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Three-Dimensional Dynamic Analysis of the Reproducibility of Verbal and Nonverbal Facial Expressions

Tiancheng Qiu, MD[1], Zulin Xue, MD[1], Ling Wu, MD[1], Rong Yang, MD[1], Xiaojing Liu, MD[1], Xing Wang, DDS, MD, PhD[1], and Zili Li, MD[1]

Abstract

Objective: The aim of this study is to compare the short- and long-term reproducibility of verbal and nonverbal facial expressions of normal people using dynamic 3-dimensional (3-D) imaging.

Design: Prospective, cross-sectional, controlled study.

Setting: Peking University School and Hospital of Stomatology, Beijing, China.

Patients and Participants: Twenty-seven participants, 12 males and 15 females, were recruited for this study.

Methods: A 3-D dynamic system was applied to capture the process of 4 nonverbal facial expressions (smile lips closed, smile lips open, lip purse, cheek puff) and 2 verbal facial expressions (/i:/, /u:/) at an initial time point, 15 minutes later, and 1 week later. Key frames were selected from each expression recording sequence.

Main Outcome Measures: The root mean square (RMS) between each key frame and its corresponding frame at rest was calculated. ΔRMS reflected the difference of the same key frames between the different sessions of the same expression of the same participant. The reproducibility of different facial expressions at different time intervals were analyzed.

Results: There was no significant difference in verbal and nonverbal expression repeatability during a 15-minute interval, except for cheek puff motion. Following a 1-week interval, verbal expression repeatability was superior to that of nonverbal expressions ($P < .01$). Compared with nonverbal expressions, the repeatability of verbal expressions did not obviously decrease with the increase in recording interval.

Conclusions: Dynamic 3-D imaging is a useful technique for facial expression analysis. Verbal expressions showed greater reproducibility than nonverbal expressions.

Keywords

dynamic 3-dimensional (3-D), nonverbal facial expressions, verbal facial expressions, reproducibility

Introduction

Facial expressions are important ways for people to communicate, and most daily social communication needs facial expressions to assist the communication process (Mehrabian & Ferris, 1967). The recovery of facial expression is an important index for evaluating the prognosis of maxillofacial surgery and facial nerve injury. The traditional method for analysis of facial movements is based on subjective scaling assessments, but its limitation lies in intrinsic observer bias (House & Brackmann, 1985; Ross et al., 1996; Rickenmann et al., 1997; Yen et al., 2003; Reitzen et al., 2009). Early objective quantitative measurement of facial movement was analyzed using 2-dimensional (2-D) photographs and videotapes(Johnson et al., 1994). However, these methods underestimated the magnitude of facial movement by 43% (Gross et al., 1996). Three-dimensional (3-D) dynamic motion capture systems based on 3-D active or passive stereophotogrammetry technology are now available. This technique was widely used to evaluate the

[1] Department of Oral and Maxillofacial Surgery, Peking University School and Hospital of Stomatology, Beijing, People's Republic of China

Corresponding Author:
Zili Li, Department of Oral and Maxillofacial Surgery, Peking University School and Hospital of Stomatology, 22 Zhongguancun South Avenue, Haidian District, Beijing 100081, People's Republic of China.
Email: kqlzl@sina.com

facial movement characteristics of normal people and patients with jaw deformity and facial nerve injury (Popat et al., 2013; Matsumoto et al., 2016; Alagha et al., 2018; Lowney et al., 2018; Xue et al., 2020). It can also be used to analyze facial expression changes before and after orthognathic surgery, cleft lip surgery, facial nerve anastomosis surgery, and maxillofacial tumor surgery (Shujaat et al., 2014; Al-Hiyali et al., 2015; Hallac et al., 2017).

Facial expressions are very complex and vary greatly, which may affect the accuracy of studies. Therefore, a technique that allows valid assessment of the reproducibility of facial expression over time is important. Sawyer et al. (2009) reported the use of still 3-D images of nonverbal facial expressions across different observational sessions for expression reproducibility analysis. However, the use of 3-D static images ignored the dynamic characteristics of facial expressions. Ju et al. (2016) selected special landmarks on the face and utilized a 3-D Motion Capture System to record the dynamic process of nonverbal facial expression. The similarity of the movement trajectories of facial landmarks represented the repeatability of facial expressions. The limitation of this study is that it only evaluated the reproducibility of facial expressions in a short time interval. In the clinical study, the recording interval can be prolonged as it includes the time of surgical treatment and recovery process.

Verbal expressions mainly involve the movement of perioral soft tissues, which is suitable for studying the changes of lip movement after the treatment of cleft lip and jaw deformity. However, there are few studies on the repeatability of verbal facial expressions. Popat et al. (2010) found that the verbal expressions “puppy,” “baby,” “rope,” and “bob” were more reproducible than the smile expression, while the pronunciation of these words contained multiple vowels and consonants appear more complex than nonverbal expressions. The consonants selected involve the complete closure of the lips and quick release or subtle lip rounding, whereas the vowels are made with lip and lower jaw movement. Vowel production generally requires substantial lip trajectories that include jaw adjustments in combination with lip rounding and lip spreading and are more suitable for perioral soft-tissue movement analysis. If the repeatability of vowel stimuli is better than nonverbal facial expressions, the analysis of facial soft-tissue movement using vowel verbal expressions will have more accurate results.

