Validation of the automatic tracking for facial landmarks in 3D motion captured images

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.... people will converse with a face on the computer screen. Both the computer and the person will be able to read each other's facial expressions, gleaning the understanding that can be communicated through a smile or a scowl, a nod of the head, an arched eyebrow or a piercing gaze. .... computers, now known for their cold logic will use their faces to convey emotions

A. Pollack, *Japanese Put a Human Face on Computers*, New York Times, June 28 1994, (p. C1)

Abstract

AIM:

The aim of this study was to validate the automatic tracking of facial landmarks in 3D image sequences captured using the Di4D system (Dimensional Imaging Ltd., Glasgow, UK).

MATERIALS AND METHODS:

32 subjects (16 males; 16 females) range 18-35 years were recruited. 23 facial landmarks were marked on the face of each subject with a 0.5 mm non-permanent ink. The subjects were asked to perform three facial animations from the rest position (maximal smile, lip purse and cheek puff). Each animation was captured by a 3D stereophotogrammetry video system (Di4D). A single operator digitized landmarks on captured 3D models and the manual digitised landmarks were compared with the automatic tracked landmarks. To investigate the accuracy of manual digitisation, the same operator re-digitized 2 subjects (1 male and 1 female).

RESULTS & CONCLUSION:

The discrepancies in x, y and z coordinates between the manual digitised landmarks and the automatic tracked facial landmarks were within 0.5 mm and the mean distance between the manual digitisation and the automatic tracking of corresponding landmarks using tracking software was within 0.7 mm which reflects the accuracy of the method(p value was very small). The majority of these distances were within 1 mm. The correlation coefficient between the manual and the automatic tracking of facial landmarks was 0.999 in all x, y, and z coordinates.

In conclusion, Automatic tracking of facial landmarks with satisfactory accuracy, would facilitate the analysis of the dynamic motion during facial animations.

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Author's Declaration

This thesis is the original work of the author

Chapter One

Introduction

1 Introduction

1.1 Introduction

Facial appearance has a major impact on how we are perceived in society and how others perceive us; however, interaction of individuals with facial functional impairments may be different. Functional impairments may be caused by facial nerve paralysis, cleft lip and palate, facial trauma and facial disfigurement. Many individual will seek help to have reconstruction or orthognathic surgery to correct their functional impairments.

Evaluation and quantification of facial movement is becoming particularly important to aid in the diagnosis, treatment planning and to improve the outcome assessment for the individual with facial functional impairment. Therefore, the need for a reliable method to record facial morphology and accurately measure animation.

Analyses of facial movements was always attempted using subjective methods and grading scales. Despite the fact that these methods are easy to apply, they lack the necessary reproducibility and are dependent on observers' personal views.

Recently, the quantifying of facial animation has been achieved using objective measurements. Some of the methods were directly applied on the patients face and others were conducted on the captured image. Two dimensional video recording and 3D images were analysed to quantify facial animations. Unfortunately, these methods do not measure the dynamic of facial animations.

The ideal method to quantify facial animations should be easy to apply, non-invasive, allow fast capture of the dynamic movements of facial muscles and produces accurate date for analysis. For wide clinical application it would be necessary to achieve a reliable capture of the face with minimal input from the operator in digitising facial landmarks of all the frames of facial animations.

It is the objective of this study to evaluate the reliability of the automatic tracking of facial landmarks during animation. This would investigate the validity of the software to be widely applied in clinical scenarios in patients with neuro-craniofacial deficiency.

Chapter Two

Literature Review

2 Literature Review

2.1 Subjective assessment of facial anthropometry

The Facial Action Coding System (FACS) has been described as one of the most extensive methods of measuring facial motion (Popat *et al.*, 2009). Ekman *et al.*, (1980) used videotape recording to examine facial animations; they investigated the specific changes that occurred with muscular facial contractions and evaluated how best to differentiate the action of one group of muscles from another. The FACS divided the facial expression into 46 Action Units (AUs), which were either contraction or relaxation for each group of muscles. This approach was labour intensive, which was the main drawback of the method. It required a trained FACS operator and it took many hours to code subjectively one minute of video data.

Kang *et al.*, (2002) reviewed the medical literature from 1985 - 2002 to assess the various methods of evaluating the function of the facial nerve that have been used over the 15 years; particularly in comparison to the House-Brackman grading scale HBGS (House *et al.*, 1983). This scale was based on grading facial animations subjectively into six grades. This was also compared with the available eight facial nerve grading systems developed by other researchers (Janssen, Smith, Adour, Swanson, Yanagihara, Stennert, Botman and Jongkees & Peitersen). They also classified each grading of facial animations into one of three categories; gross, regional and specific. A standard videotape for patients was used to test the inter-observer consistency. The major criticisms of the HBGS have been its inability to distinguish fine deficits or subtle facial nerve dysfunction. The subjective nature of the scale and the ambiguity of analysing the secondary defects of facial nerve functions were the main limitations of the method.

The Burres-Fisch system (1986) had the benefit of eliminating observer bias and subjectively quantified facial nerve function with a defined linear measurement index which was calculated by a series of equations using the percentage displacement of various facial anatomic landmarks during movement. The evaluation was based on facial biomechanics of seven standard facial expressions in “normal” subjects. The advantage of the Burres-Fisch system over the HBGS was the application of the linear measurement index which allowed finer evaluation of function. The Burres-Fisch system was a time consuming process which was the main disadvantage and therefore, unlikely to be used as an assessment tool by a busy clinician.

In 1994, the Nottingham system was developed (Murty *et al.*, 1994). It was based on three distinct steps. Firstly, two distances (supraorbital point to infraorbital point and lateral canthal angle to angle of the mouth) were measured bilaterally at rest and at maximum activation of the muscles during three facial animations, smiling, eye brow raising and closing eyes tightly. The differences between rest and maximal animation were measured; the lower value was expressed as a percentage of the movement of the opposite side. The second step was assigning a letter for either absence (A) or presence (P) of any of the following; hemifacial spasm, contractions and synkinesis. The third step was assigning a letter for absence (N) or presence (Y) of gustatory tears, dry eyes or dysgeusia. The main advantage of the Nottingham system was the scoring could be performed rapidly (within 3 minutes). However, the system was unable to assess the symmetry of facial animation. Also the lettering system used to assess secondary defects did not contribute to the overall numerical score and it was therefore useful as a descriptive modifier only. The dynamic of facial movements were not assessed by this method.

Ritter *et al.,* (2002) studied thirteen patients with unilateral cleft lip and palate with varying degrees of severity of scarring following cleft repair. A case with artificial scars of varying severity was also analysed. The aims of the study were to determine and compare the level of agreements among examiners' assessments of static and dynamic lip form, to assess possible bias of examiners' subjective assessments and to determine the impact of lip scarring on an examiners' subjective assessment of dynamic lip form. Photographs and videotape were recorded at rest and at smiling. The outcome was measured by a 6-point ranking scale that ranged from "1 = not visible" to "6 = very severely impaired". A panel of fifteen professionals, which included nine graduated orthodontic residents and six graduate paediatric dentistry residents, and a panel of fifteen laypersons, which consisted of fifteen first year dental students, who had no training in cleft palate or craniofacial treatment, took part in the assessment. The results showed for the lower facial regions, intra- and inter-examiner reliability was good in the rest position but not during movements. Professionals gave a rating of greater severity and impairment than laypersons and professionals agreed when rating the lower faces at rest more than when they rated the lip during movement. Lip scarring affected perceptions of impairments during movement by both panels. Although the study produced some excellent findings and tested the authors' hypothesis, the sample size was insufficient; the duration of smile was not measured and the dynamic of animation was not evaluated. The study provided subjective rather than objective assessment of facial animation.

In summary the subjective assessments of facial animation can be affected by methodological approaches, professional experience and types of stimulus. Further research in facial motion analysis should focus on establishing objective techniques to evaluate facial expression during animation. Objective evaluation of facial function is important for effective treatment planning and valid post surgical assessment.

2.2 Objective facial measurements

2.2.1 Direct measurements

Frey *et al.*, (1994) developed a simple instrument to measure distances on the face. It functioned on the principle of using callipers for direct distance measurement between two points to measure the deformation of the soft tissue. The Faciometer was designed to reach all points of interest on the face, Figure 2.1. The face of twenty "normal" subjects and ten unilaterally paralyzed cases were analysed in the study. The authors found small but interesting differences between the groups and of the same face at different time intervals of analyses (mean range of 0.673 mm ± 0.659 mm). They also recorded significant differences between the two observers who carried out the study. This new instrument did not measure the dynamics of facial animation. Furthermore, the calliper could be harmful due to any possible unexpected patient's movements.

Figure 2.1 The Faciometer during clinical application in an individual with normal facial function (Frey *et al.,* 1994).

The method lacked reproducibility due to wide range of the reproducibility of measurements.

Manktelow *et al.*, (2008) studied the facial movements of 21 patients with unilateral facial paralysis. Two transparent 15 cm plastics handheld rulers were used to assess the positions and the movements of five points marked on the lips, Figure 2.2. The points included the right and the left commisures, the centre of the bow at the vermilion border and the midpoints of the right and left halves of the upper lip at the vermilion margin. The measurements were used to characterise the positions of the lip at rest and at smiling. Two experienced examiners, separately, measured the distances between landmarks at rest position, twice. The accuracy of the method was assessed by measuring the movement of left and right commisures and mid-upper lip during smiling on 10 volunteers using both the hand held ruler and the facial reanimation measurements system using video and electronic images. The facial movements were evaluated using the captured images. The results showed an average correlation coefficients for inter-rater and intra-rater reliability of 0.89. The mean difference between the handheld ruler and facial reanimation measurements system was 1.7 mm. The authors concluded that the handheld ruler technique was simple, reliable and accurate instrument for evaluation of facial paralysis. Although the study made some excellent findings it also had some limitations for instance gender difference were not evaluated. There was lack of information regarding the stabilization of patient head position during the analysis, head movement may have affected the measurements. Finally, the smile on a given patient that one examiner has measured may not be the same smile that the subsequent examiner has assessed. This may have been the cause of disagreement between observers despite the high inter observer reliability.

2.2.2 Indirect measurements

2.2.2.1 2D measurements

Two dimensional facial analyses were based either on photograph or video recording. Farkas *el al.*, (1980) investigated the reliability of facial photography compared with direct anthropometric measurements of the face. The authors

Figure 2.2 Plastics handheld rulers (Manktelow et al., 2008)

compared 104 direct facial measurements from 36 subjects with measurements taken from frontal and profile photographs. The results showed that only 60% (62 out of 104) of the direct anthropometric measurements could be recorded from the photographs and out of these only 42% (26 out of 62) were found to be reliable and accurate. The authors concluded that errors were introduced by incorrect head positioning in both the vertical and horizontal planes and by measuring landmarks on the photograph that were not labelled on the face. Also, even though landmarks were identified on the face, it was not easy to locate them on the photographic measurements. However, the authors found that the areas of the mouth and lips showed the greatest reliability for measurements.

Johnson *et al.*, (1994) studied seven healthy subjects (3 male and 4 female) and 3 patients with abnormal facial movements. The photographic data was analysed by three observers, one premedical student, one surgical resident and one plastic surgeon and each subject image was analysed by each observer three times. Nine dots were localized on each subject face; a ruler was also photographed to allow the calibration of the image. Each subject was instructed to do the following animations; maximal brow left, maximal smile and maximal whistle. The photographs were taken at rest and at maximal animation. The study measured the amplitude of facial landmarks motion during animation using these standardize photograph. The study quantified all regions of the face simultaneously; the amplitude was measured from sequentional animations rather than during each individual animation. This study did not describe the mechanism and dynamic nature of facial animation and was limited to measuring the changes of the anatomical landmarks due to facial muscle movements at the end of each animation.

To overcome the limitation of a static photograph, a video camera has been used to measure facial animation. Platez J. *et al.*, (1994) studied twenty subjects (10 male and 10 female) to analyse the “normal” smile. They used a video camera to record the smile, which was captured from various angles of view. Eight points were marked on the face along the vermilion border of the lip, at each commissure, at the centre points of upper and lower lips and at points midway between them. The results showed no difference in direction of muscle movement in either male or female subjects, but surprisingly there was a relatively greater amount of upper lip and nasal base movement in an upward direction secondary to the smile. The author concluded that consideration should be given for the unilateral facial paralysis reconstruction to match the direction of the movement of the upper lip and commissure between the affected and contra lateral side. This study suffers from a small sample which affects the interpretation of the results and the method used was unable to study the dynamic and symmetry of lip movement from rest to maximum smile.

De Menezes *et al.,* (2009) investigated the suitability of using 3D digital photographs supported by three-dimensional software for measuring the facial soft tissue of healthy subjects; these were compared with data obtained by a three-dimensional computerized electromagnetic direct digitizer. Fifteen healthy young adults (11 male and 4 female) were enrolled in the study and fifty facial landmarks were digitized at rest, using a three-dimensional electromagnetic digitizer and a new low-cost 3D photogrammetric system, 12 linear and 18 angular measurements were recorded. Errors of the methods and repeatability of the technique were calculated. The study showed statistically significant differences between direct and indirect measurements in two distances and three angles ($p<0.05$). The mean absolute differences between methods were always less than 3mm and 3 degrees. The 3D photography technique provided reproducible results (random errors lower than 1.6 mm and 3 degree). Repeated sets of photographs showed random errors of up to 5.3 mm and 5.6 degree without systemic bias at different times. Although the study made some excellent findings it also had some limitations; male and female were not equally represented in the sample and the method did not test the dynamic and duration of facial animations.

