Original Research Article

Optical impression method to measure three-dimensional position and orientation of dental implants using an optical tracker

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ABSTRACT

Objectives: The aim of this study was to devise an optical impression method that could make impressions of dental implants accurately and rapidly.

Material and Methods: Four paper markers (4 × 3 mm, 8 × 6 mm, 16 × 12 mm, and 24 × 18 mm) and one titanium marker (8 × 6 mm) were prepared to determine the measuring accuracy of the three-dimensional optical tracker. For a proposed and conventional impression taking method, we compared the reproduction accuracies of the positions and orientations of dental implants and the times to obtain impressions. Finally, we fabricated computer-aided designing (CAD)/computer-aided manufacturing (CAM) superstructure frameworks to determine the adaptation accuracy.

Results: The 8 × 6-mm titanium marker was optimal among the prepared markers. Dental implants made by the proposed and conventional impression taking methods had measurement errors of 71 ± 31 μm and 32 ± 18 μm, respectively. The proposed method took a significantly shorter time to obtain an impression than did the conventional method. The connection between the CAD/CAM superstructure frameworks and four implant analogs had uplifts of 55 ± 10 μm, 94 ± 35 μm, 2 ± 1 μm, and 66 ± 3 μm.

Conclusion: Our proposed method and fabricated titanium markers enabled us to measure the positions and orientations of dental implants both accurately and rapidly.

We then used the reproducible measurement results for the positions and orientations of the dental implants to fabricate CAD/CAM superstructure frameworks within an acceptable accuracy range.

KEYWORDS: optical impression, impression taking, dental implant, CAD/CAM, optical tracker

1. INTRODUCTION

In implant treatment in which superstructures are fabricated, an indirect method is used to take an impression of the positions and orientations of the dental implants in the oral cavity. Superstructures with poor adaptation can cause screw loosening and fractures, implant fractures, abnormal occlusions, and inflammation of the gingiva and bone around implants due to plaque accumulation at the margins (Augthun & Conrads 1997, Balshi 1996, Burguete, et al. 1994, Eckert, et al. 2000, Jemt, et al. 1996, Leonhardt, et al. 1999, Lindhe, et al. 1992, Sahin & Cehreli 2001, Wee, et al. 1999). It is thus important to fabricate superstructures with the best possible adaptation and to obtain an accurate impression as quickly as possible. However, even if the accuracy of impressions is improved, errors in positioning and orienting dental implants in the oral cavity and errors in the working model will be uncorrected due to the permanent strain of the impression material and the setting expansion of the plaster in the indirect method (Assif, et al. 1992, Assif, et al. 1996, Assuncao, et al. 2004, Cabral & Guedes 2007, Del'Acqua, et al. 2008, Naconecy, et al. 2004, Vigolo, et al. 2004, Vigolo, et al. 2003). Multiple dental implants are generally connected to brace them against lateral force and torque. To compensate for connection errors, a connected superstructure framework is divided once, fixed in the oral cavity, and soldered (de Sousa, et al. 2008, Jemt &

Linden 1992). Slight errors are permissible in production due to the periodontal membrane around natural teeth. However, dental implants that are osseointegrated do not have any physiological perturbation (Assif, Marshak & Schmidt 1996, Rudd, et al. 1964). Therefore, a new method is required that can accurately measure the relationship between implants in the oral cavity without dividing or soldering superstructures.

From the early 1980s, Mörmann proposed a method for fabricating ceramic restorations that uses computer-aided designing (CAD)/computer-aided manufacturing (CAM) technology as an alternative to conventional restorations (Mormann 2006). Various optical (laser or stereoscopic camera) impression systems have been developed that directly take impressions in the oral cavity. They include Cerec 3 (Sirona, Germany) (Magne, et al. 2011), Lava™ Chairside Oral Scanner (3M ESPE, US) (Syrek, et al. 2010), E4D Dentist (D4D Technologies, LLC, US) (Kachalia & Geissberger 2010), and iTero (Cadent, US) (Garg 2008). However, the presence of an oral submucous platform makes it impossible to optically take impressions of dental implants. In any optical impression system, taking impressions of dental implants is essentially at the abutment level. We can expect improved fabrication accuracy of superstructures and simplified procedures if impressions can be taken at the implant level.

As stated above, measuring the relationship between dental implants in the oral cavity directly and reproducing them outside the oral cavity without taking impressions and fabricating models overcomes some problems of the indirect method. These problems include measurement errors between the oral cavity and the model and the long chair time for impression taking. Moreover, superstructures can be fabricated in a single piece and thus do not require cumbersome procedures such as soldering.

Adaptation accuracy is guaranteed even for different types of dental implants because the platform for dental implants and the piece connecting the superstructures are standardized. Therefore, taking an optical impression of a natural tooth must include measuring the entire abutment tooth. In contrast, superstructures of dental implants can be fabricated with good adaptation by measuring only part of an implant.

In this study we propose a method that can take optical impressions of dental implants both accurately and rapidly.

2. MATERIALS AND METHODS

2.1 Determining the measurement accuracy of a three-dimensional optical tracker and fabricated titanium markers

We used a Micron Tracker 2 Sx60 (MT2; Claron Technology, US), a three-dimensional optical tracker, to measure positions and orientations of dental implants. It has a coordinate system whose origin is located at the midpoint of a straight line connecting the two camera centers (**Fig. 1a**). A dedicated marker is attached to the measurement object. It has a pattern of black and white squares in which there are three points, a, b, and c (**Fig. 1b**). The MT2 can be used to measure the translation and rotation matrices between the camera and the marker coordinate system.

We printed four markers (ac × ab: 4 × 3 mm, 8 × 6 mm, 16 × 12 mm, and 24 × 18 mm) on paper. The displacement between the MT2 and the markers on the measurement object (e.g., a jawbone or model) was varied between 350 and 500 mm in steps of 10 mm. The fabricated markers were fixed on an XYZ stage (CAMM-3, Roland, Japan) that had a positioning accuracy of ± 0.01 mm following the specification sheet. We calculated the average and standard deviation of measurement errors $\mathbf{e}$ using the equation $\mathbf{e} = | \mathbf{m} - 10 |$, where $\mathbf{m}$ is a distance measured between each step by MT2.