Therefore, the purpose of this study was to compare the short- and long-term reproducibility of common nonverbal facial expressions and verbal facial expressions using a 3-D dynamic motion capture system. We chose vowels /i:/ and /u:/ as the verbal stimuli.

Methods

Ethical approval (approval no. PKUSSIRB-201837104) was obtained from Peking University School of Stomatology (Beijing, China). To be included in the study sample, hospital employee and student volunteers were required to have class I occlusion without facial surgery history, facial paralysis, dentition defects, or dental maxillofacial deformity. We conducted medical history inquiry and oral inspection to ensure that the participants met the inclusion criteria. The sample included 27 Chinese participants, 12 males and 15 females aged 23 to 30 years, with a mean age of 25.8 years. Each participant gave informed consent to participate in this study.

Facial Expression Recording

Before recording, each participant was told that the facial expressions started from rest position with lips pressed together lightly and then to make the most vigorous expressive action before returning to the resting state. Smile lips closed, smile lips open, lip purse, cheek puff, and vowels /i:/ and /u:/ were repeatedly practiced before every recording session to assure that each facial expression process in each participant was visually repeatable (Figure 1). The 3dMD-Face Dynamic System is based on active stereophotogrammetry and simultaneously captures both pattern- and nonpattern-projected white light images by random infrared speckle projection. The process was used to record movement patterns at 60 frames per second. During recording, all participants sat in a natural head position and were asked to perform 4 nonverbal expressions and 2 verbal expressions in sequence. The recording time of each expression was approximately 2 to 3 seconds, and it took participants 5 to 10 minutes to complete one experimental session. Each participant was recorded 3 times for each expression. There were 3 sessions: session 1, initial capture; session 2, 15 minutes after initial capture; and session 3, 1 week after initial capture.

Image Analysis

Three-dimensional facial expression image sequence analysis was performed using 3dMDvultus software. Six key frames were selected for every expression process. The rest position (T0) was considered as the base frame. The quartile frame of the expression (T1), just after reaching the maximum motion (T2), just before the end of the maximum state (T3), the third quartile frame of the expression (T4), and the end of motion (T5) were selected as key frames (Alagha et al., 2018; Figure 2).

Using a stable part of the face such as the forehead, each key frame (T1-T5) of the different expressions was aligned on the corresponding frame at rest (T0). The root mean square (RMS) between each key frame and its corresponding frame at rest was calculated. The root-mean-square represents the square root of the mean of the squares of the same pixel distance for two 3-D images, which can precisely evaluate the differences between the 3-D images (Taylor et al., 2014; Patel et al., 2015; Kornreich et al., 2016; Ozsoy, 2016).

$$\mathrm{RMS} = \sqrt{\frac{x_1^2 + x_2^2 + x_3^2 + \ldots + x_n^2}{\mathrm{n}}}$$

$(x_1, x_2, x_3, \ldots, x_n$ is a set of measured distances)