Gross *et al.*, (1996) compared the amplitude of facial motion in 3D and 2D using video cameras. Four subjects participated in the study, two of them were control subjects and other two were patients who had had repaired unilateral cleft and palate. The movements of fifteen defined anatomical landmarks were measured by applying small reflective markers on the face. Subjects were instructed to perform five maximal facial animations from rest position which included smile, eye closure, lip purse, cheek puff and grimace; these were recorded using a video based system. The study showed that the three dimensional amplitude of landmarks was significantly larger than in two dimensions, especially for landmarks on the lower face during smiling. The two dimensional amplitude underestimated the three dimensional amplitude of landmarks movement by 43%. The author suggested that the two dimensional analysis may not be an adequate method to asses facial motion during maximal animation. Although the study managed to support the authors' hypothesis, the sample size was small, the patient's gender was not mentioned and the dynamic movements of reflective markers during animation were not studied.

In summary, the two dimensional measurement system failed to deliver information on the movements of facial landmarks in the antero-posterior dimension. Direct measurements of facial animation may cause inconvenience to both clinician and patients.

2.3 3D imaging measurements

2.3.1 Direct digital measurement

Facial anthropometry is used to quantify facial animation for surgical planning as well as surgical outcome. Clinicians use numerous techniques to diagnose facial deformity, to plan and to evaluate the outcome of surgery. Direct manual measurement of the face has been a widely accepted method for the quantitative assessment of facial surface anatomy.

Ozsoy *et al.*, (2009) compared three different techniques, which were used frequently in recording facial measurements. Seventy volunteers were recruited in this study (35 male and 35 female), three methods were used to measure facial landmarks; manual anthropometry, 2D photogrammetry and a computer-aided 3D digitizer. All facial measurements were recorded by a senior experienced author. In manual anthropometry, a digital calliper was used to measure the distance between landmarks, which were identified and/or directly palpated on the face (Figure 2.3A). In two dimensional photogrammetry, the volunteers were asked to sit and lean back against the wall to achieve relaxed facial expression (Figure 2.3B). The faces were photographed in frontal, right and left lateral views with a high resolution camera. Surface landmarks were identified on the photographs and all measurements were saved on a computer and the facial landmarks distances were measured using computer software. In three-dimensional digitization, the author used a Micro-Scribe 3D digitizer which had a mechanical arm with a stylus which had an accuracy of up to 0.009 inches and a sampling rate of up to 1000Hz. Subjects were asked to lie on their back on a stretcher to use the digitizer. The head has immbolised during digitisation (Figure 2.3C). The author found that by comparing three methods, the 3D digitizer method was an easy, robust and sensitive method to obtain the necessary data. Although the sample size was sufficient, the study did not discuss the time needed to complete one set of measurements using the manual calliper and if the same results could be achieved by an inexpert clinician. It would be impractical to measure facial landmarks on a child using 3D digitizer. Moreover, the study did not investigate the dynamic motion of the facial landmark.

Wong *et al.*, (2008) compared the validity and reliability of 3D digital photogarmmetry with direct anthropometry. Twenty adults were recruited in this study (12 male and 8 female). Using direct anthropometry 18 facial landmarks were digitized on each subjects face by a single investigator, who was trained in the direct anthropometric technique. The points were marked on each subjects face using a sharpened eyeliner pencil prior to each direct measurement session. The digitization was repeated twice to assess the errors of the methods. Landmarks were identified on digital 3D images and distances between landmarks were calculated by using the 3dMD software. Two sets of measurements were recorded on the digital image by one investigator on two occasions. A minimum 24-hour interval was kept between measurement sessions. The results showed that 17 of 18 direct measurements correlated highly with digital values (mean r=0.88). The overall precision of all 17 digital measurements was less than 1 mm and the reliability was high (mean r=0.91). The authors concluded that facial anthropometry measurements using the 3dMDface system was valid and reliable. This study confirmed the validity of 3D imaging at rest; it did not address the measurement of facial animation which was beyond the scope of the study.

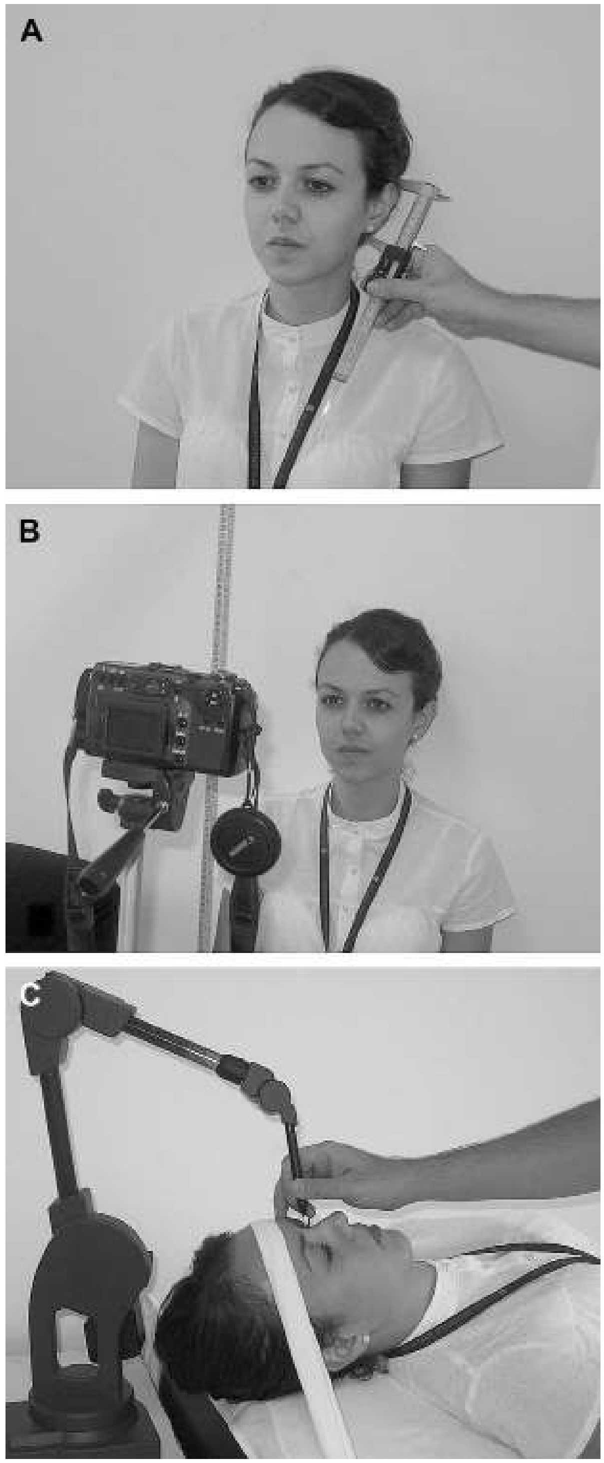

Figure 2.3 2A digital callipers, 3B 2D photograph, and 3C three dimensional digitizer (Ozsoy *et al.*, 2009)

Trotman *et al.,* (1996) studied the reliability of a three-dimensional method for assessing the functional repertoire of the face. Four subjects were enrolled in this study and instructed to perform repeated sequences of five maximal facial animations. Facial motions were captured by three 60Hz video cameras and three–dimensional maximum motion amplitudes were calculated. Student's *t*-test and Pearson product-movement correlation coefficients were applied to test for any significant difference between repetitions of animations. The results showed moderate to excellent reliability of amplitude of motion for the landmarks over all animations (cheek puff, grimace, eye closure and smile). For each specific animation, certain landmarks (nasal tip and left canthal) demonstrated more reproducibility than others in tracing facial movements. Although the study reported some excellent results, the sample size was small which affects the interpretation of the results, subject selection criteria was not addressed and the duration of each animation was not mentioned.

Valid and accurate three dimensional recording of soft tissue facial surface are fundamental for the objective analysis of craniofacial deformities and for effective treatment planning and post surgical assessment. Several techniques are available for recording three dimensional facial measurements, including laser scanning, stererophotogrammetry and ultrasound. Based on stereophotogrammetry, several groups of recorders developed their own camera system which consists of one or more camera station connected to a personal computer.

Ayoub *et al*., (1998) described a vision-based three dimensional facial data captured system for the planning of maxillofacial surgery. The system was based upon imaging the face using two stereo pairing sets of cameras. Scale spaced based stereo-matching was then used to recover corresponding points between each of the captured stereo pairs. The authors found the system able to capture three dimensional facial data within seconds which could be used to assess children with cleft palate and to avoid any possible change of facial configuration during capture. The system was accurate within 0.5 mm. In a later study, the same system was used to assess the accuracy of the system in recording facial landmarks (Ayoub *et al*., 2003). Twenty one facial casts of infants with cleft lip were scanned and 5 landmarks across the mouth and nose were pre-labelled on each cast. The results showed that the operator error was within 0.2 mm. The casts were captured within C3D sterophotogrammetry system and the same landmarks were digitized. Landmark localization on the digitized facial models recorded by the C3D system was accurate within 0.4 mm. The authors concluded that the C3D system was reliable in recording facial deformity and could be utilized in measuring facial deformity and changes following surgery.

Weinberg *et al.*, (2004) assessed the precision and accuracy of facial measurements obtained from digital 3D images capture using a Genex 3D stereophotogrammetry camera system (Rainbow 3D Imaging System). The authors evaluated the precision and accuracy of the system for measuring a series of 19 standardised linear facial distances derived from 17 landmarks according to the definition produced by Farkas *et al* .,(1994) obtained from the face of 20 subjects aged 16 to 62 years with obvious craniofacial abnormalities by two independent observers. Facial measurements were recorded directly with digital callipers and indirectly from the 3D images. Landmarks were pre-labelled as dots on the face and when there was no pre-labelled landmark. The results showed that measurements recorded from the 3D images system had a higher precision factor compared with direct digital anthropometry, irrespective of the landmarks being labelled on the face or not. In addition pre-labelled landmarks prior to taking measurements improve precision. The authors concluded that the digital 3D photogrammetry with the Genex camera system was sufficiently precise and accurate for facial analyses. The main drawback of this 3D system is that it did not measure facial animation in static and dynamic motion.

3dMD face system was another stereophotogrammetry camera system which was used in facial capture. Aldridge *et al.*, (2005) evaluated the precision, error and repeatability associated with facial landmarks derived from 3D images of the faces of 15 cases recorded by the 3dMDface system. Twenty standard facial landmarks were identified on the face and ears. Three dimensional co-ordinate locations of these facial landmarks were recorded by single observer using the 3dMD software. Fourteen landmarks showed a high degree of precision; in repeated measurements the error was less than 1mm along each of the three coordinates of the landmarks. Regarding the remaining 6 landmarks, three of them showed an error greater than 1 mm but less than 2 mm and the other 3 landmarks had an error of greater than 2 mm.

Khambay *et al.*, (2008) assessed the accuracy and reproducibility of a high resolution commercial camera based system (Di3D, Dimensional Imaging, Glasgow, UK) in vitro by using 12 adults facial plaster casts, which had marked points and the positions of digitizing these points on the three-dimensional imaging captured by the Di3D system were compared with those obtained by a co-ordinate measuring machine. As with the C3D system, the Di3D system produced high quality full face lifelike photorealistic images of the 3D facial model. The results showed the reproducibility of the Di3D system was satisfactory with the overall system error found to be within 0.21 mm and the reproducibility error to be within 0.13 mm. Also the operator error of landmark localization on the Di3D image was reported to be within 0.07 mm, which was clinically acceptable and offered considerable improvement in stererophotogrammetry for facial capture and analysis.

Laser scanning has also been used to capture surface topography of human face in three dimensional images (Moss *et al.*, 1987). Laser scanning is an active technique based on the use of a directional light source and detector. A laser beam is deflected by a mirror onto the subject face. As the laser beam is projected onto the face the beam is scattered and then captured by a detector and converted into a computer generated three-dimensional image.

Kau *et al.*, (2004) investigated the feasibility of measuring soft tissue morphology in children using a 3D laser-scanning technique. Forty subjects were recruited in the study. Subject images were captured using two high-resolution Konica Minolta Vivid (VI900) cameras assembled as a stereo-pair. Natural head posture (NHP) was adopted for this study. The total scan time was approximately 7.5 seconds. One raw data set was captured by the right and the left laser scan to generate 3D images of the face. Artefacts and unwanted data were removed by in-house developed software. After the images were smoothed, left and right scans were aligned to one another based on the areas of overlap of the face. Finally one whole face was generated for each subject.

The tolerance level was set for a mean shell deviation at levels corresponding to 0.3 mm, 0.5 mm and 0.75 mm. Using Rapidform 2004™ software package, a shell-to-shell deviation map was computed and automatically produced. The results included the maximum and minimum range of shells. Any subjects who had large differences between the two shells indicated that the subject was not still during capture. The results showed that the mean differences between shell deviations for adult's scans and children scans was 0.25 mm ± 0.09 and 0.30 mm ± 0.09 mm, respectively. The mean error between subject groups were 0.05 ± 0.15 mm indicating that there was no difference between the two subject groups (p = 0.18). The authors concluded that the 3D laser scanning was clinically reproducible for children and adults and can be used for studies assessing facial changes due to growth or clinical intervention.