We designed and fabricated titanium markers for three-dimensional measurements

(8 × 6 mm) using CAD/CAM technology (**Fig. 2a**). An antirotation mechanism was incorporated for the titanium markers (**Fig. 2b**). We performed an experiment to determine the influence of different materials (paper and titanium) and different marker orientations. For the orientations, the titanium marker was fixed on an XYZ stage at 400 mm from the MT2 and rotated at intervals of 10° (□ = 0–50°) (**Fig. 3**).

2.2 Reproduction accuracy of positioning and orienting dental implants and impression taking time

2.2.1 Conventional impression taking method

We used a conventional impression taking method known as the open-tray method. Four impression copings (Brånemark RP, Nobel Biocare, Sweden) were connected to the implant analogs on the fabricated measuring model. Each coping was connected via dental floss and fixed with acrylic resin (Pattern Resin, GC, Japan) around the copy and the floss. After curing for five minutes, adhesive (Examixfine Adhesive, GC, Japan) was applied to a custom tray (Tray Resin II, Shofu, Japan), and we took an impression using a silicon impression material (Examixfine Regular Type, GC, Japan) (Papaspyridakos, et al. 2011). After five minutes, the impression material was detached. We fabricated a working model by combining the implant analog and a dental stone with the detached impression material (n = 3).

2.2.2 Proposed impression taking method

We measured a homogeneous transformation matrix ${}^{m1}_{mt}\mathrm{D}$ from the MT2 coordinate system Σ_{mt} to the coordinate system Σ_{m1} of a marker. The homogeneous transformation matrix consisted of translation and rotation matrices. The homogeneous transformation matrix ${}^{m1\_i}_{m1}\mathrm{D}$ from Σ_{m1} to the coordinate system Σ_{m1_i} of an implant connected by the marker can be used as a known value by measuring the position of the marker for a connector (**Fig. 4**). Therefore, the transformation from Σ_{mt} to Σ_{m1_i} is given by

$$ {}^{m1\_i}_{mt}\mathrm{D} = {}^{m1}_{mt}\mathrm{D}\,{}^{m1\_i}_{m1}\mathrm{D}\ . \qquad (1) $$

By measuring the three-dimensional position of each marker connected to two dental implants, the relative position and orientation ${}^{mn\_i}_{m1\_i}\mathrm{D}$ of the implant can be calculated via

$$ {}^{mn\_i}_{m1\_i}\mathrm{D} = {}^{m1\_i}_{mt}\mathrm{D}^{-1}\,{}^{mn\_i}_{mt}\mathrm{D}\ , \qquad (2) $$

where the n in mn_i represents the number of dental implants, excluding the first one. It makes no difference if marker 2 as shown in **Fig. 4** is selected as the first marker. By iteratively calculating the relative position and orientation of the implant between *n* and 1, we can obtain all the positions and orientations of the implant. This algorithm was implemented in the C language (Visual Studio 2005, Microsoft, Japan).

To confirm whether the algorithm could used to measure the position and orientation of the implants without relying on movement of the MT2 or patients, we prepared a model and measured with two procedures. We made a measuring model by inserting four parallel implant analogs (Brånemark RP, Nobel Biocare, Sweden) into a plaster model. The fabricated model was measured with three-dimensional scanners (Rexcan ARX, Solutionix, Korea). We generated a three-dimensional image of the implant analog as a fiducial model and located it according to the measured fabricated model in virtual space. The positions and orientations of the dental implants on the fabricated model were measured individually and following the algorithm respectively (n = 3). Both results were overlaid onto the fiducial model to evaluate validity of implementation.

2.2.3 Comparison of reproduction accuracies for positions and orientations of dental implants

Each platform of an implant analog was measured with three-dimensional scanners (Rexcan ARX, Solutionix, Korea) to determine the central coordinate of the platforms. We used reverse modeling software (Leios 2009, Data Design, Japan) to minimize errors in aligning the position and orientation between two point groups of each central coordinate and a measurement result using the proposed method.

2.2.4 Comparison of impression taking time

Using the conventional impression taking method, we measured the time after connecting an implant analog on the measuring model and an impression coping, and before the detachment of an impression body (n = 5). In contrast, in the proposed method, we measured the time after connecting the titanium marker and the implant analog, and before calculating the position and orientation of the dental implants (n = 5). To compare an actual impression taking time, neither measurement result was included for fabricating frameworks.

2.3 Fabrication and adaptation accuracy of superstructure framework

We generated three-dimensional dental implants in virtual space based on the position and orientation of the implant analogs measured by the proposed method. Superstructure frameworks were designed for the dental implants using CAD software

(FreeForm Modeling, SensAble Technologies, US). The designed superstructure frameworks were fabricated with a rapid prototyping machine (Eden, Objet Geometries, Israel) using ultraviolet-curable resin. The fabricated superstructure frameworks were mounted on the measuring model. We used a level gauge (Ebisu Diamond, Ebisu, Japan) and a digital camera (IXY Digital 2000 IS, Canon, Japan) to set the measuring model such that the *y*-axis of the camera coordinate system was parallel to the long axis of the implant analog. The uplift in the connection part between the superstructure framework and the implant analog was measured from six viewing directions using image processing software (Image J, NIH, US). After calculating the uplift by averaging image measurement results of six viewing directions once connection parts, we calculated the mean and standard deviation of uplifts for three fabricated superstructure frameworks (n=3).