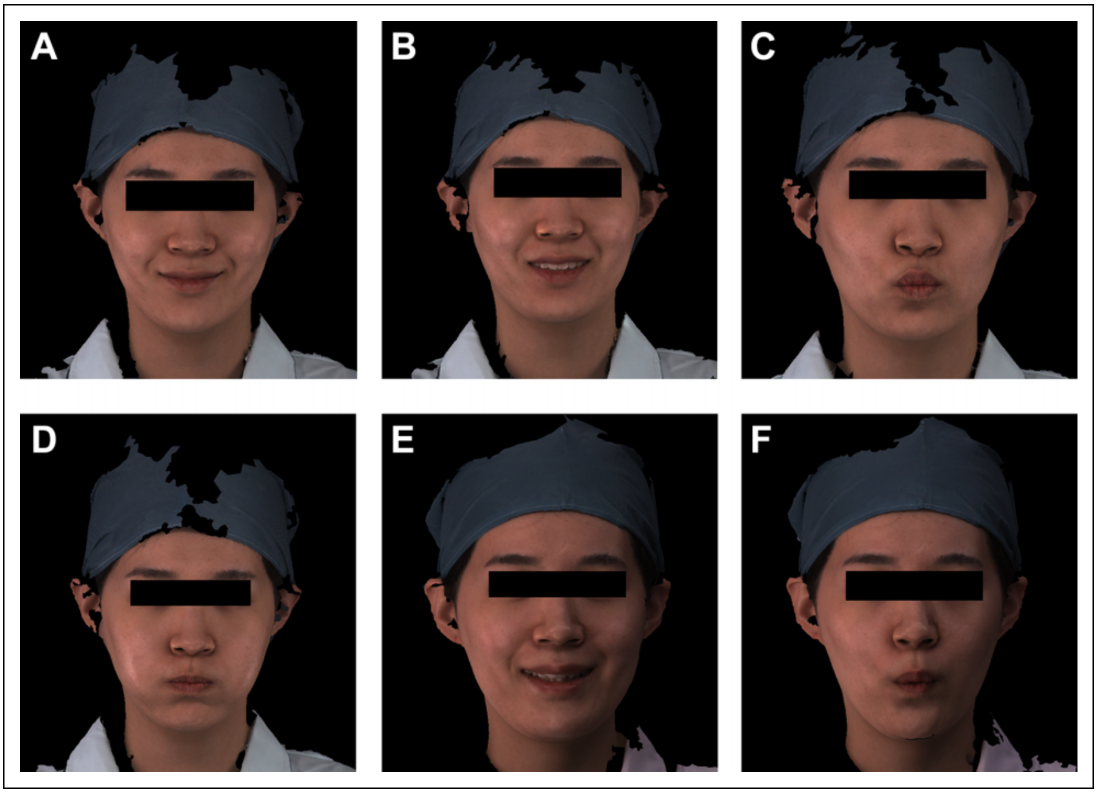

Figure 1. Nonverbal and verbal facial expressions used for this study. (A) Smile lips closed; (B) smile lips open; (C) lip purse; (D) cheek puff; (E) vowel /i:/; (F) vowel /u:/.

The distinction between the T1 to T5 frames and the T0 frame of the first session was recorded as RMS_1. The distinction between the T1 to T5 frames and the T0 frame of the second session was recorded as RMS_2. The distinction between the T1 to T5 frames and the T0 frame of the third session was recorded as RMS_3 (Figure 3).

ΔRMS reflected the difference of the same key frames between the different sessions for the same expression of the same participant. ΔRMS_1 reflected the difference between the same participant, same expression, and same frame 15 minutes after the initial recording. Similarly, ΔRMS_2 reflected the difference between the same participant, same expression, and same frame 1 week after the initial recording.

$$\Delta RMS_1 = RMS_2 - RMS_1; \; \Delta RMS_2 = RMS_3 - RMS_1$$

Statistical Analysis

Intraclass correlation coefficients were utilized to examine intraoperator and interoperator reliability by repeatedly calculating RMS values between 54 randomly selected non-T0 images and corresponding T0 images. Intraoperator reliability was calculated from measurements made by the same operator (T.Q.) twice within 1 week. Interoperator reliability was evaluated by comparing measurements made at the same time by 2 operators (T.Q. and R.Y.). Descriptive statistics were applied to show the variation of RMS and ΔRMS values of different expressions in different sessions. All ΔRMS data were logarithmically transformed so that the sample data obeyed a normal distribution with homogeneous variance. Three-way analysis of variance (ANOVA) was used to evaluate the reproducibility between different facial expressions and expressions at different time intervals. SNK-q and Bonferroni tests were used to compare repeatability of every different expression at the same time intervals. Paired-sample t tests were used to study the reproducibility of the same facial expressions recording at different time intervals. The significance level was set at $P < .05$. All analyses above were performed using SPSS, version 23.0.

Results

Due to technical problems in operating the 3dMD-Face Dynamic System, several facial expressions could not be reconstructed from the image sequences. In general, 26 vowels /i:/ and /u:/ and the lip purse expressions were collected (from 12 male participants and 14 female participants), together with 27 smile lips closed, smile lips open, and cheek puff expressions. The intraoperator reliability was 0.945 and the interoperator reliability was 0.954, indicating highly accurate and repeatable RMS value measurements.

The RMS values that represented the dissimilarities between non-T0 frames and corresponding T0 frames were evaluated. T2 and T3 frames of all expressions that represent the