Toma *et al.*, (2009) assessed the reproducibility of facial soft tissue landmarks using laser scan 3D imaging technology. Thirteen children were recruited in this study and facial imagines were captured for each subject using two high-resolution Konica Minolta Vivid (VI900) cameras. Twenty one facial landmarks were identified (Farkas, 1994) and recorded by two examiners for each image. The landmark reproducibility was determined by repeat capturing 2-weeks apart and re-assessing. The results showed that the reproducibility of recording and digitization 10 landmarks were less than 1 mm for both intra- and inter-examiners. The accuracy of landmark identification ranged from 0.39 mm to 1.49 mm. All the image capture was carried out at rest. Measuring and analysing facial animations were not considered in this study.

Ma *et al.*, (2009) validated a three-dimensional structured light scanning system for facial morphology. The authors investigated the accuracy and precision by using a plaster model with 19 marked landmarks. Three observers identified the landmarks on the screen. For each image, each observer digitised the landmarks on three occasions. There were 27 measurements for each landmark. The results showed that the accuracy was 0.93 mm and the precision was 0.2 mm. The authors concluded that the light scanning system was accurate, precise and sufficiently reliable to record the facial morphology for both clinic and research.

The laser scanning technique was simple, easy to use and non-invasive to the subjects. Also, the three-dimensional laser scanning can provide an efficient, valid and reproducible method of measuring the subjects face, with reproduction of 90% of facial morphology recorded as accurate to within 0.8 mm for male and 0.7 mm for female (Kau *et al.*, 2005). However, there are a number of disadvantages with the three-dimensional laser scan system, including the time taken to capture a subject face, 8-13 seconds rather than milliseconds with stereophotogrammetry and any change in the subjects head or facial muscles will distort the captured images. Moreover, with a laser beam, the subjects eyes must be closed due to safety issues related to exposure to a laser beam but with the eyes closed the identity of the captured 3D image will be affected.

Aynechi *et al.*, (2011) studied the influence of landmarks labelling on the accuracy and precision of indirect facial anthropometry. Ten adults (8 males and 2 females) were recruited in this study. On each subject face 18 facial measurements were derived from 19 anthropometric soft tissue landmarks. Three consecutive recordings were carried for each subject: (1) 3D photograph acquisition without landmarking the face (unlabelled 3D), (2) direct calliper based assessment with labelled landmarks (calliper), and (3) 3D photograph acquisition with labelled landmarks (labelled 3D). To assess the reproducibility of the method, facial measurements were recorded twice, one week apart for each subject (T1 and T2). Three-dimensional images were captured by using the 3dMDface system. Each subject was instructed to sit on a chair facing the centre of the 3dMD system in natural head position and with normal facial rest animation; the volunteer wore a headband to remove hair strands from their face and ears (Figure 2.4). All landmarks except endocanthion, exocanthion and stomion were marked on each subjects face using a surgical marking pen. The capture was repeated on the unlabelled faces using the 3dMD system. A digital calliper was also used to measure the linear measurements on each subjects labelled face. Special attention was given to apply minimal pressure to avoid any soft tissue displacement by the calliper during facial measurements. After the direct facial measurements were completed, a second 3D photograph image was captured with labelled facial landmarks. All procedures were repeated twice by

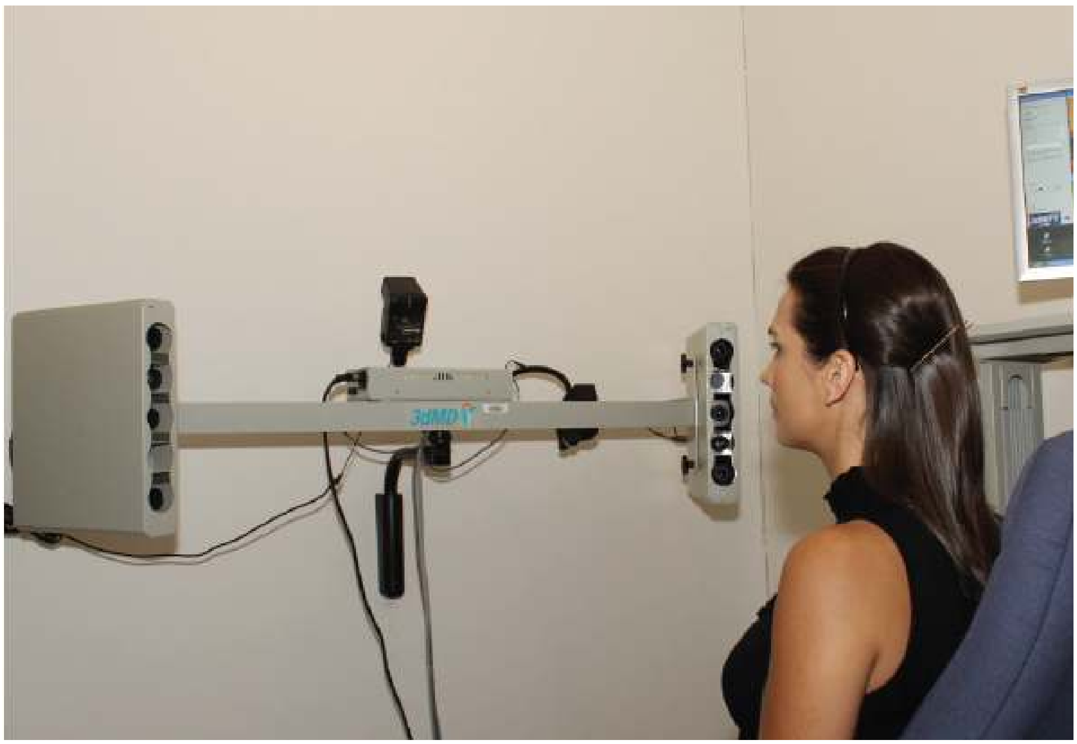

Figure 2.4 3dMDface system. (Aynechi *et al.*, 2011)

the same operator. The results showed that the majority of measurements obtained from three-dimensional images and direct anthropometry were similar. However, statistically significant differences between the two methods of 3D images ($p<0.01$) were noted for seven measurements in labelled 3D image and in six measurements of the unlabeled 3D image. Also, the labelled 3D was more precise compared with the two other technique ($P<0.05$). The authors found that the labelled 3D provided the most precise values and the use of callipers was the least capable method of generating accurate measurements. The author concluded that the 3dMDfcae system showed similar accuracy and precision to calliper measurements. The images captured by the 3dMDface system produced a high level of measurement precision, especially when facial landmarks were labelled. Despite the excellent results achieved by this study, the sample size was insufficient and gender was not equally selected. The authors did not mention if the unlabeled 3D photographic images were digitized by an expert operator or an inexpert operator which may influence the accuracy of the method. In the other hand, labelling facial landmarks before 3D capture could introduce systematic errors which have not been quantified in the study.

In reviewing the previous literature, there were insufficient papers to analyse the dynamics of facial animation which inspired this study, Table 2.1.

2.4 Facial Motion Measurements

An evaluation of the motion of facial animation plays an important role in many clinical situations: for example; cleft lip and palate repair, in the assessment of motor nerve deficits and in patients after reconstruction. Clinical staging and evaluation of treatment outcome could be improved by the ability of measuring the changes in facial animation in an objective, repetitive and comparable method that could be handled statistically.

Mishema *et al.,* (2006) analysed the lip motion of six adults during phonation using a video-based motion capture system. Ten landmarks of the upper lip on a 3D image were manually located on a screen. The landmarks represented the upper and lower lip movements as well as the vermilion border. The accuracy of the system was investigated using a one-axis parallel motion apparatus with high accuracy (positioning actuator) and known objects (cube of 150 mm on each

Authors	Systems	Sample	Accuracy	Landmarks	Identification	Method of analysis	Comments
Ozay *et al.*, 2009	Manual anthropometry 2D photograph 3D digitizer	35 males 35 females	0.03 mm manual calliper 0.009 inches 3D digitizer	Not Stated	Direct / Indirect	Paired sample t-test	Comparing 3 methods, the authors found the 3D digitizer easy, robust and sensitive method. 3D digitizer was more reliable than manual calliper & 2D photograph. Validity was not stated.
Wong *et al.*, 2008	Direct anthropometry 3dMD face system	12 males 8 females	1 mm	18 facial landmarks (eyeliner pencil)	Indirect	18 Linear distances	Reliability was 0.91 Precision was 0.8 mm. Validity was 0.88.
Trotman *et al.*, 1996	3 video cameras	4	Not Stated	14 facial landmarks	Direct	3D maximum motion amplitudes for facial landmarks were calculated	Assess the reliability of: (1) marker positions between animations within a trail and with patient at rest, (2) marker positions between sessions. Reliability was ranged from r=0.64 to 0.96. Validity not stated.
Ayoub *et al.*, 1998	C3D Stereophotogrammetry	21 facial cast	0.5 mm	5 landmarks	Direct	Three-dimensional polygonized facial model.	Accuracy within 0.5 mm. Validity not stated. The method was non-invasive and cost effective.
Weinberg *et al.*, 2004	Digital calliper Genex 3D Stereophotogrammetry	20	< 2 mm	17 landmarks	Direct / Indirect	19 linear facial measurements	Digital calliper was less precise than 3D photo. 14 of the 19 variable was accurate < 0.2mm

Table 2.1 Summary of literature investigating direct 3D landmark measurement.

Authors	Systems	Sample	Accuracy	Landmarks	Identification	Method of analysis	Comments
Aldrige *et al.*, 2005	3dMD Face system	7 Adults 8 children	Not stated	20 landmarks 6 midline 7 bilateral	Indirect	Linear measurements distance.	14 landmarks precision was < 1 mm 6 landmarks precisions >1 mm < 2mm. Validity was not stated. Reliability was not stated.
Khambay *et al.*, 2008	Di3D stereophotogrammetry	12 plaster casts	0.07 mm	10 landmarks	Indirect	Ordinary Procrustes Analysis (OPA)	The Di3D system error was within 0.2 mm. The reproducibility of the Di3D system was 0.13 mm, range 0.11mm-0.14 mm. The validity & reliability of Di3D system was not addressed in this study.
Kau *et al.*, 2004	3D laser scanner	40 children	Not Stated	Not Stated	Not Stated	Rapidform, shell to shell deviation computing map.	The purpose of this article was to evaluate the reliability of 3D facial scanning technique. Validity not stated.
Toma *et al.*, 2009	3D laser scanner	30 children	Not Stated	21 landmarks	Not Stated	Not Stated	10 landmarks were reproducible both intra & inter examiner 0.39-1.49 mm.
Me *et al.*, 2009	3D light scanning system	A plaster model	0.93 mm	19 landmarks	Not Stated	Not Stated	The precision was 0.79 mm The reliability was 0.2 mm.

Table 2.1 (Continued) Summary of literature investigating direct 3D landmark measurement.

checkerboard). The actuator was moved at speed of 50 mm/s in a direction parallel to the optical axis of the central camera. The results showed that the accuracy of the system ranged from 0.53 to 0.73 mm, with a mean of 0.64 mm ± 0.08 mm in length direction, and ranged from 0.14 to 0.44 mm, with a mean of 0.31 mm ± 0.11 mm in the width direction. Also, the quantity of movement of the white lip was greatest at the later timing during phonation than that of the vermilion border. The authors concluded that the presented system possessed sufficient accuracy for clinical use.

In another study Mishema *et al.,* (2010) used the same system to analyse lip motion by principal component analyses. They studied lip motion of 14 "normal" individuals during the phonation of 5 Japanese vowels, /a/, /i/, /u/, /e/, and /o/. A motion analyses system was used to capture lip movement and the principal component was applied to measure movements. Thirty frames were captured per seconds, 10 landmarks of the upper lip were directly located on the 3D image on the screen. The 10 landmarks represented the upper and lower lips as well as the vermilions border. Twelve principal component analyses were produced to describe lip movement in relation to the landmarks. The authors showed that there was little movement of mouth opening during the phonation of /u/. The authors concluded that the principal component analysis was distinguishable at measuring lip movement. The main drawback of these two studies was a limited facial area was covered and there was insufficient tracking of the system data.

Popat *et al.,* (2011) conducted a cross-sectional study to construct 3D templates of average lip movement. One hundred and fifteen white subjects were included in this study and were asked to perform two reproducible verbal gestures (/puppy/and/rope/) in a normal relaxed manner. Six lip landmarks were placed manually around the lips by one examiner. The sequences were captured using 3D motion scanner (3dMDFace Dynamic System) at 48 frames per second. The results showed there was a statistical significant difference in the lip movement between gender for visemes /pu/ and /ppy/ ($p<0.05$), although when quantified these were found not to be of clinical significance the mean difference lip movement between groups being less than 2 mm. Women favoured right sided movement and men favoured left sided movement. The authors concluded that it was possible to quantify and create normal templates of lip movement for the words /puppy/ and /rope/. Men and women showed similar standardized lip movements for these two words. Despite the sufficient sample size and robust results reached, the authors did not examine the validity of the system and if the speed of the system capture (48 frames per second) was sufficient to capture the path of the facial animation. The six facial landmarks described a limited area of the face during animation; more coverage of the face may have been more beneficial.