3. RESULTS

3.1 Determination of measurement accuracy of optical trackers and fabricated markers

Although the measurement error varied with the size of the fabricated markers, no significant differences were found (**Fig. 5**). The means and standard deviations of the measurement error for the 8 × 6-mm, 16 × 12-mm, and 24 × 18-mm markers were 52 ± 37 μm, 31 ± 28 μm, and 58 ± 27 μm, respectively. It was not possible to measure the 4 × 3-mm marker because it was too small. The measurement error for the distance between the MT2 and the markers showed no significant differences (**Fig. 5**). The maximum measurement error was 98 μm in the measurement range 350–500 mm. The means and standard deviations of the measurement error for paper and titanium markers were 42 ± 44 μm and 48 ± 37 μm, respectively, which shows no significant difference. The measurement error varied with the marker orientation but showed no significant differences. For angles of 10°, 20°, 30°, 40°, and 50° relative to the *y*-axis, the means and standard deviations of the measurement error were 67 ± 31 μm, 86 ± 11 μm, 154 ± 75 μm, 119 ± 59 μm, and 139 ± 52 μm, respectively. Based on these experimental results, we decided to use the 8 × 6-mm titanium marker in the range 350–500 mm.

3.2 Validation of proposed impression taking method

We validate an algorithm of our proposed impression taking method by comparing the measurement results obtained using our method and individual measurements in three-dimensional virtual space. The dental implants were discretely located depending on the movements of the camera and the model. On the other hand, for the proposed method, the positions and orientations of the dental implants could be reproduced independently of movements of the camera and model.

3.3 Evaluation of reproduction accuracy for positions and orientations of dental implants and impression taking time

The means and standard deviations of the measurement error for the dental implants by the proposed and conventional methods were 71 ± 31 µm and 32 ± 18 µm, respectively, which are not significantly different (**Fig. 6**). The means and standard deviations of the measurement error for the *x*-, *y*-, and *z*- axes in the coordinate system of the MT2 were, respectively, 53 ± 55 µm, 59 ± 39 µm, and 42 ± 10 µm, which are also not significantly different (**Fig. 6**). For the impression taking time, the proposed method was significantly faster compared with the conventional one (**Fig. 7**).

3.4 Evaluation of adaptation accuracy for superstructure framework

The means and standard deviations of the uplift in the connection part between the superstructure framework and the four implant analogs were 55 ± 10 μm, 94 ± 35 μm, 2 ± 1 μm, and 66 ± 3 μm (**Fig. 8**).

4. DISCUSSION

Currently, conventional optical systems could take impressions for impression copings but not at the implant level. Therefore, to fabricate superstructures with good adaptation, we tried to record the positions and orientations of the dental implants in the oral cavity by using standard implant shapes.

We first evaluated the measurement conditions for the MT2 in terms of its effect on the measurement accuracy by accounting for the different sizes, distances, and orientations of the markers. In terms of the effect of marker size, the 4 × 3-mm marker printed on paper could not be measured because the developer of the MT2 recommends a 2-mm difference between the two vectors forming the marker. We could measure the 8 × 6-mm, 16 × 12-mm, and 24 × 18-mm markers, but no significant differences were evident. Therefore, we selected the 8 × 6-mm marker to use in the oral cavity. In clinical settings, for a posterior area such as the molar region, the marker should be illuminated from outside of the oral cavity for capture by MT2.

As for the influence of marker distance on the measurement accuracy, the distance between the MT2 and the markers was set between 350 and 500 mm based on a specification of the MT2 that ensures measurement accuracy in this range. We may say that one reason for lacking any systematic tendency was the use of the least difference of 2 mm mentioned above. Ideally, the distance between two vectors should be more than 2 mm. However, the difference should not be bigger for use in the oral cavity.

We investigated the effect of marker materials on measurement accuracy using a fabricated titanium marker (Adell, et al. 1981) that was biocompatible and thus could be used in the oral cavity. The measurement error did not show any significant differences, and the usability of the fabricated titanium marker was the same as that of a paper marker. We investigated the effect of marker orientation on measurement accuracy. An angle greater than 20° between the MT2 and a marker tended to give a large mean and standard deviation for measurement error. This is mainly because one of the two line segments of the measurement feature became extremely short when the angle was too large. Thus, to reduce measurement error, the marker surface should be placed perpendicular to the *z*-axis of the MT2. Based on this result, three-dimensional measurements of the positions and orientations of dental implants were performed between 350 and 500 mm using the 8 × 6-mm titanium marker in later experiments. To show the usability of the proposed method, we compared it with the reproduction results for the positions and orientations of dental implants in three-dimensional virtual spaces. The measurement results were not affected by movement of the MT2 or the model.

Even if there is no antirotation mechanism for the titanium markers, our method can be used when no marker rotates during measurement.

There are two conventional methods: open and closed trays. The accuracies of these two methods show no significant differences for three or fewer implants (Cabral & Guedes 2007, Carr 1992, Conrad, et al. 2007, Daoudi, et al. 2004). However, for four or more implants, the open-tray method is more accurate (Assuncao, Filho & Zaniquelli 2004, Barrett, et al. 1993, Carr 1991, Del'Acqua, Arioli-Filho, Compagnoni & Mollo Fde 2008). In this study, we used the open-tray method as the conventional method because our fabricated model had four implant analogs.

The proposed and conventional methods showed no significant difference in their reproduction accuracies for the position and orientation of dental implants. However, there was a significant difference in impression taking time.

Finally, we validated the adaptation accuracy of the superstructure frameworks that were fabricated with CAD/CAM based on the reproduction results for the position and orientation of dental implants obtained with our method. The maximum mean uplift of the frameworks was 94 μm for each implant analog in the measurement model. As shown in **Fig. 8**, one reason for the lower measurement errors of the third implant is that the mean angle between the marker attached to the third implant and the MT2 is only

4.457° (close to 0°). Jemt (1991) has reported that a half turn of an occlusal screw is an acceptable superstructure error for retaining screws in clinical cases. This is equivalent to a measurement error of about 150 μm. Some studies have reported that a measurement error of less than 150 μm is acceptable (al-Turki, et al. 2002, Kan, et al. 1999). Based on this, it seems reasonable to conclude that the adaptation accuracies of the superstructure frameworks fabricated in this study fall within the acceptable range. Although there is no comparison between superstructure frameworks fabricated by the proposed and conventional methods, the result in **Fig. 6** suggests that the mean uplift of the conventional method will be less than that of the proposed method.