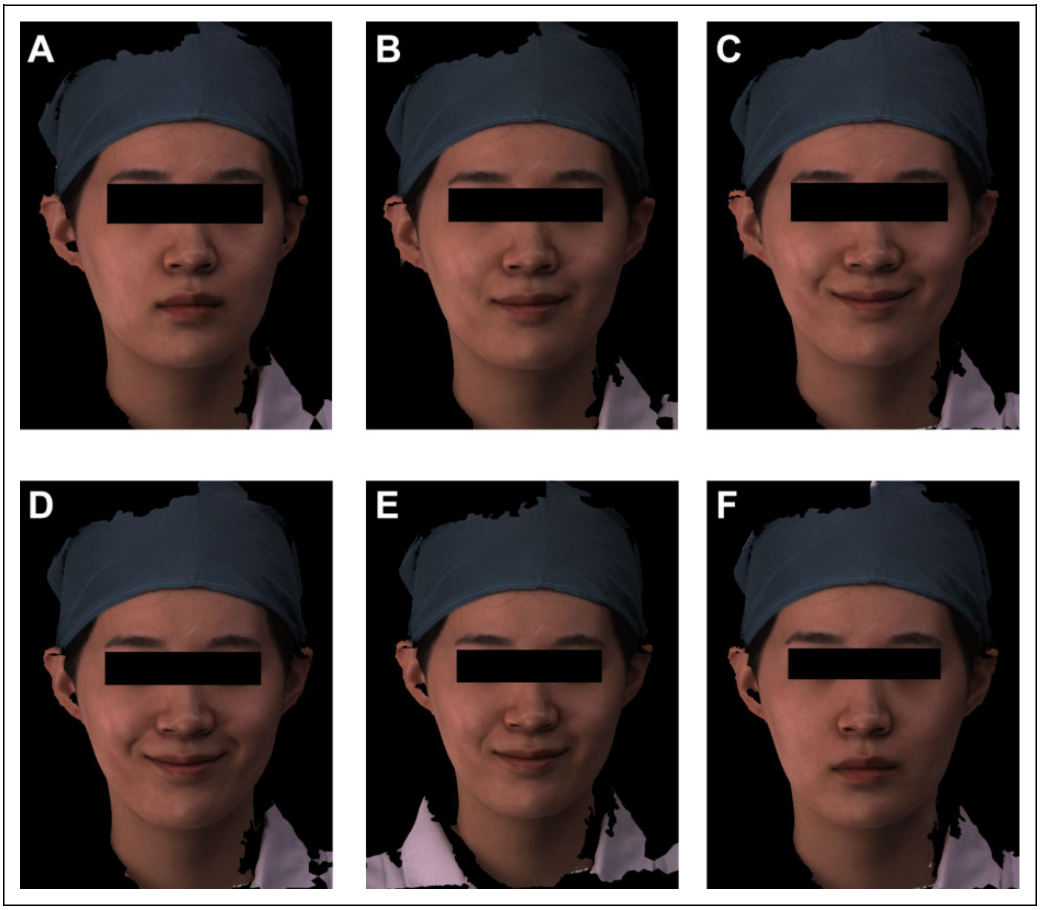

Figure 2. Six key frames of smile with lips closed. (A) The base frame (T0); (B) the quartile frame (T1); (C) just after reaching the maximum state (T2); (D) just before the end of the maximum state (T3); (E) the third quartile frame (T4); (F) the end of motion (T5).

maximum motion states showed RMS values varied from 1.48 to 2.56 mm. The quarter motion states T1 and T4 also differed from the initial T0 images, but the variation of RMS values (0.91-1.49 mm) was not as large as for T2 and T3 frames. T5 frames, which represented the expression returned to a baseline state, were different from the corresponding T0 images. The RMS values between T5 and T0 frames were about 0.5 mm. This may be due to the difference in facial muscle tension before and after completing the expression.

The results of a 3-way ANOVA showed that except for the 3 single factors that influenced the value of ΔRMS, there was an interaction between factors for facial expression types and the length of the recording interval, while the key frames factor had no interaction with the other factors (Table 1). To examine the influence of frame factors on ΔRMS values, we used the SNK-q test to evaluate the differences of ΔRMS values in different key frames. The ΔRMS values on T5 frames were significantly lower than those in other key frames. The T5 frames represented the motion returned to the static state; the range of facial soft-tissue movement was small and more repeatable than other key frames. As the frame factor was not related to the other factors, the repeatability of all facial expressions was evaluated at the same interval.

The mean variations of different expressions between session 1 and session 2 are shown Figure4A. Lip purse was found to be the most reproducible expression after 15 minutes, followed by the vowel /i:/, smile with lips closed, vowel /u:/, smile with lips opened, and cheek puff action. SNK-q tests were applied to analyze the repeatability of different facial expressions between sessions 1 and 2. The results showed that there was no significant difference in the repeatability of each expression, except for the cheek puff motion.

Also, the mean variations of different expressions between sessions 1 and 3 were analyzed and are shown Figure 4B. The vowel /u:/ was the most reproducible expression after 1 week, followed by the vowel /i:/, smile with lips closed, lip purse, smile with lips opened, and cheek puff action. SNK-q tests and Bonferroni tests were used to analyze the repeatability of different facial expressions between sessions 1 and 3. The results showed that the repeatability of the vowel /u:/ was significantly superior to all nonverbal expressions. The repeatability of the vowel /i:/ action was also obviously better than that of smile with lips opened and cheek puff action.

With regard to the study of the reproducibility of the same facial expressions recording at different time intervals, the repeatability after 15 minutes was significantly better for the