In summary:

With advanced technology to measure facial animation, there is still insufficient data recorded during the path of facial animation with limited coverage to comment on the whole face during animation. Moreover, there is inadequate information to compare the accuracy between the manual and automatic tracking system, Table 2.2.

2.5 Automated landmarks identification

An ideal analyses system would be completely automated and free from human intervention. Images would be captured without having to place landmarks on the subject face. Computerised identification of pre-programmed software would be able to automatically align and superimposed groups of facial landmarks. This process would be carried out accurately by the computer and the system could be able to cope with minor changes such as growth changes, long term studies or those involving children.

Wachtman *et al.,* (2001) validated a method of quantifying facial motion, Automated Face Analysis (AFA), by comparing it with a manual marking method, the Maximal Static Response Assay (MSRA) which is a static assay in which the operator selects one frame of maximal facial excursion from a video sequence of standard facial expression. Nine patients with various facial nerve disorders participated in this study. The patients were instructed to perform three facial animations which were captured on videotape at 30 frames/seconds. For comparison with MSRA, 9 physical markers were located on the patients face (5 mm blue paper marking dots), and 7 were anatomic landmarks. Two additional

Table 2.2 Summary table of studies investigating facial movement measurements.

Authors	Systems	Sample size	Accuracy	Landmarks	Speed	Method of analysis	Comments
Mishema *et al.*, 2008	Video-based motion capture system	6	0.53 mm to 0.73 mm in length. 0.14 mm to 0.44 mm in width.	10 landmarks on the upper lip.	30 frames/ second	Accuracy was investigated using a one-axis parallel motion apparatus	The authors investigated the dynamic motion of lip area only. The validity & reliability of system were not stated.
Mishema *et al.*, 2010	Video-based motion capture system	14	0.53 mm to 0.73 mm in length. 0.14 mm to 0.44 mm in width.	10 landmarks on the upper lip.	30 frames/ second	Principal component analysis	The study quantified the lip movement characteristics during the phonation of Japanese vowels using principal component analysis.
Popat *et al.*, 2011	3dMDFace Dynamic System	150	Not stated	6 landmarks were manually placed around the subjects' lip for each facial shell.	48 frames/ second	Mesh registration software was used to align sequential facial shells to a standardized reference plane	The study constructed 3D templates of average lip movement for words /puppy/and /rope/. The range in total landmark distance error for both intra- and inter-examiner assessments was 0.59 mm to 1.32 mm. Validity & reliability were not stated in this study.

marks with marking dots were used to scale the image from pixel to centimetres with a 2-cm ruler taped the nose. As defined for the MSRA, the coordinates of the centre of each marker were manually recorded in the initial and final digitized frames, which correspond to repose and maximal response. For AFA, these points were tracked automatically in the image sequence. In this method no artificial landmarks were used. The results showed a Pearson correlation of 0.96. The authors concluded that the AFA demonstrated strong concurrent validity with the MSRA for pixel-wise displacement. Unfortunately this method only gives a two-dimensional representation of facial animation. Another deficiency of this study was the insufficient sample size which may have not be enough to reach a sound conclusion. The validity of automated tracking system was limited to the initial and final frames, which did not record the path of animation in between.

Deli *et al.*, (2010) studied automated landmark extraction for orthodontic measurements of faces using the 3D camera photogrammetric methodology. Thirty coded targets were applied on dummy heads and under room lighting conditions a stereophotogrammetry image was captured using three cameras. The authors applied software for automatic locating of the landmarks. The precision of the method was tested against the manual measurements which were carried out by a calliper and compared with those measurements derived from laser scanning. The reported mean value for the precision of the automatic landmarks' location was 0.02 mm.

The dummy heads are inanimate objects; conducting the same investigation on live subjects may have produced different results. The study did not investigate then accuracy of the tracking software in recording facial landmarks during dynamic movement. This study is a step in the right direction which should be followed by clinical application in humans.

Chapter Three
Aims & Null Hypotheses

3 Aims & Null Hypotheses

Aim of the study

The aim of this study was to determine the validity of the automatic tracking of facial landmarks in image sequences captured using the four dimensional capture systems (Dimensional Imaging Ltd. Glasgow, UK).

Null Hypotheses

1. No statistical significant differences exist between the 3D location of manually digitized landmarks and those recorded automatically by a tracking system.

2. No clinical significant differences exist between the 3D location of manually digitized landmarks and those recorded automatically by a tracking system.

Chapter Four

Materials & Methods

4 Materials and Method

4.1 Study design

The aim of this study was to determine the validity of automatic tracking software in tracking facial landmarks in image sequences captured using a four dimensional capture system (Dimensional Imaging Ltd., Glasgow, UK). Ethical approval was obtained from the Faculty of medicine ethics committee for non-clinical research involving human subjects at the University of Glasgow.

4.2 Subjects

Subjects were recruited from the Glasgow Dental Hospital and School. Posters were placed in the Glasgow Dental Hospital and School to recruit student or other adults i.e. parents of patients (Appendix 1). The age range was from 15-35 years. In total 16 females and 16 males were recruited for the study. Subjects were given verbal and written explanations of the project purpose and details of their involvement (Appendix 2).

4.2.1 Inclusion criteria

- Consented to participate in the study.
- No history of facial deformity.
- No history of orthognathic surgery.

4.2.2 Exclusion criteria

- History of orthognathic treatment.
- Subjects with history of facial palsy.
- Subjects with history of facial trauma.
- History of facial asymmetry.
- Subjects with history repaired cleft lip or cleft palate.

4.3 Materials

4.3.1 The 4D imaging system

The subjects were imaged using the Di4D system (Di4D, Dimensional Imaging Ltd, Glasgow, UK) (Figure 4.1). The specification for the 4D system was based on a three camera system, a single-pod comprising of two greyscale cameras (Model avA 1600-65km/kc, resolution 1600x1200 pixels, Kodak sensor model KAI-02050, Basler, Germany) and one colour camera functioning at 60 frames per second. The 4D capture system was connected to a personal computer which had the following specifications:

- Windows 7 professional (Microsoft, USA).
- Intel core ™ i7 CPU - 3.07 GHz.
- LCD Monitor.
- Lighting system (Model DIV-401-DIVA LITE, KINO FLO Corporation, USA).

4.3.2 Calibration

Prior to image capture the Di4D system was calibrated. The purpose of the calibration was to determine the intrinsic camera parameters, the location of focal length, image centres and orientation of each camera to the other. The process itself was fully automated and required the use of a calibration target (Figure 4.2). The target was made up of number of black circles of known sizes which were separated by a known distance on a white background. In order to capture the entire three dimensional space, the calibration target was captured eight times at various angles. The camera parameters of the three cameras were determined automatically by the calibration software which extracted the centres of the circles on the calibration images and from this information the software determined the all three cameras and their intrinsic parameters without any further operator intervention.

Figure 4.1 Shows the Di4D system.

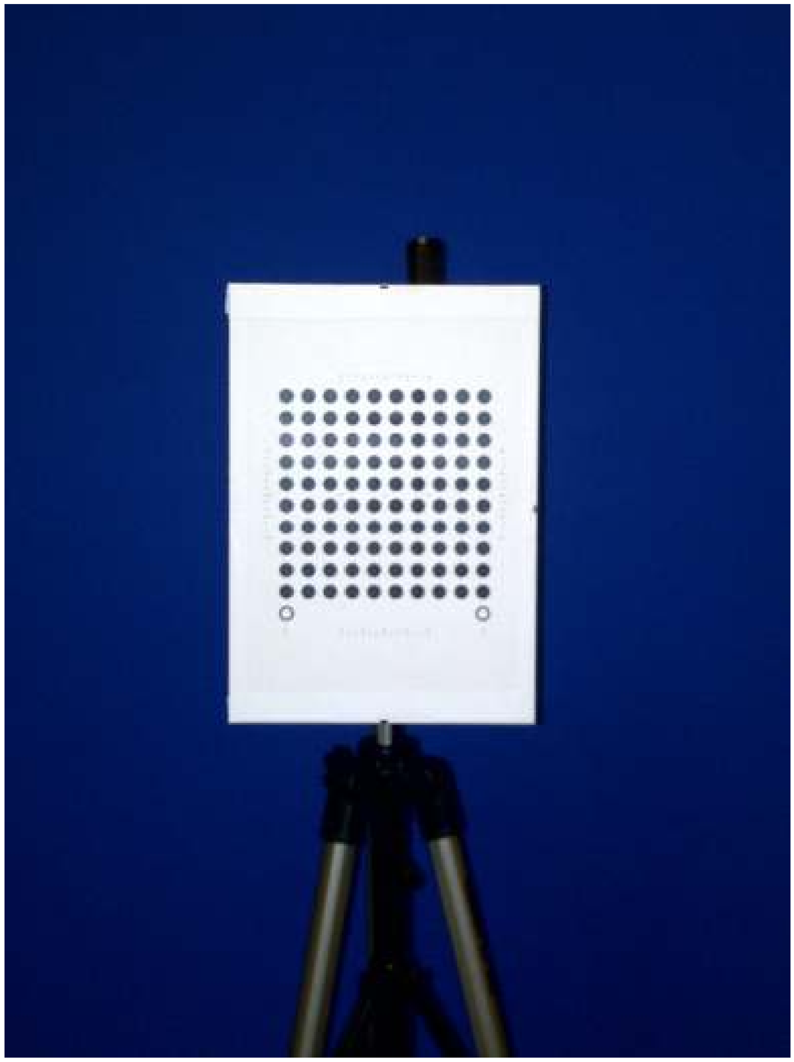

Figure 4.2 Shows the calibration target used to calibrate the Di4D system.

4.4 Facial landmarks

Twenty three facial landmarks (Table 4.1 & Figure 4.3) were marked on each subjects face (Farkas *et al.,* 1994; Hajeer *et al.,* 2002) by the same operator using a 0.5 mm non-permanent coloured ink (Staelier, Germany) before animation capture. For each subject landmark identification took approximately five minutes. A cloth or tissue paper was provided to wipe the marks from the subject face following capture.

4.5 Image capture

The operator demonstrated three facial animations and rest position in front of the subject and trained the subject for 5 minutes before the capture started. Subjects were asked to perform the following three facial animations together with rest position:

<u>Maximal smile</u>

Subjects were asked to bite their back teeth tightly together and to smile as widely as possible i.e. say "cheese".

<u>Maximal lip purse</u>

Subjects were asked to purse their lips together and whistle or pretended to whistle.

<u>Maximal cheek puff</u>

Subjects were asked to bite together on their back teeth and hold their lips together while the cheeks were puffed maximally.

<u>Rest position</u>

The subject asked to keep in rest position by say "Mississippi", then instruct to swallow once and say "N" (guidelines to obtaining rest position natural facial expression as proposed by Zachrisson 1998).

Landmark number	Landmark name	Definition
1 & 2	Superciliary points	The points located above most superior aspects eye brows.
3	Glabella	The most prominent midline point between the eyebrows, identical to bony glabella on the frontal bone.
4 & 7	Exocanthion	The point at the outer commissure of the eye fissure, located slightly medial to bony exocanthoin.
5 & 6	Endocanthion	The point at the inner commissure of the eye fissure, located lateral to bony landmark.
8	Nasion	The point in the midline of both the nasal root and the nasofrontal suture, always above the line that connects the two inner canthi, identical to bony nasion.
9 & 10	Zygio	The most prominent point on the cheek area beneath the outer canthus and slightly medial the vertical line passing through it; different from bony zygion.
11	Pronasale	The most protruded point of the apex nasi identified in lateral view of the rest position of the head.
12 & 13	Alar curvature	The most lateral point on the curved base line of each ala, indicating the facial insertion of the nasal wingbase.
14 & 15	Subalare	The point on the margin of the base of the nasal ala where the ala disappears into the upper lip skin.
16	Subnasale	The mid point of angle at the columella base where the lower border of nasal septum and surface of the upper lip meet.
17 & 18	Cheilion	The point located at each labial commissure.
19 & 20	Crista philtre	The peak of Cupid's bow of the upper inferior.
21	Labiale superius	A point indicating the muco-cutaneous junction of the upper lip and philtrum.
22	Labiale inferius	A point indicating the muco-cuteneous border of the lower lip.
23	Pogonion	The most anterior midpoint of the chin, located on the skin surface in front of identical bony landmark of the mandible.

Table 4.1 Landmark definitions

Figure 4.3 Shows facial landmarks.

Subjects were shown photographic cue cards of an individual demonstrating each of the expressions (Appendix 3). Prior to each capture session, each expression was practiced 5 times with the operator to ensure that the subjects had fully understood the instructions.

For all captures, subjects were seated on a chair directly in front of the camera system. Subject sat in an upright and comfortable position. For image captures, subjects were asked to:

- Remove all make-up.
- Keep their eyes open.
- Remain still during image capturing.

A distance of 95 cm was measured using a measuring tape from the cameras to the subject's cheek. A second operator cheeked the focal length before each capture. The lighting system was set to maximum power before the image capture started.

Dynamic capture of each facial animation, at 60 frames per second, took around 3 seconds using DiCapture software (Dimensional Imaging Ltd, Glasgow, UK), Figure 4.4. Each capture began at rest position and over 3 seconds maximal animation was recorded with return to rest position. The images were reviewed immediately after capture using Di4D software (Dimensional Imaging Ltd, Glasgow, UK) to ensure absence of acquisition error such as image blurring and artefacts. The images were saved for future processing. This was repeated for the all three facial animations, maximal smile, maximal lip purse and maximal cheek puff.

