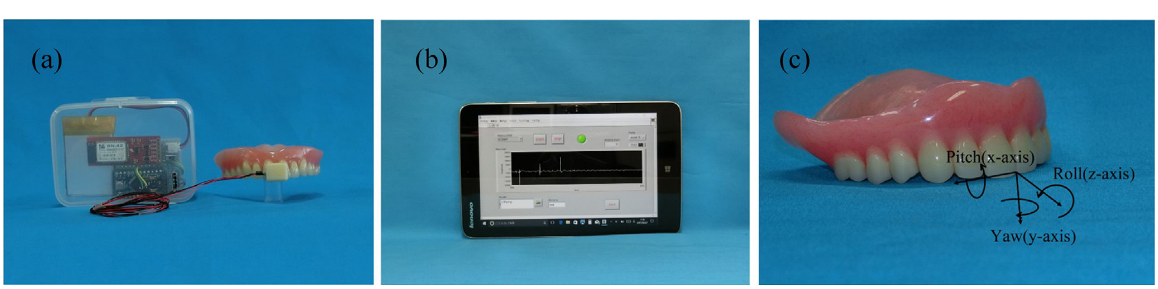

Fig. 1. Photograph showing the design of our sensor on the central incisors of the upper denture with the wax (right side) connected with PTFE ultra-fine electric wires to the data transmitter (left side). The IMU was embedded with self-curing acrylic resin. The size of the sensor is $13 \times 11 \times 4$ mm. The weight is 0.9 g (a). The data receiver (Tablet PC) (b). The attitude angle of the denture and x, y, z-axis of the gyroscope and the accelerometer (c).