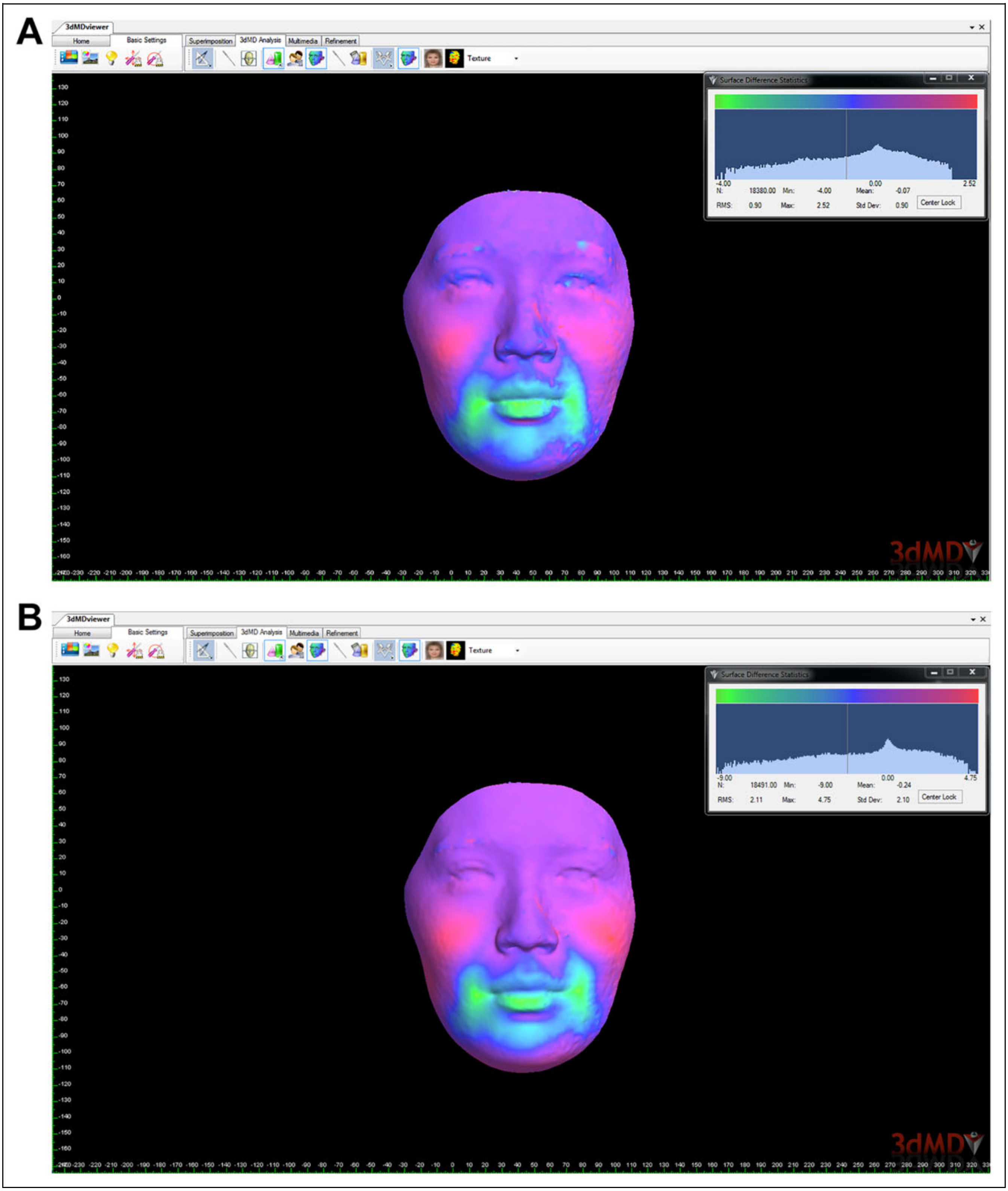

Figure 3. Vowel /i:/ action of a research participant in session 2. Key frames (T1-T5) were aligned on the corresponding frame at rest (T0). A, The distinction between the T1 and T0 frames, RMS = 0.90 mm. B, The distinction between the T2 and T0 frames, RMS = 2.11 mm. C, The distinction between the T3 and T0 frames, RMS = 2.41 mm. D, The distinction between the T4 and T0 frames, RMS = 1.52 mm. E, The distinction between the T5 and T0 frames, RMS = 0.66 mm.