4.6 Facial landmark tracking

4.6.1 Automatic tracking

Each facial expression dynamic image sequence was imported into DiView software and the first frame was selected for each subject (Figure 4.5). The 23 facial landmarks were digitised on-screen and using the appropriate function within DiView software, these landmarks in sequential frames were automatically tracked.

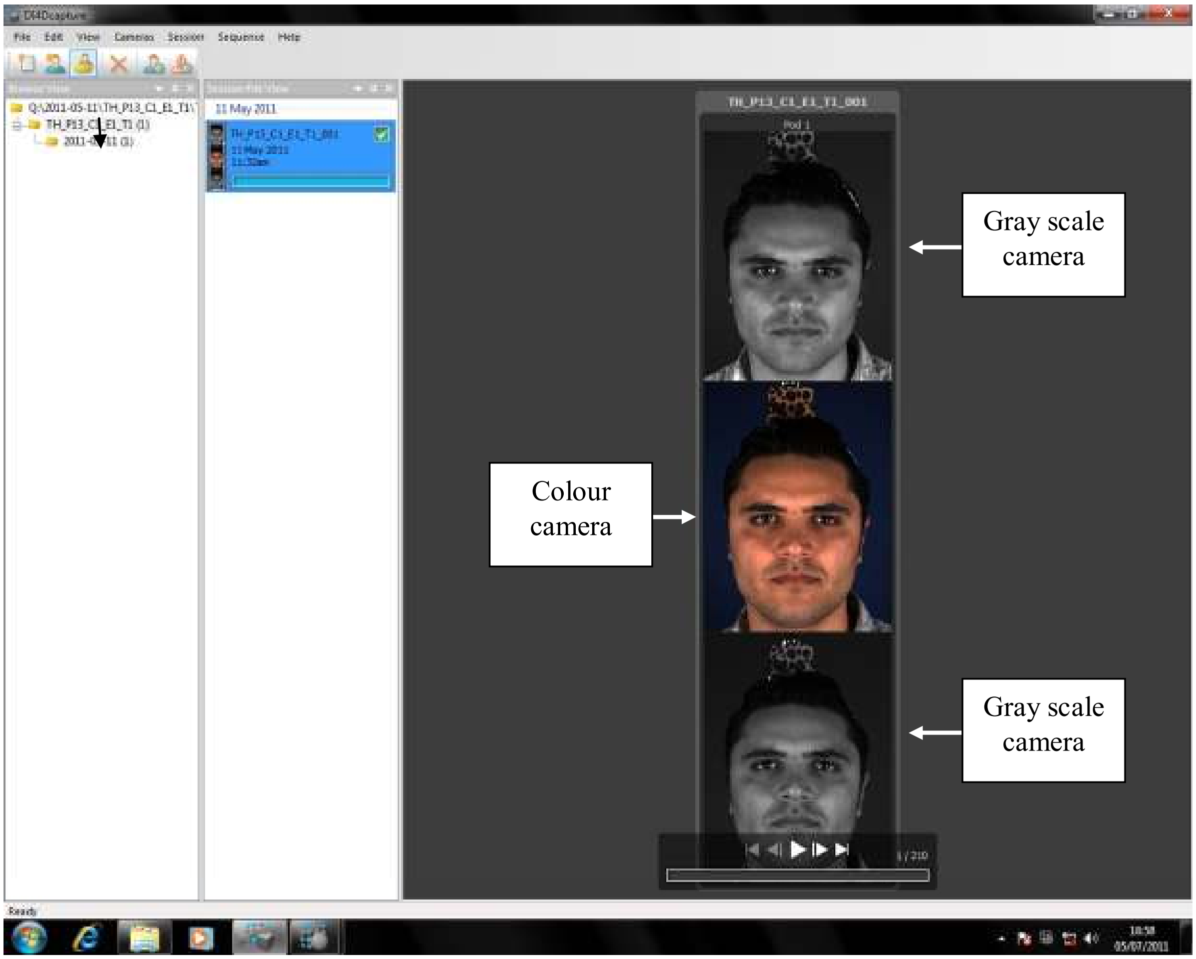

Figure 4.4 Shows DiView capture software user interface

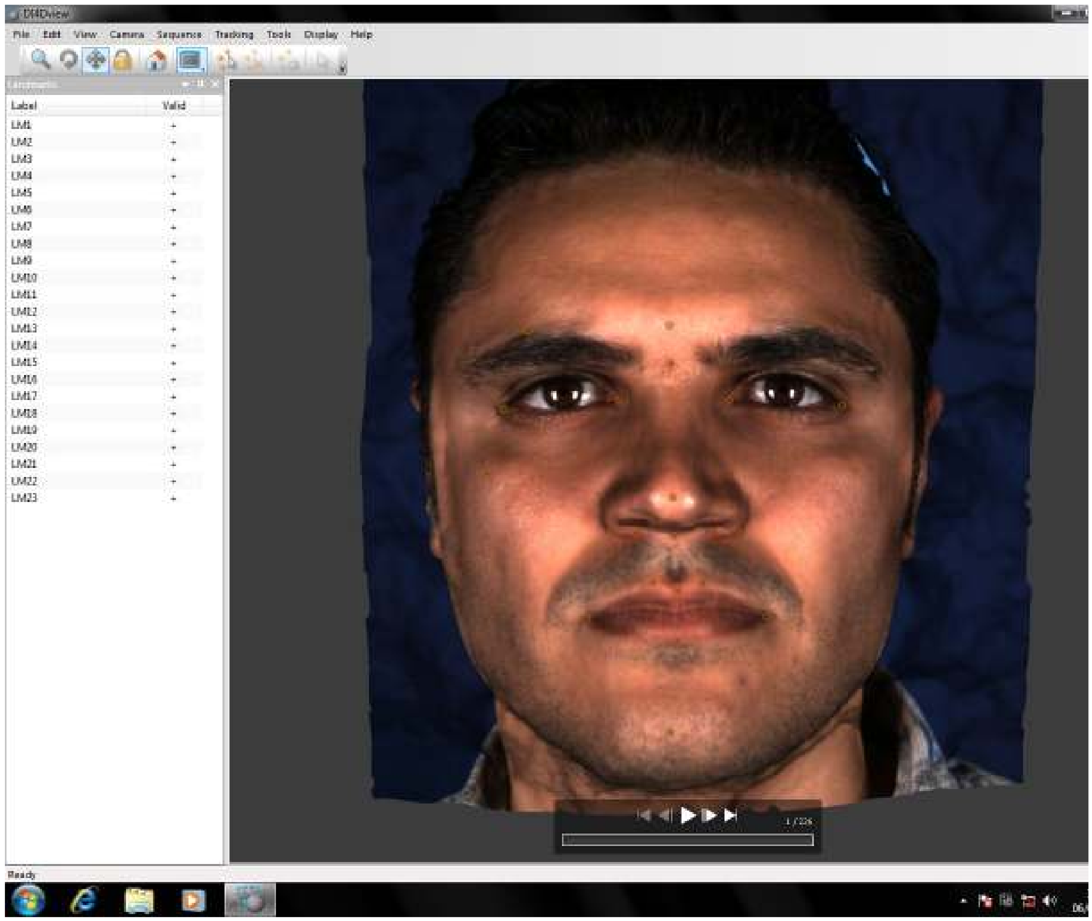

Figure 4.5 Shows the first frame ready for automatic tracking. Subject in rest position.

4.6.2 Error study

To assess the manual landmark digitisation error, ten subjects were selected at random (5 male & 5 female). For each subject five 3D images from each of the three facial expressions were chosen at random, 150 images in total. For each image the landmarks were re-digitised on two separate occasions, with a one month interval in-between to reduce memory bias.

4.6.3 Manual tracking

Each facial expression dynamic image sequence was imported into Di4D software ready for landmarking. Five frames were selected from each animation which represented the following time frames,

- Rest position, (Figure 4.6).
- Middle frame between rest position and maximal animation, (Figure 4.7).
- Maximal animation, (Figure 4.8).
- Middle frame between maximal animation and rest position, (Figure 4.9)
- Rest position.

The frame numbers digitised were noted. Each frame was digitised using the landmarks pre-marked on the subjects face. The x, y and z coordinates of each of the landmarks were extracted and analysed on Excel (Microsoft, USA). This procedure was repeated for each subject and for each animation. It took 5 mintues of digitisation of 23 landmarks on the 3D model in a single frame.

4.7 Comparison of manual and automatic landmarks tracking

Following automatic tracking, the corresponding frame landmarked during the manual tracking procedure was identified. The automatically tracked x, y and z co-ordinates of the landmarks in these frames where exported into an in-house developed software package which converted the output of DiView software file (*.pc2) into Excel file (*.xls) for later analysis.

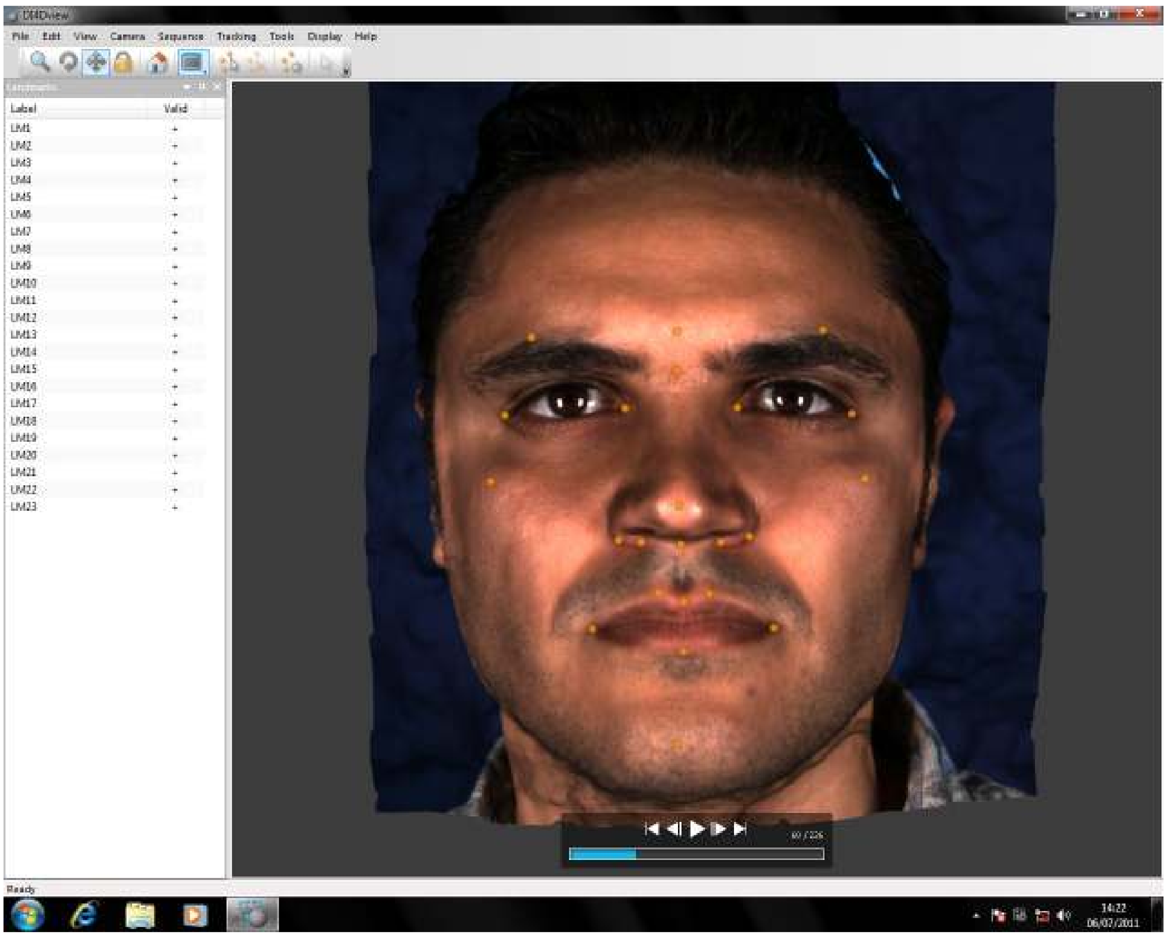

Figure 4.6 Rest position frame was showed the subject on rest position for manual tracking. Note position of blue image sequence bar under subjects chin.