In currently used optical systems, it is possible to take impressions of abutment teeth, remaining teeth, and mucosal faces. However, for implants that allow impression taking at the abutment level, it is possible to take impressions at the implant level because the platform is hidden under the mucosa. Furthermore, implant superstructures can be fabricated only for single crowns; there have been no reports of coupling crowns in multiple implants (Magne, Paranhos, Burnett, Magne & Belser 2011, Syrek, Reich, Ranftl, Klein, Cerny & Brodesser 2010). However, using the proposed method it is possible to take impressions at the implant level as well as fabricate superstructures for multiple implants.

The results of this study clearly show that our measurement algorithm can reproduce the positions and orientations of dental implants even when the MT2 or patient moves. In addition, our system has the potential to fabricate superstructure frameworks using digital data sets without any working model. Consequently, it will be redundant to divide and braze superstructure frameworks, and we expect improved clinical efficiency.

5. CONCLUSIONS

In this study, our measurement algorithm and fabricated titanium markers enable rapid measurement of the positions and orientations of dental implants even when the MT2 or the patient moves. We fabricated CAD/CAM superstructure frameworks within an acceptable accuracy range using the reproducible measurement results for the positions and orientations of dental implants.

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REFERENCES

Adell, R., Lekholm, U., Rockler, B. & Branemark, P. I. (1981) A 15-year study of osseointegrated implants in the treatment of the edentulous jaw. *Int J Oral Surg* **10**: 387-416.

al-Turki, L. E., Chai, J., Lautenschlager, E. P. & Hutten, M. C. (2002) Changes in prosthetic screw stability because of misfit of implant-supported prostheses. *Int J Prosthodont* **15**: 38-42.

Assif, D., Fenton, A., Zarb, G. & Schmitt, A. (1992) Comparative accuracy of implant impression procedures. *Int J Periodontics Restorative Dent* **12**: 112-121.

Assif, D., Marshak, B. & Schmidt, A. (1996) Accuracy of implant impression techniques. *Int J Oral Maxillofac Implants* **11**: 216-222.

Assuncao, W. G., Filho, H. G. & Zaniquelli, O. (2004) Evaluation of transfer impressions for osseointegrated implants at various angulations. *Implant Dent* **13**: 358-366.

Augthun, M. & Conrads, G. (1997) Microbial findings of deep peri-implant bone defects. *Int J Oral Maxillofac Implants* **12**: 106-112.

Balshi, T. J. (1996) An analysis and management of fractured implants: A clinical report.

Int J Oral Maxillofac Implants **11**: 660-666.

Barrett, M. G., de Rijk, W. G. & Burgess, J. O. (1993) The accuracy of six impression techniques for osseointegrated implants. *J Prosthodont* **2**: 75-82.

Burguete, R. L., Johns, R. B., King, T. & Patterson, E. A. (1994) Tightening characteristics for screwed joints in osseointegrated dental implants. *J Prosthet Dent* **71**: 592-599.

Cabral, L. M. & Guedes, C. G. (2007) Comparative analysis of 4 impression techniques for implants. *Implant Dent* **16**: 187-194.

Carr, A. B. (1991) Comparison of impression techniques for a five-implant mandibular model. *Int J Oral Maxillofac Implants* **6**: 448-455.

Carr, A. B. (1992) Comparison of impression techniques for a two-implant 15-degree divergent model. *Int J Oral Maxillofac Implants* **7**: 468-475.

Conrad, H. J., Pesun, I. J., DeLong, R. & Hodges, J. S. (2007) Accuracy of two impression techniques with angulated implants. *J Prosthet Dent* **97**: 349-356.

Daoudi, M. F., Setchell, D. J. & Searson, L. J. (2004) An evaluation of three implant level impression techniques for single tooth implant. *Eur J Prosthodont Restor Dent* **12**: 9-14.

de Sousa, S. A., de Arruda Nobilo, M. A., Henriques, G. E. & Mesquita, M. F. (2008)

Passive fit of frameworks in titanium and palladium-silver alloy submitted the laser welding. *J Oral Rehabil* **35**: 123-127.

Del'Acqua, M. A., Arioli-Filho, J. N., Compagnoni, M. A. & Mollo Fde, A., Jr. (2008) Accuracy of impression and pouring techniques for an implant-supported prosthesis. *Int J Oral Maxillofac Implants* **23**: 226-236.

Eckert, S. E., Meraw, S. J., Cal, E. & Ow, R. K. (2000) Analysis of incidence and associated factors with fractured implants: A retrospective study. *Int J Oral Maxillofac Implants* **15**: 662-667.

Garg, A. K. (2008) Cadent itero's digital system for dental impressions: The end of trays and putty? *Dent Implantol Update* **19**: 1-4.

Jemt, T. (1991) Failures and complications in 391 consecutively inserted fixed prostheses supported by branemark implants in edentulous jaws: A study of treatment from the time of prosthesis placement to the first annual checkup. *Int J Oral Maxillofac Implants* **6**: 270-276.

Jemt, T. & Linden, B. (1992) Fixed implant-supported prostheses with welded titanium frameworks. *Int J Periodontics Restorative Dent* **12**: 177-184.

Jemt, T., Rubenstein, J. E., Carlsson, L. & Lang, B. R. (1996) Measuring fit at the implant prosthodontic interface. *J Prosthet Dent* **75**: 314-325.

Kachalia, P. R. & Geissberger, M. J. (2010) Dentistry a la carte: In-office cad/cam technology. *J Calif Dent Assoc* **38**: 323-330.

Kan, J. Y., Rungcharassaeng, K., Bohsali, K., Goodacre, C. J. & Lang, B. R. (1999) Clinical methods for evaluating implant framework fit. *J Prosthet Dent* **81**: 7-13.

Leonhardt, A., Renvert, S. & Dahlen, G. (1999) Microbial findings at failing implants. *Clin Oral Implants Res* **10**: 339-345.

Lindhe, J., Berglundh, T., Ericsson, I., Liljenberg, B. & Marinello, C. (1992) Experimental breakdown of peri-implant and periodontal tissues. A study in the beagle dog. *Clin Oral Implants Res* **3**: 9-16.