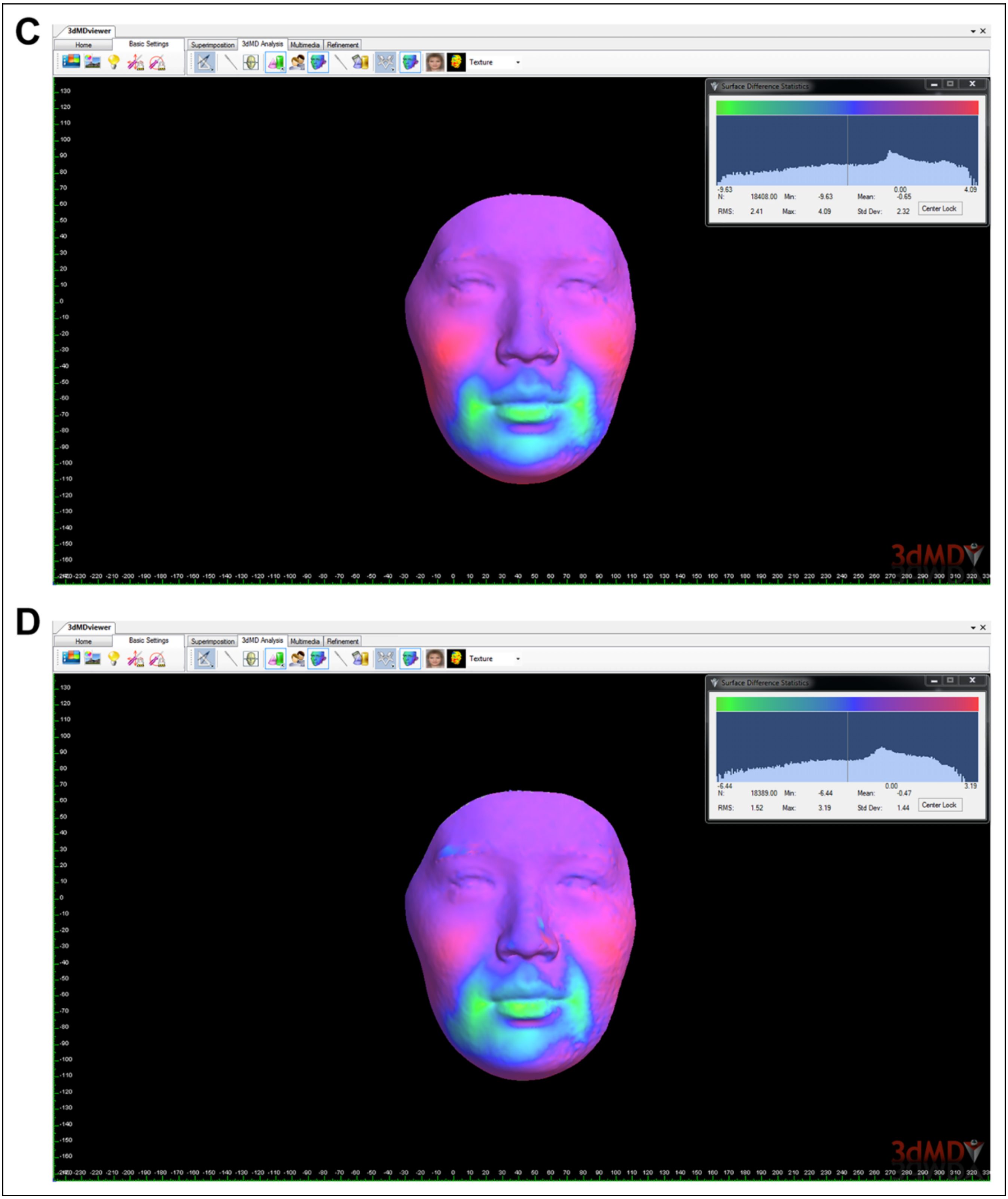

Figure 3. (continued).

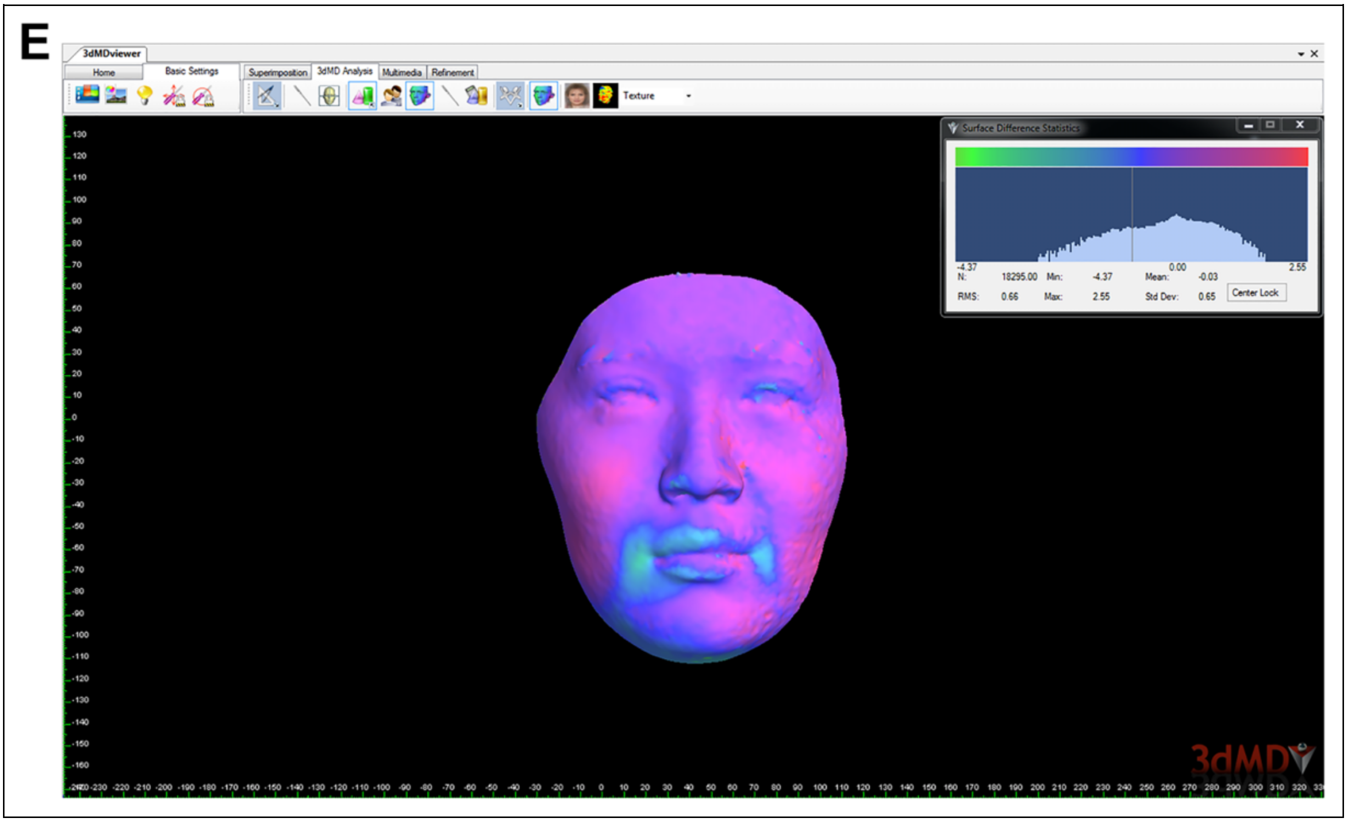

Figure 3. (continued).