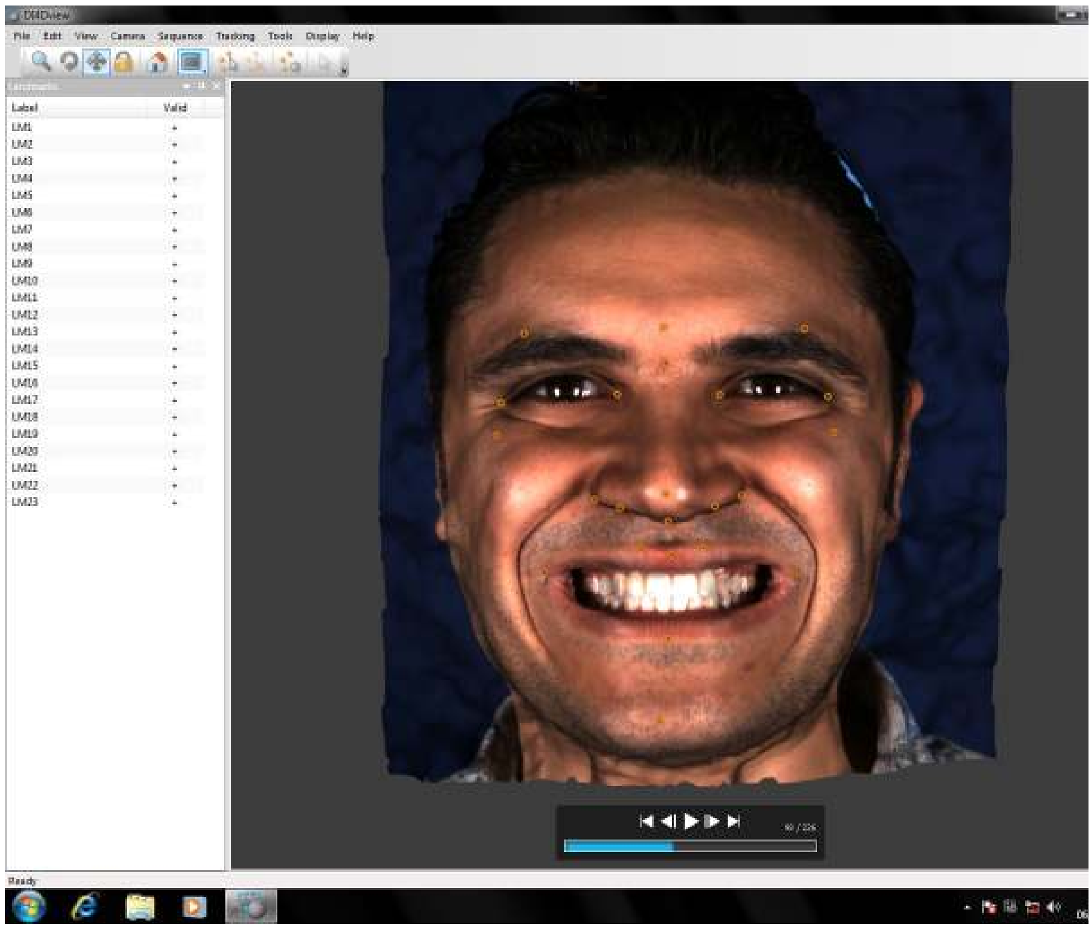

Figure 4.7 Shows middle frame between rest position and maximal animation. Note position of blue image sequence bar under subjects chin.

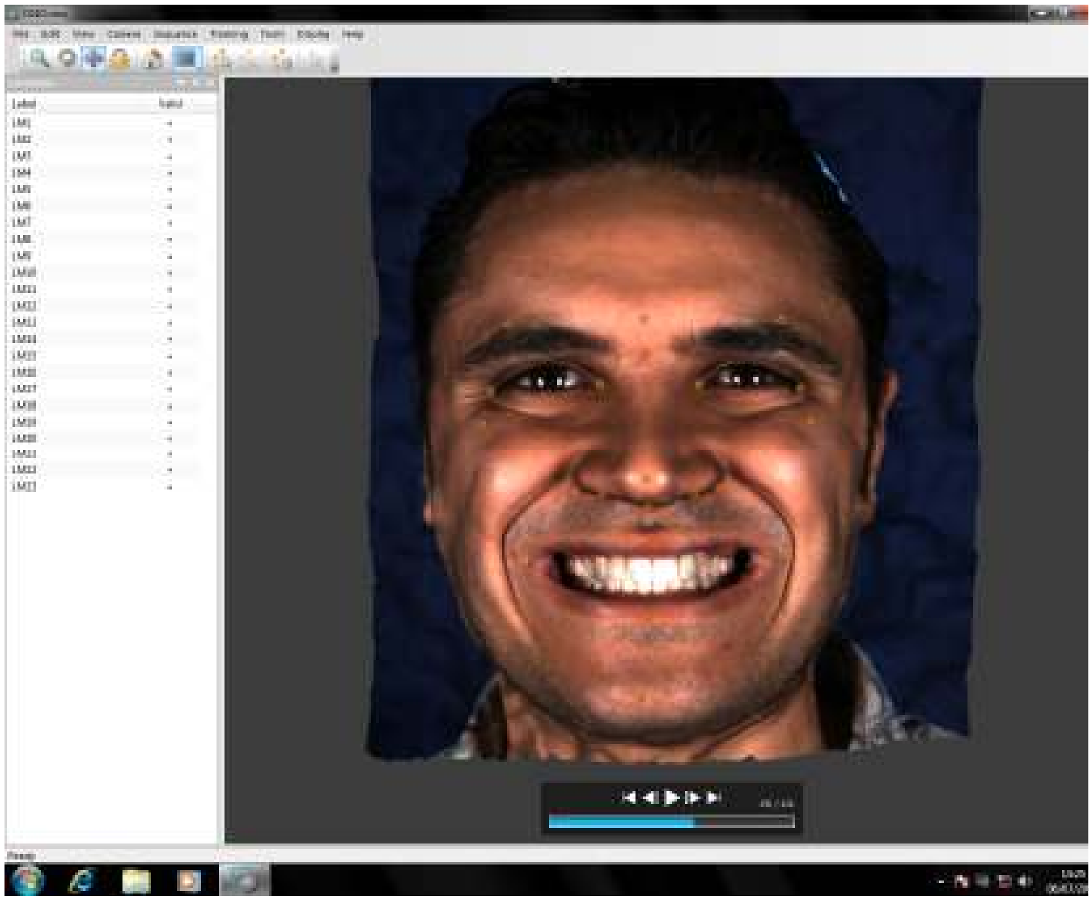

Figure 4.8 Shows maximal animation frame. Note position of blue image sequence bar under subjects chin.

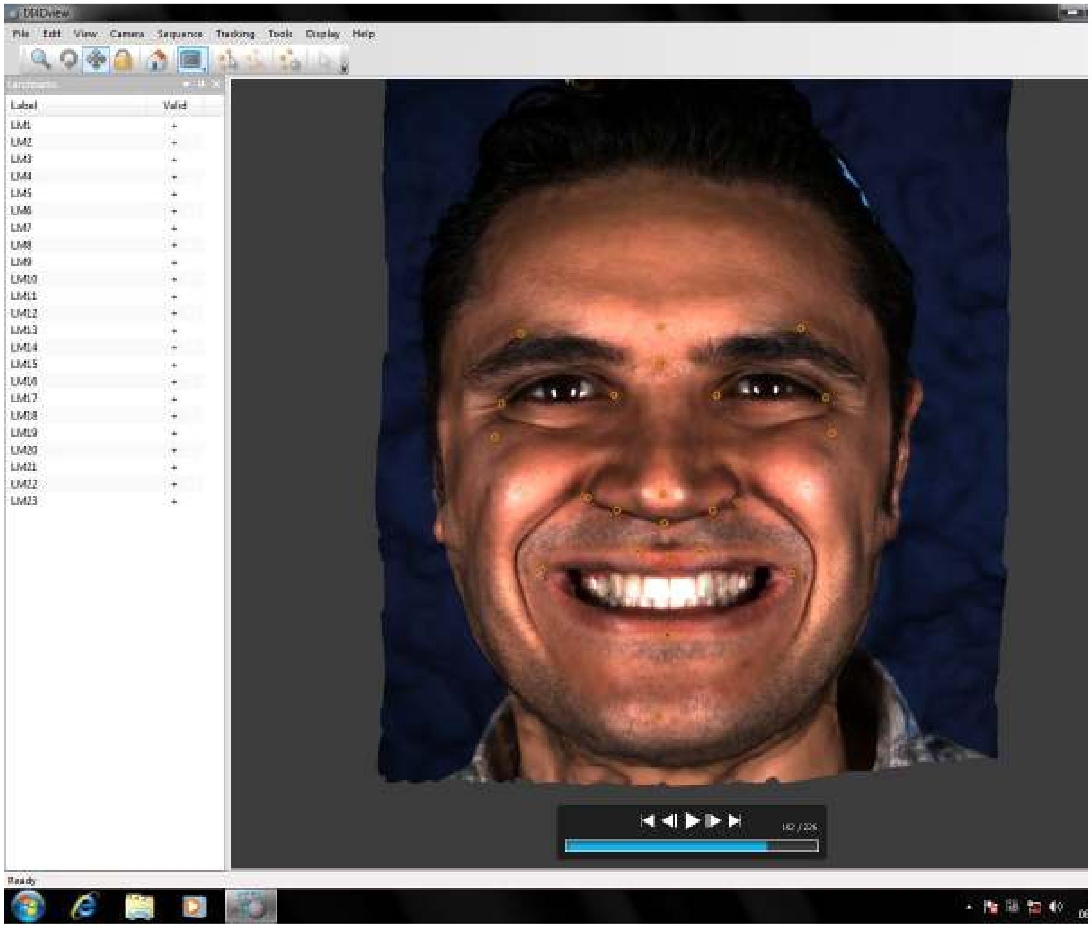

Figure 4.9 Shows middle frame between maximal animation and rest position. Note position of blue image sequence bar under subjects chin.

Chapter Five

Results

5 Results

5.1 Subjects

This is a single cohort study, which was carried out on 32 subjects, 16 males and 16 females with an age range from 21-30 years. Each subject was captured three times for each facial animation. For each of the three facial animations 5 frames were selected for manual digitisation which represented the path of animation. A total of 576 frames were captured from the 32 subjects included in the study.

5.2 Manual landmark identification error

To assess the landmark identification error, the 4D images of 10 randomly selected subjects were selected (5 male and 5 female) and 150 frames from all three facial animations were selected to re-digitised. This was carried out after one month from the first occasion of digitisation.

Table 5.1 shows the differences in the x, y and z coordinates between manual digitisation at the two separate occasions. The mean distance between the corresponding landmarks of the first and second digitisation was within 0.2 mm.

For all three animations combined the repeated digitisation errors of landmarks were less than 0.1 mm in the x, y and z direction with a mean distance between corresponding landmarks of repeated digitisation of 0.21 mm. Landmarks 12 & 13 were associated with the largest repeated digitisation errors, however, this was less than 0.5 mm.

5.3 ALL ANIMATIONS COMBINED

5.3.1 The mean absolute distance between the manually and automatically tracked landmarks for all animations in the female group

The mean absolute distance in the x, y and z coordinates between manually digitised and automatically tracked landmarks were all within 0.4 mm, Table 5.2. However, there was a larger standard deviation of the y coordinate. The

	Mean difference(mm)	SD (mm)	Median	Range	
				Min	Max
Maximal smile					
X direction	0.10	0.14	0.07	0.00	1.45
Y direction	0.11	0.23	0.04	0.00	2.67
Z direction	0.12	0.16	0.09	0.00	2.15
Euclidian distance	0.23	0.28			
Lip purse					
X direction	0.09	0.11	0.07	0.00	1.34
Y direction	0.09	0.19	0.04	0.00	2.74
Z direction	0.11	0.12	0.08	0.00	1.65
Euclidian distance	0.19	0.23			
Cheek puff					
X direction	0.10	0.14	0.07	0.00	2.37
Y direction	0.09	0.16	0.04	0.00	1.69
Z direction	0.12	0.15	0.09	0.00	2.86
Euclidian distance	0.20	0.24			
Animations combined					
X direction	0.10	0.13	0.07	0.00	2.37
Y direction	0.10	0.19	0.04	0.00	2.74
Z direction	0.11	0.14	0.09	0.00	2.86
Euclidian distance	0.21	0.25			

Table 5.1 The differences in the x, y and z coordinates between manual digitisation at the two separate occasions.

	x direction	y direction	z direction	Euclidian distance
Mean (mm)	0.35	0.32	0.30	0.64
Standard Deviation (mm)	0.61	0.70	0.46	0.99
Median (mm)	0.13	0.08	0.14	0.28
Range				
Minimum (mm)	0.00	0.00	0.00	0.00
Maximum (mm)	6.77	11.98	5.62	12.03

Table 5.2 The mean absolute distance between landmarks for all animations in the female group.

maximum difference in distance between the two methods was similar in the x and z direction (6.77mm and 5.62mm respectively) and greatest in the y direction (11.98mm). The overall mean distance between the manually digitised and automatically tracked landmarks was 0.64 ± 0.99mm. Figure 5.1 shows the mean distance for all landmarks between the automatically tracked and manually located landmarks, the largest difference is associated with landmarks 12 and 13.

5.3.2 The mean absolute distance between the manually and automatically tracked landmarks for all animations in the male group

Similar findings were also found for the male group of subjects, Table 5.3. The mean absolute distance in the x, y and z coordinates between manually digitised and automatically tracked landmarks were all within 0.4 mm. The maximum difference between the two methods was similar in the x and z direction (5.86mm and 5.36mm respectively) and greatest in the y direction (13.02mm).

The overall mean distance between the manually digitised and automatically tracked landmarks was 0.68 ± 1.06mm. Figure 5.2 shows the mean distance for all landmarks between the automatically tracked and manually located landmarks, the largest difference is associated with landmarks 12 and 13.

5.3.3 The mean absolute distance between the manually and automatically tracked landmarks for all animations combining the female and male groups

The mean absolute distance in the x, y and z coordinates between manually digitised and automatically tracked landmarks were all within 0.4 mm, Table 5.4. Bland-Altman plots showing the distance difference between the automatically tracked landmark and the manually placed landmark in the x, y and z direction, and the average of the automatically tracked landmark and the manually placed landmark are shown in Figures 5.3, 5.4 and 5.5 respectively.