Magne, P., Paranhos, M. P., Burnett, L. H., Jr., Magne, M. & Belser, U. C. (2011) Fatigue resistance and failure mode of novel-design anterior single-tooth implant restorations: Influence of material selection for type iii veneers bonded to zirconia abutments. *Clin Oral Implants Res* **22**: 195-200.

Mormann, W. H. (2006) The evolution of the cerec system. *J Am Dent Assoc* **137 Suppl**: 7S-13S.

Naconecy, M. M., Teixeira, E. R., Shinkai, R. S., Frasca, L. C. & Cervieri, A. (2004) Evaluation of the accuracy of 3 transfer techniques for implant-supported prostheses with multiple abutments. *Int J Oral Maxillofac Implants* **19**: 192-198.

Papaspyridakos, P., Benic, G. I., Hogsett, V. L., White, G. S., Lal, K. & Gallucci, G. O. (2011) Accuracy of implant casts generated with splinted and non-splinted impression techniques for edentulous patients: An optical scanning study. *Clin Oral Implants Res*.

Rudd, K. D., O'Leary, T. J. & Stumpf, A. J., Jr. (1964) Horizontal tooth mobility in carefully screened subjects. Techn docum rep sam-tdr-64-12. *Tech Doc Rep U S Air Force Syst Command Electron Syst Div* **94**: 1-6.

Sahin, S. & Cehreli, M. C. (2001) The significance of passive framework fit in implant prosthodontics: Current status. *Implant Dent* **10**: 85-92.

Syrek, A., Reich, G., Ranftl, D., Klein, C., Cerny, B. & Brodesser, J. (2010) Clinical evaluation of all-ceramic crowns fabricated from intraoral digital impressions based on the principle of active wavefront sampling. *J Dent* **38**: 553-559.

Vigolo, P., Fonzi, F., Majzoub, Z. & Cordioli, G. (2004) An evaluation of impression techniques for multiple internal connection implant prostheses. *J Prosthet Dent* **92**: 470-476.

Vigolo, P., Majzoub, Z. & Cordioli, G. (2003) Evaluation of the accuracy of three techniques used for multiple implant abutment impressions. *J Prosthet Dent* **89**: 186-192.

Wee, A. G., Aquilino, S. A. & Schneider, R. L. (1999) Strategies to achieve fit in implant prosthodontics: A review of the literature. *Int J Prosthodont* **12**: 167-178.