Table 1. The results of the 3-way ANOVA analysis.

Factors	Sigma
Expressions	<.001[a]
Intervals	<.001[a]
Frames	<.001[a]
Expressions × Intervals	<.001[a]
Expressions × Frames	.075
Intervals × Frames	.787
Expressions × Intervals × Frames	.891

[a]The factor has significant influence on the value of ΔRMS.

same nonverbal facial expressions than that after an interval of 1 week. However, there was no significant difference in repeatability between 15-minute recordings and 1-week recordings of verbal facial expressions (Figure 5).

Discussion

With the development of medical science and technology, facial dynamic aesthetics have been given more attention by both surgeons and patients. Patients' facial expression muscle movement status before and after surgical treatment can be quantitatively analyzed using a 3-D dynamic analysis system (Shujaat et al., 2014; Al-Hiyali et al., 2015; Hallac et al., 2017). It is very important that the expressions are repeatable during the quantitative measurement of facial expressions. Only when facial expressions are reproducible can we determine that changes in facial soft-tissue movements are caused by interventions and not by variations in facial expressions themselves. Therefore, this study compared the short- and long-term repeatability of nonverbal expressions and verbal expressions in a group of participants without facial deficiencies and provides guidance for future studies about the selection of facial expressions.

At present, 2 main types of expressions are used to study facial soft-tissue movement: verbal expressions and nonverbal expressions. For verbal expressions, all participants in this research have studied English for at least five years and can accurately pronounce English syllables. The pronunciation and lip movement of the English vowels /i:/ and /u:/ are similar to those of the Chinese vowels /i/ and /u/. This study selected the vowels /i:/ and /u:/ for 2 reasons: (1) They are single sounds, easy to analyze, and the corresponding key frame images can be found more accurately; (2) during the articulation of these sounds pronunciation, the /i:/ pronunciation involves a lip spreading movement, and the /u:/ pronunciation involves a lip rounding movement.

Facial expression reproducibility in previous studies was defined in terms of the similarity of the displacement amplitude, speed, and movement trajectory of landmarks. A previous study used the mean variation of landmarks in static 3-D images of facial expressions to assess reproducibility (Johnston et al., 2003; Sawyer et al., 2009). These studies evaluated the

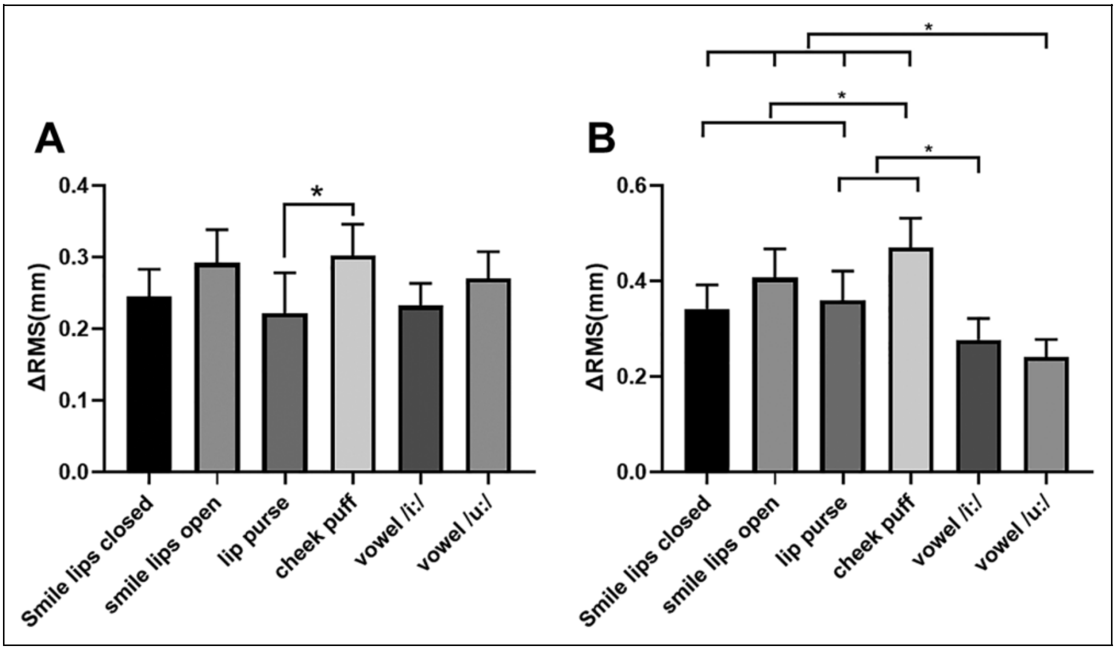

Figure 4. Short- and long-term reproducibility of all facial expressions. A, Reproducibility of all expressions for sessions 1 and 2 (*$P < .05$). B, Reproducibility of all expressions for sessions 1 and 3 (*$P < .05$).