The overall mean distance between the manually digitised and automatically tracked landmarks was 0.66 ± 1.02mm. A *t*-test comparing the female group to

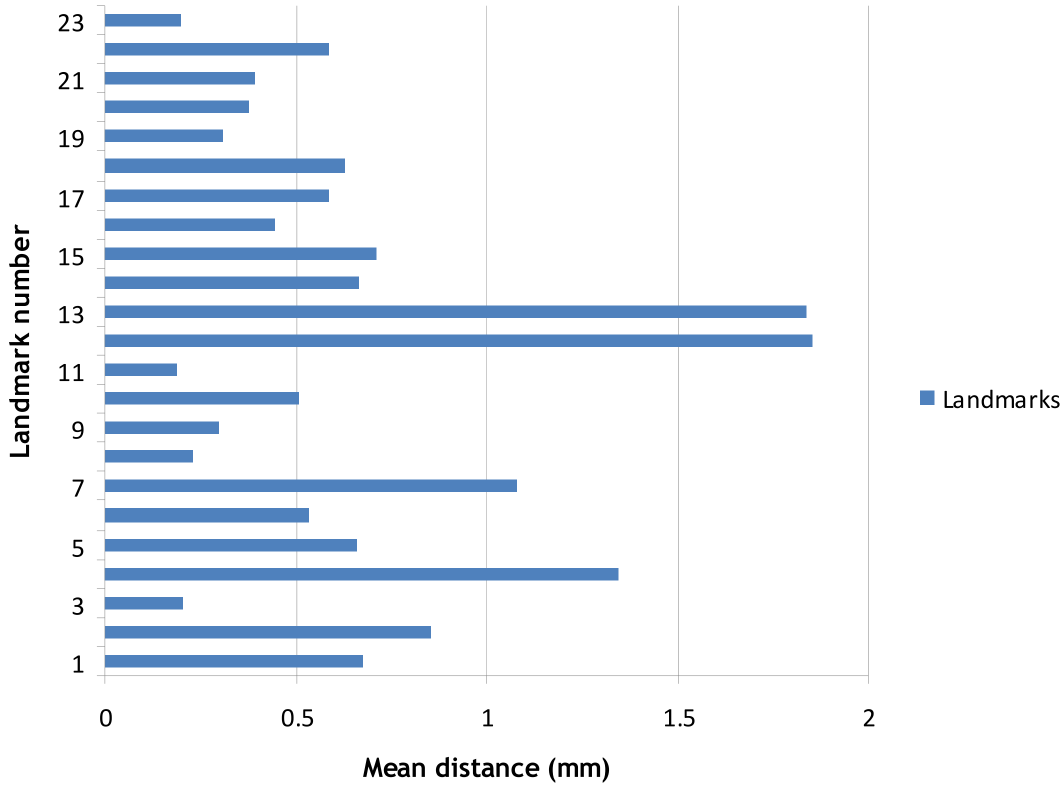

Figure 5.1 The mean distance for all landmarks between the automatically tracked and manually located landmarks in the female group.

	x direction	y direction	z direction	Euclidian distance
Mean (mm)	0.35	0.36	0.31	0.68
Standard Deviation (mm)	0.58	0.80	0.51	1.06
Median (mm)	0.16	0.09	0.15	0.30
Range				
Minimum (mm)	0.00	0.00	0.00	0.00
Maximum (mm)	5.86	13.02	5.36	13.07

Table 5.3 The mean absolute distance between landmarks for all animations in the male group.

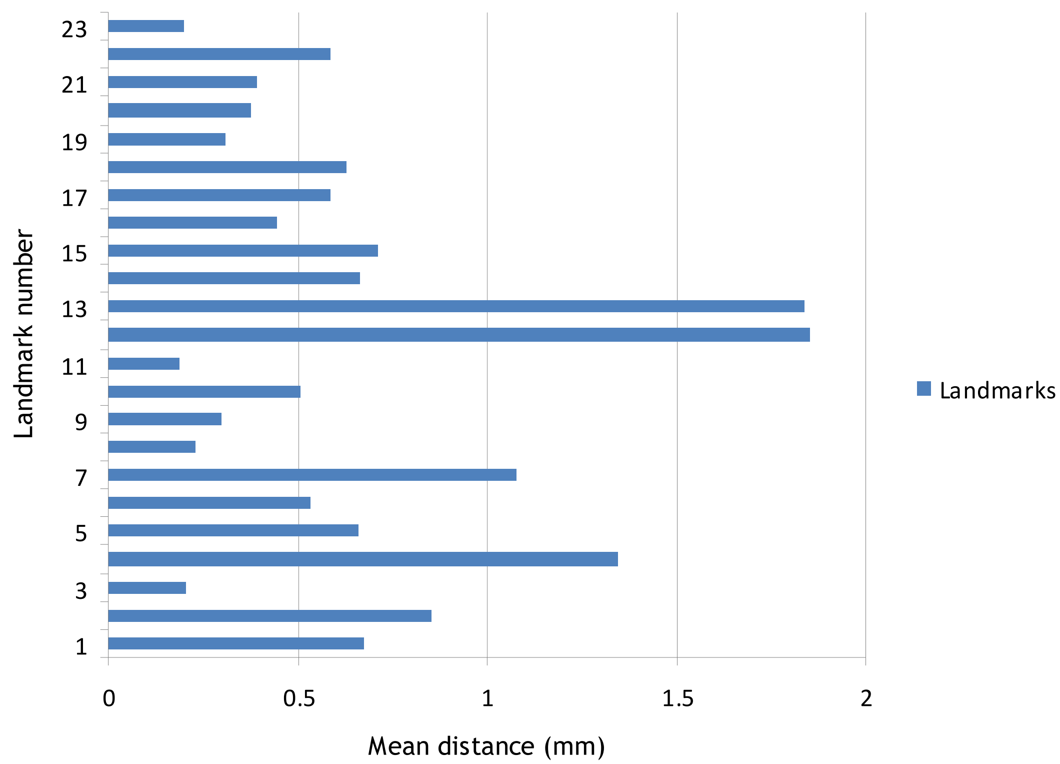

Figure 5.2 The mean distance for all landmarks between the automatically tracked and manually located landmarks in the male group.

	x direction	y direction	z direction	Euclidian distance
Mean (mm)	0.35	0.34	0.30	0.66
Standard Deviation (mm)	0.60	0.75	0.49	1.02
Median (mm)	0.14	0.08	0.15	0.29
Range				
Minimum (mm)	0.00	0.00	0.00	0.00
Maximum (mm)	6.77	13.02	5.62	13.07

Table 5.4 The mean absolute distance between landmarks for all animations in the combined females and male groups

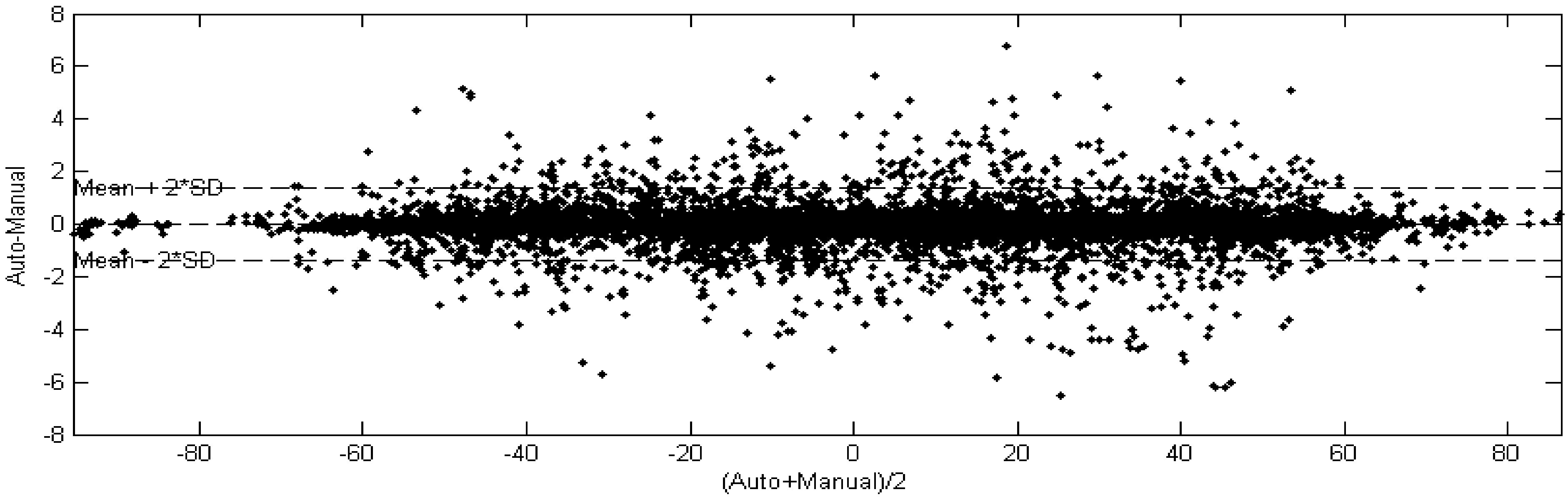

Figure 5.3 Bland-Altman plots showing the distance difference between the automatically tracked landmark and the manually placed landmark in the x direction, and the average of the automatically tracked landmark and the manually placed landmark.

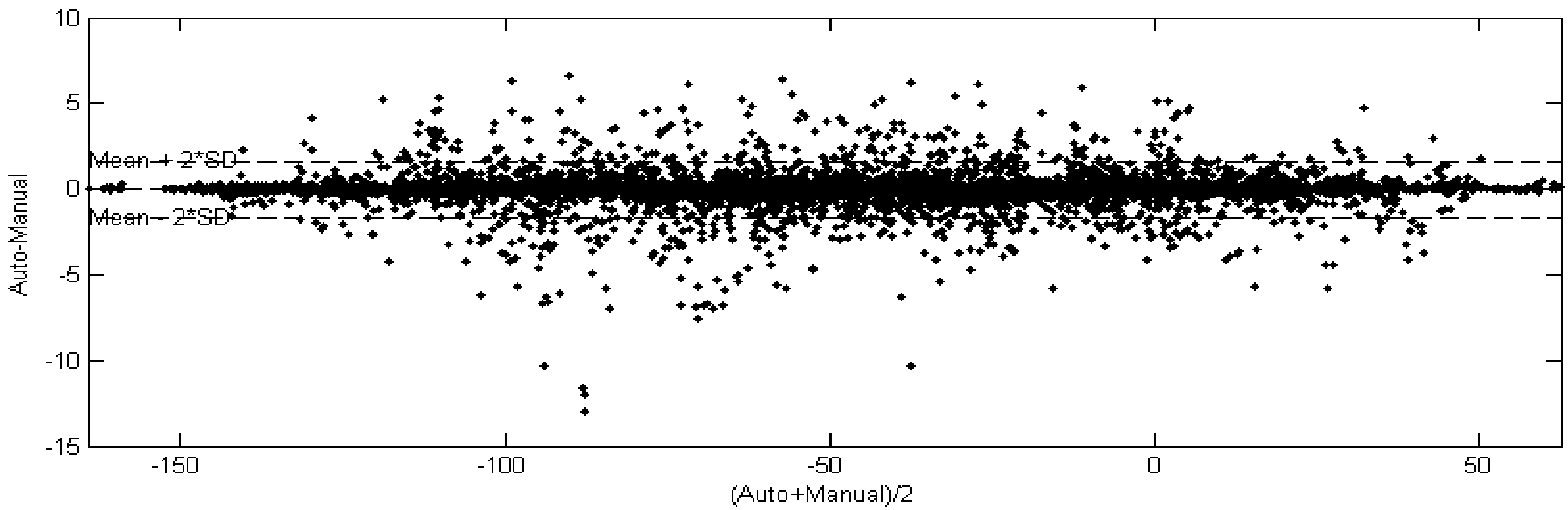

Figure 5.4 Bland-Altman plots showing the distance difference between the automatically tracked landmark and the manually placed landmark in the y direction, and the average of the automatically tracked landmark and the manually placed landmark.