1) FIGURES AND TABLES

Fig. 1

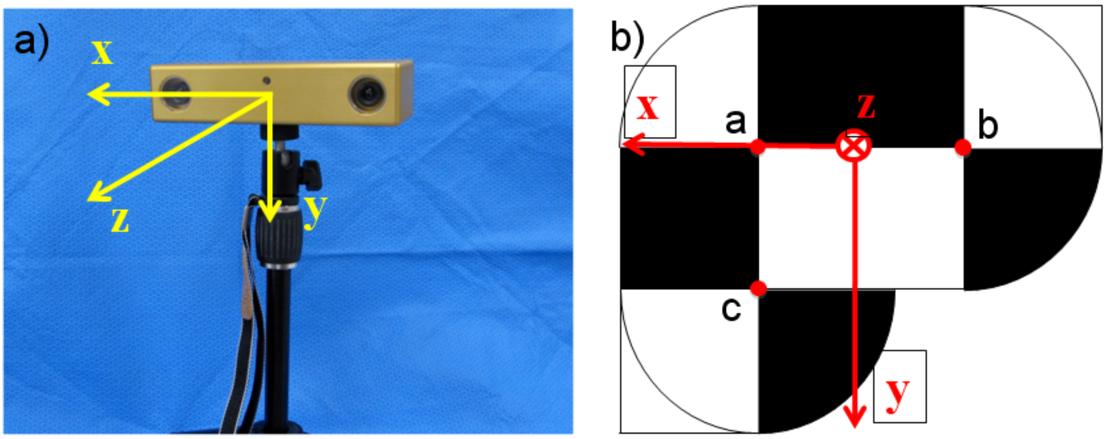


Fig. 2

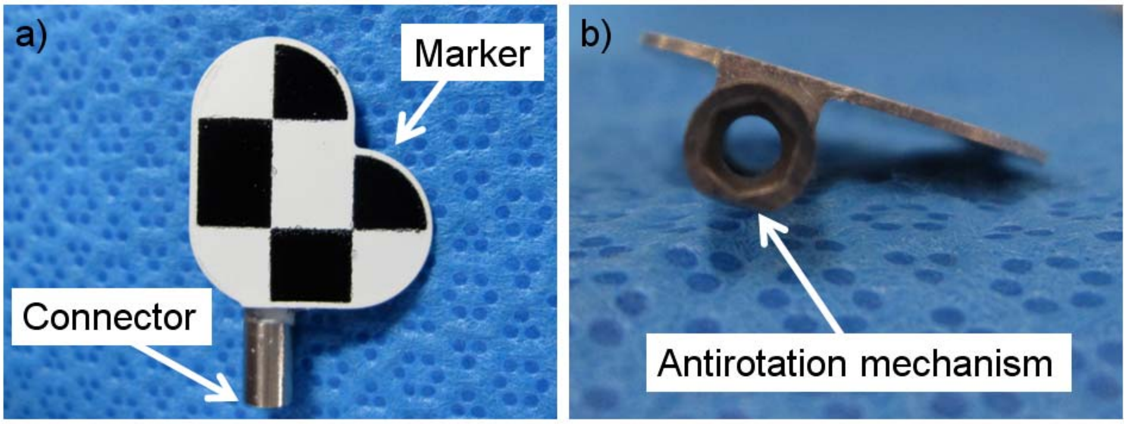


Fig. 3

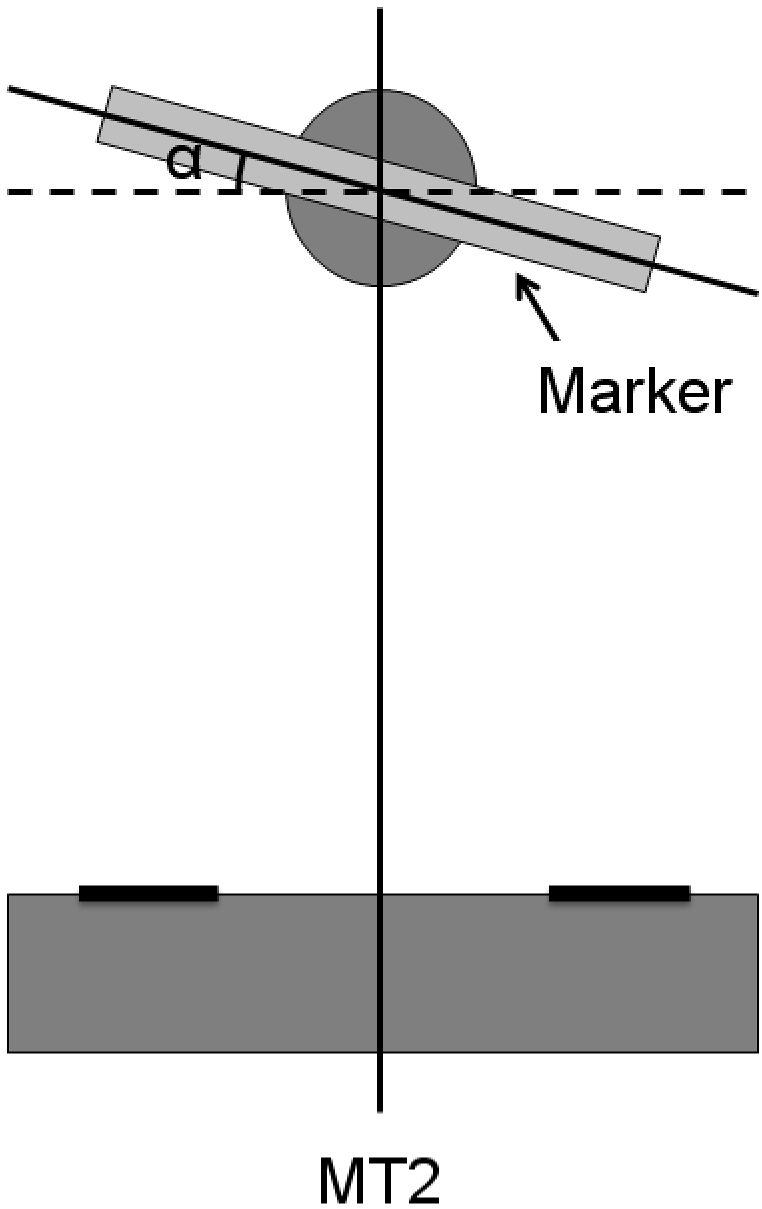
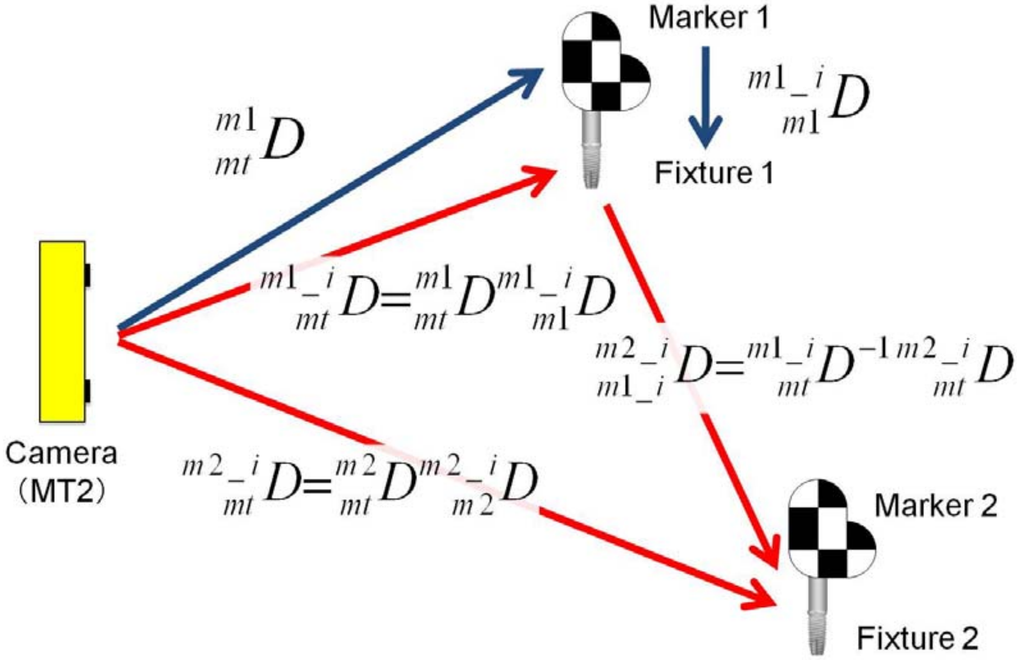


Fig. 4



Marker 1
$^{m1}_{mt}D$
$^{m1\_i}_{m1}D$
Fixture 1
$^{m1\_i}_{mt}D = ^{m1}_{mt}D \, ^{m1\_i}_{m1}D$
$^{m2\_i}_{m1\_i}D = ^{m1\_i}_{mt}D^{-1} \, ^{m2\_i}_{mt}D$
Camera
(MT2)
$^{m2\_i}_{mt}D = ^{m2}_{mt}D \, ^{m2\_i}_{m2}D$
Marker 2
Fixture 2