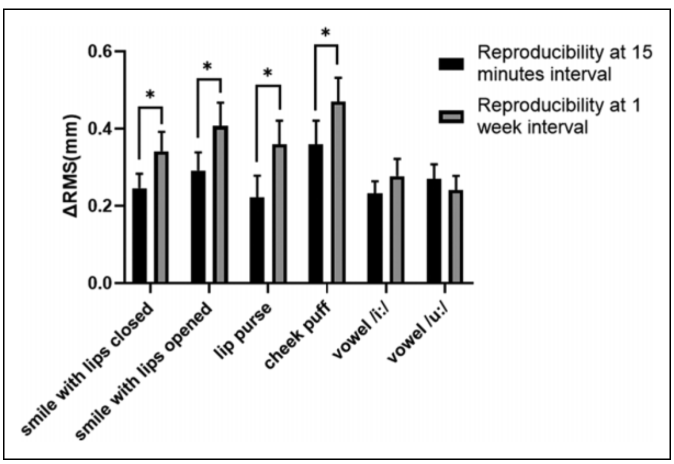

Figure 5. The reproducibility of the same facial expressions recorded at different time intervals. *$P < .05$.

repeatability of maximum motion state of expressions but did not consider that facial expression is a dynamic motion process. Another study evaluated expression reproducibility by comparing differences of the amplitude, speed, and similarity of the trajectory of the same facial landmark between repeated recordings (Ju et al., 2016). That research reflected the dynamic characteristics of facial expressions; however, the use of landmarks to analyze facial expressions still has its limitation: The characteristic landmarks mostly are distributed in the eyes, nose, and lips, while other positions such as the forehead and cheek could be overlooked. Moreover, the anatomical structure of the nasal and lip region is complex, and the analysis is somewhat limited using individual marker points instead of the nasal lip region for analysis (Alqattan et al., 2015). Therefore, this study selected the key frame images in the expression process, which reflected not only the dynamic characteristics of the expression but also the overall facial expression area (Alagha et al., 2018).

Except for cheek puff action, there was no significant difference between session 1 and session 2 expression recordings, consistent with the results of previous studies (Johnston et al., 2003; Sawyer et al., 2009). Almost all facial expressions showed good repeatability for short-term–repeated measurements. However, in clinical studies of facial expression changes after surgery, the interval between recordings can be prolonged, so it is more important to evaluate the long-term repeatability of facial expressions.

The repeatability of verbal expressions between session 1 and session 3 was significantly better than that of nonverbal expressions, corresponding to a previous study (Popat et al., 2010). Verbal expressions used in this study were more similar to nonverbal expressions than "puppy," "baby," "rope," and "bob" used in that previous study. Prior to Popat et al. (2010), there was no research on the reproducibility of verbal facial expressions over time. In this study, we also found that the longer the interval, the poorer the reproducibility of nonverbal facial expressions, while the reproducibility of verbal facial expressions did not change significantly over time. The reason may be that verbal communication in daily life of the research participants is more common than nonverbal communication. The coordination and cooperation of the perioral muscles in the process of verbal communication are practiced abundantly in daily life so that the muscle memory of verbal expression is deeper and more refined. Further, nonverbal expressions are more likely to be affected by the emotions of the participants themselves (Popat et al., 2010). Any negative emotions such as sadness or impatience will affect the recording of smile-related expressions. Relatively introverted participants may be less prone to make facial expressions that express their emotions.

In the present study, a noninvasive imaging system that is a recent innovation in the field, capable of recording 3-D soft-tissue dynamic images was used. The results of this study confirmed that the reproducibility of verbal expressions is better than that of nonverbal expressions. Reproducibility becomes better as the interval becomes longer. Therefore, to analyze the impact of interventions such as oral and maxillofacial surgery on the movement of soft tissue in the face, and the use of verbal stimuli can minimize the effect of significant variation on the final results. However, verbal expressions only involve the movement of the peripheral muscle groups, and to analyze the dynamic movement of other muscles in the face, other highly repeatable facial expressions may also need to be utilized.

Conclusion

This article examined a measurement technique that can be used to evaluate the dynamic movement of facial soft tissues accurately. In short-term sampling, there was no significant difference in the repetitiveness of verbal and nonverbal expressions, except for cheek puff movements. After an interval of 1 week, the repeatability of verbal expression was better than that of nonverbal expression. Compared with nonverbal facial expressions, the measurement of verbal facial expressions has better long-term reproducibility. This provides preliminary data that can be utilized in the study of facial soft-tissue movement changes after surgeries, such as orthognathic or cleft lip surgery or facial nerve anastomosis.

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Declaration of Conflicting Interests

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ORCID iD

Zili Li, MD https://orcid.org/0000-0002-8529-1235

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