Fig. 5

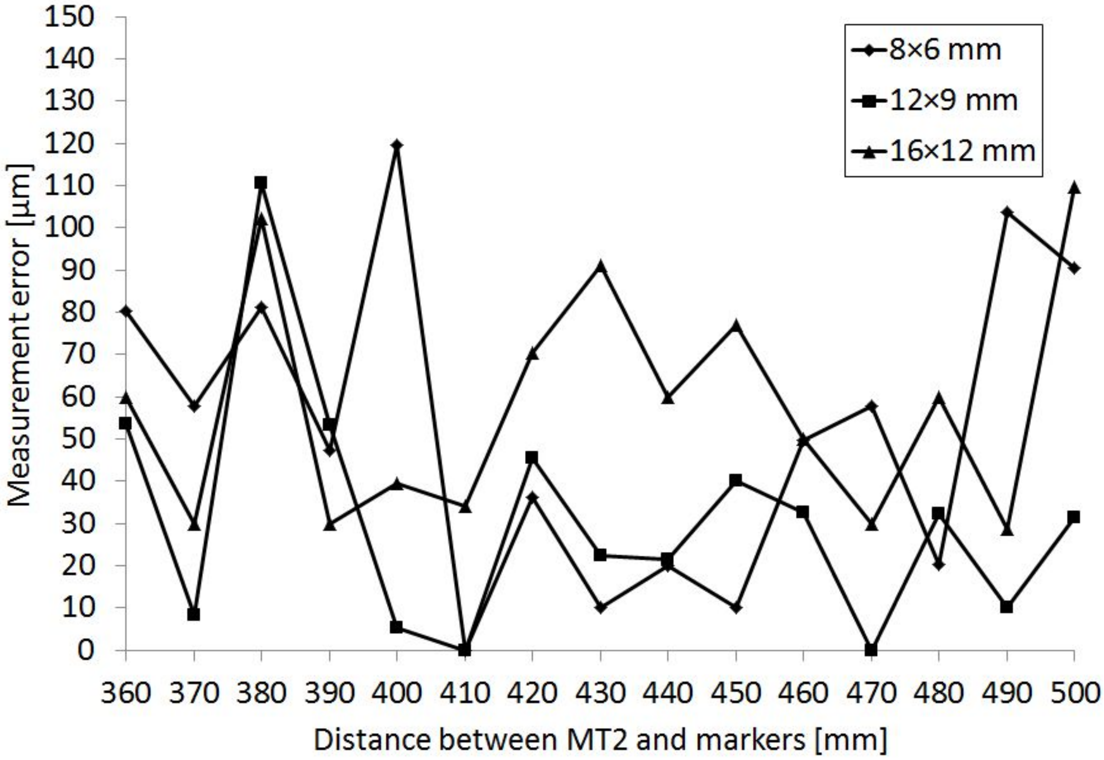
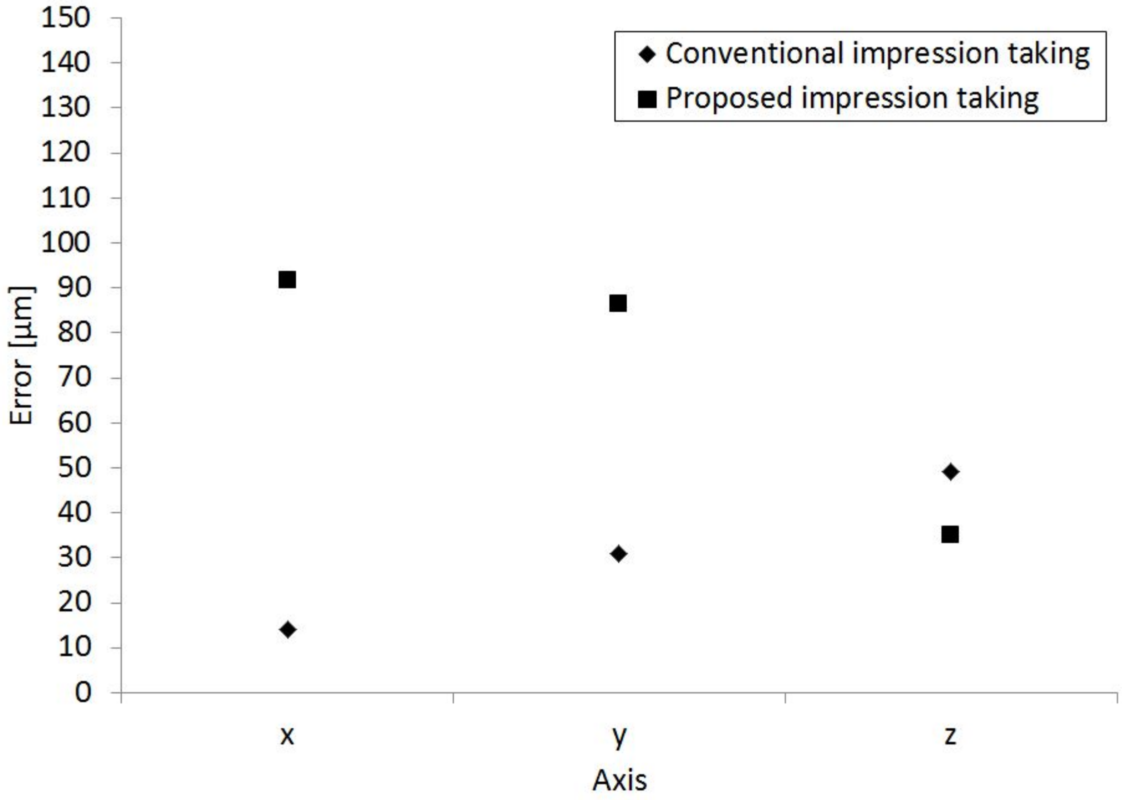
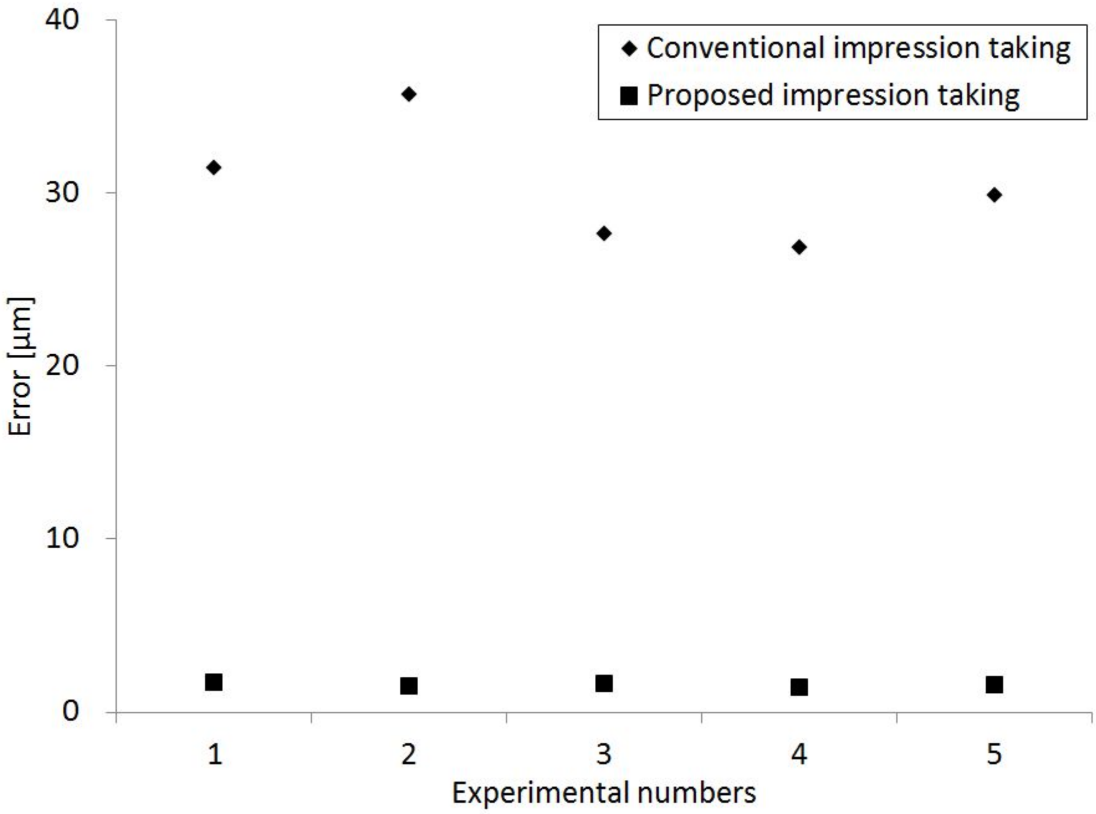

8×6 mm
12×9 mm
16×12 mm
Measurement error [μm]
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
360 370 380 390 400 410 420 430 440 450 460 470 480 490 500
Distance between MT2 and markers [mm]

Fig. 6



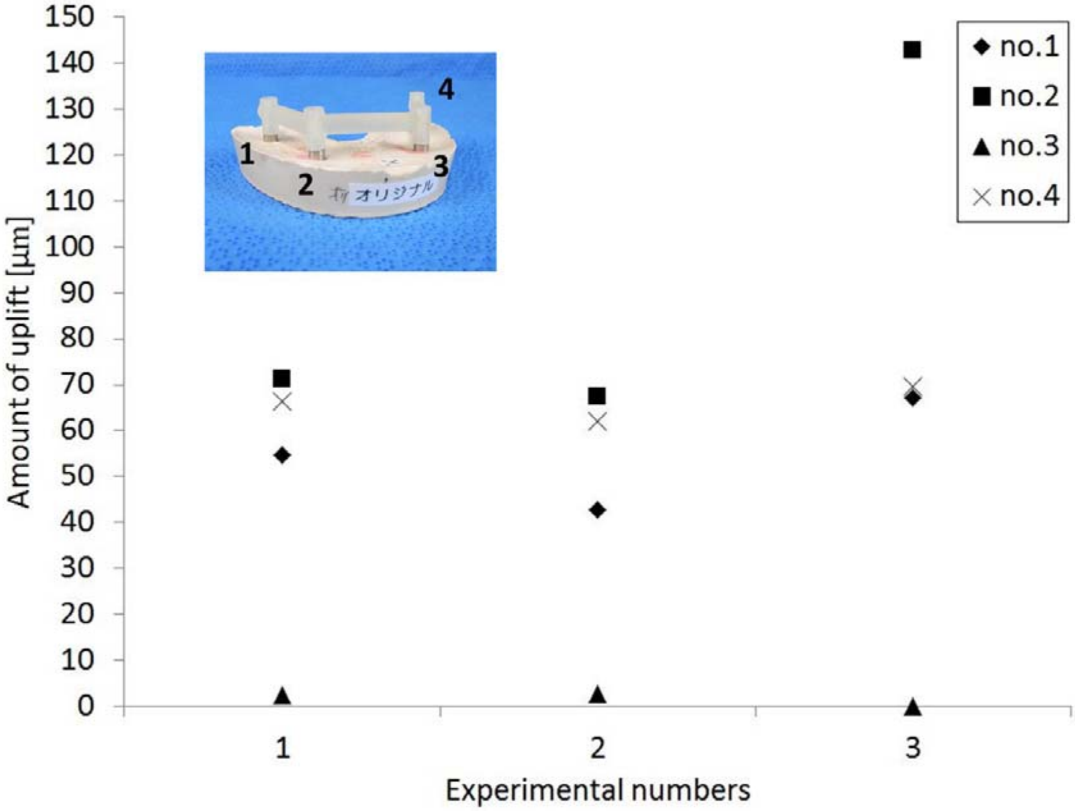
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
Error [µm]
Conventional impression taking
Proposed impression taking
x
y
z
Axis

Fig. 7



40
30
20
10
0
Error [µm]
Conventional impression taking
Proposed impression taking
1
2
3
4
5
Experimental numbers

Fig. 8



150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
Amount of uplift [µm]
1
2
3
4
オリジナル
no.1
no.2
no.3
no.4
1
2
3
Experimental numbers

CAPTIONS

Fig. 1 Coordinate system of MT2 and fiducial markers: a) three-dimensional optical tracker (Micron Tracker 2 Sx60, Claron Technologym US); b) fiducial markers.

Fig. 2 Fabricated titanium markers for three-dimensional measurement of dental implants: a) front and b): lateral views.

Fig. 3 Proposed impression taking method.

Fig. 4 Relationship between MT2 and fiducial markers.

Fig. 5 Effect of marker size on measurement accuracy.

Fig. 6 Position and orientation reproducibility dependence on impression method.

Fig. 7 Time required to take impression.

Fig. 8 Uplift of framework for measurement model.