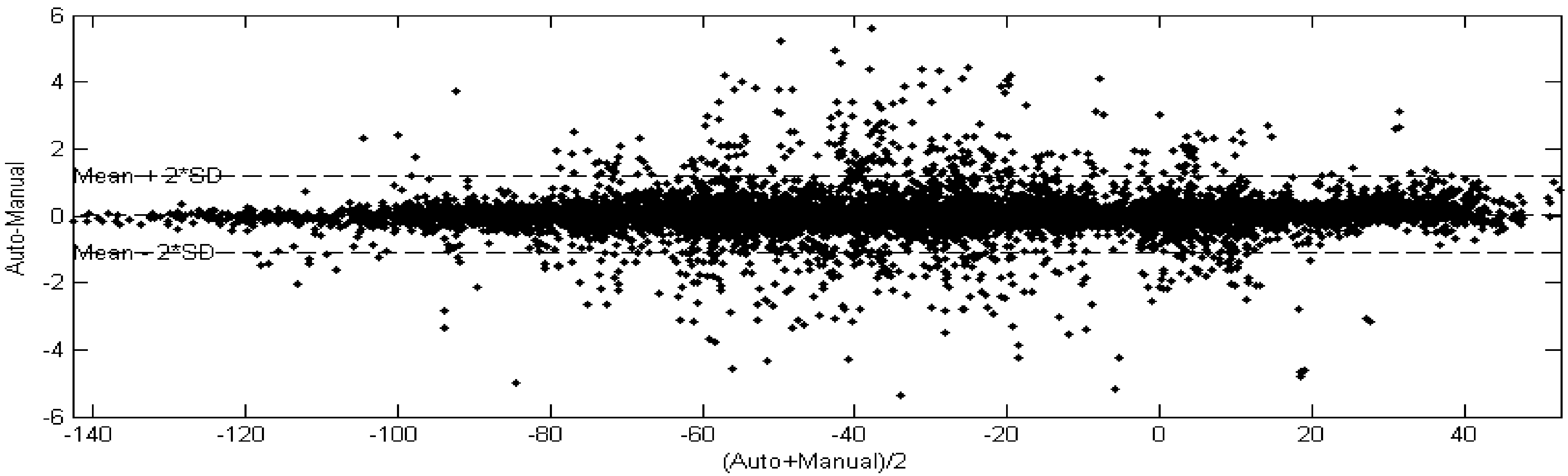

Figure 5.5 Bland-Altman plots showing the distance difference between the automatically tracked landmark and the manually placed landmark in the Z direction, and the average of the automatically tracked landmark and the manually placed landmark.

the male group for all the animations showed no statistical difference (P=0.068) at a significance level of 0.01. Figures 5.6 to 5.28 show the differences in distance (mm) between the manual and automatically tracked landmark, for each of the 23 landmarks, on a 3D plot (top left) and in the individual planes, for all expressions and genders combined. Ideally the difference should be zero but landmarks 12 and 13 are associated with a larger "envelope" of scatter (Figure 5.17 and Figure 5.18).

5.4 MAXIMAL SMILE

5.4.1 Differences in all landmarks for maximal smile animation of all frames in males and females separately

Table 5.5 shows the differences regarding the discrepancies in the x, y and z coordinates between manually digitised and the automatically tracked landmarks for females and males separately. All were less than 0.5 mm. As previously, there was a larger standard deviation of the y coordinates in both groups. The maximum difference between the two methods was similar in the x and z direction and greatest in the y direction. The overall mean distance between the manually digitised and automatically tracked landmarks was 0.69 ± 1.09mm for females and 0.82 ± 1.34mm for males.

5.4.2 The mean absolute distance between landmarks for maximal smile animation for all animations in the combined female and male groups

The maximum difference between the two methods was similar in the x and z direction (6.77mm and 5.62mm respectively) and greatest in the y direction (13.02mm), Table 5.6. The overall mean distance between the manually digitised and automatically tracked landmarks was 0.38 ± 0.64mm. A t-test comparing the female group to the male group for all the animations showed a statistical difference (P=0.0016) at a significance level of 0.01.

The mean distance between the manual and automatically tracked landmarks is shown in Figure 5.29 and 5.30. The majority of the differences between the landmarks are less than 1.0mm, except landmarks 12 and 13 which are between 1.5mm and 2.0mm. This is similar for females and males.

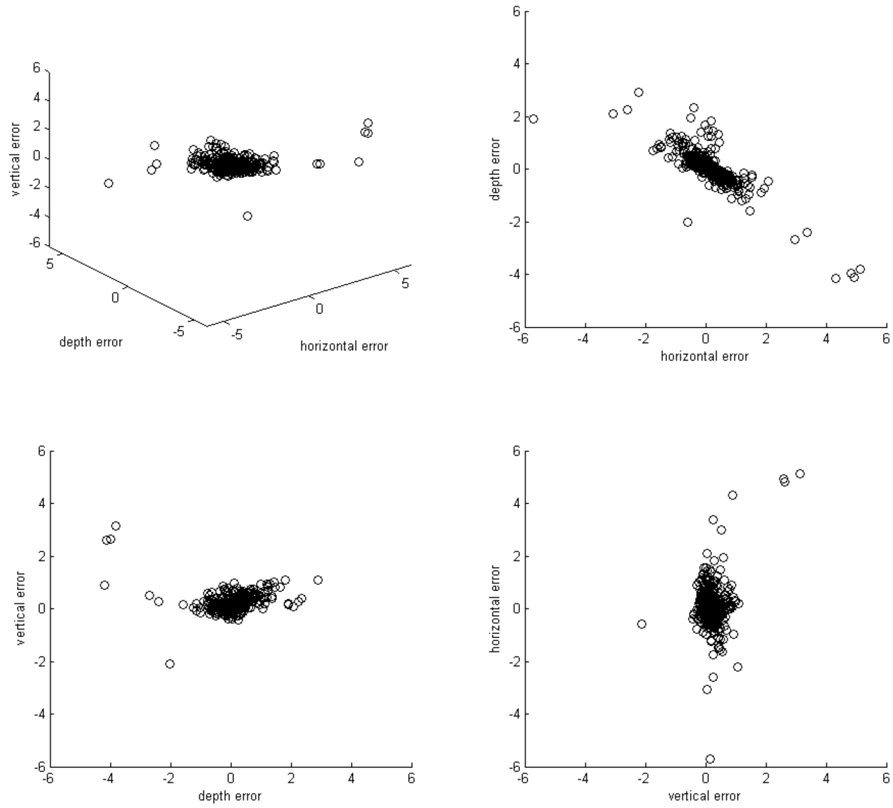

Figure 5.6 Plots showing the differences in distance (mm) between the manual and automatically tracked landmark, for Landmark number 1 on a 3D plot (top left) and in the individual planes, for all expressions.

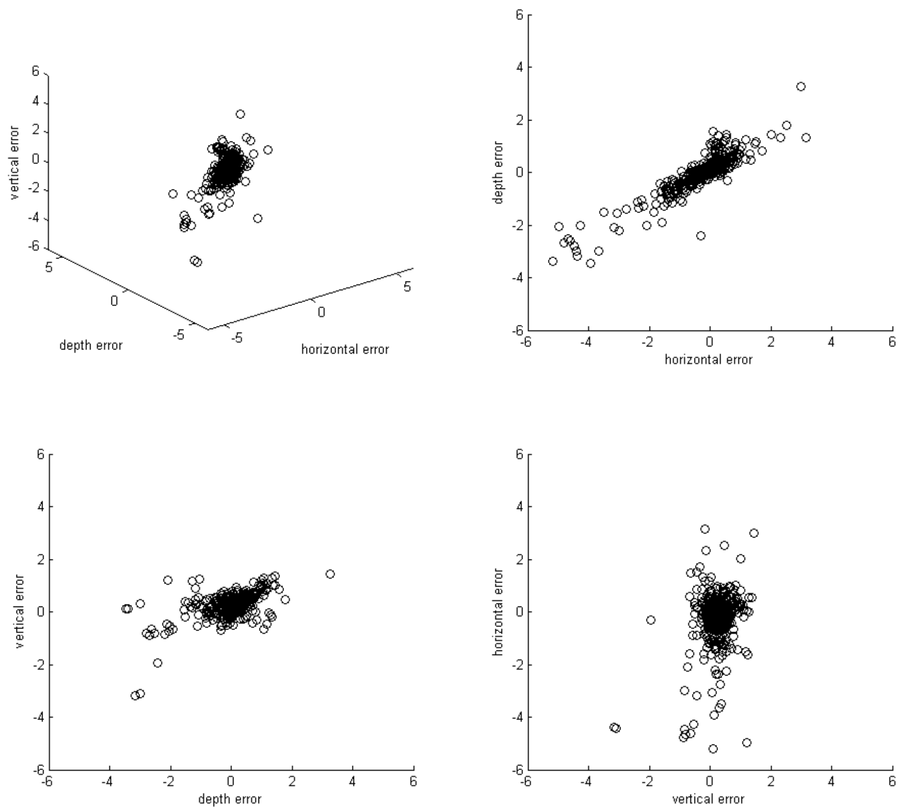

Figure 5.7 Plots showing the differences in distance (mm) between the manual and automatically tracked landmark, for Landmark number 2 on a 3D plot (top left) and in the individual planes, for all expressions.

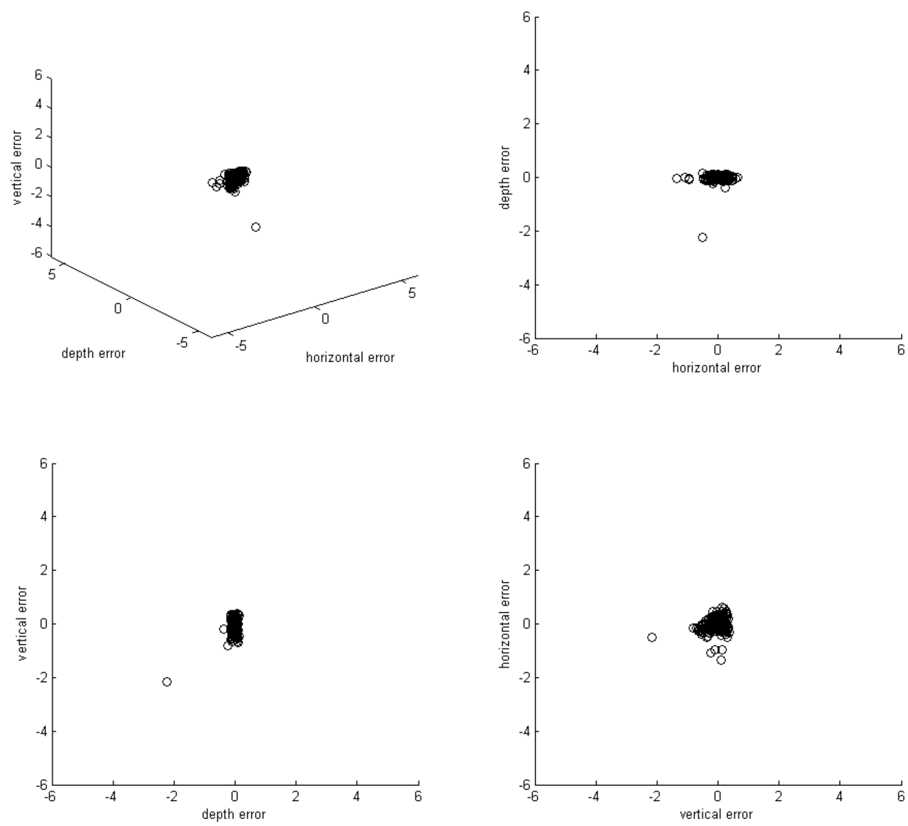

Figure 5.8 Plots showing the differences in distance (mm) between the manual and automatically tracked landmark, for Landmark number 3 on a 3D plot (top left) and in the individual planes, for all expressions.

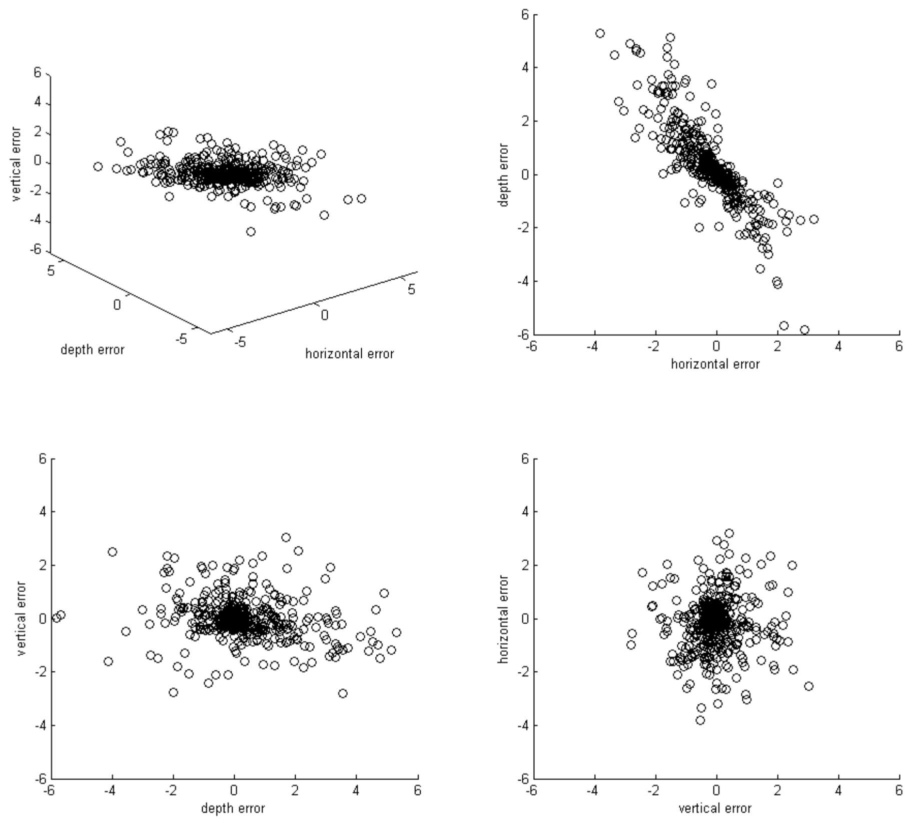

Figure 5.9 Plots showing the differences in distance (mm) between the manual and automatically tracked landmark, for Landmark number 4 on a 3D plot (top left) and in the individual planes, for all expressions.

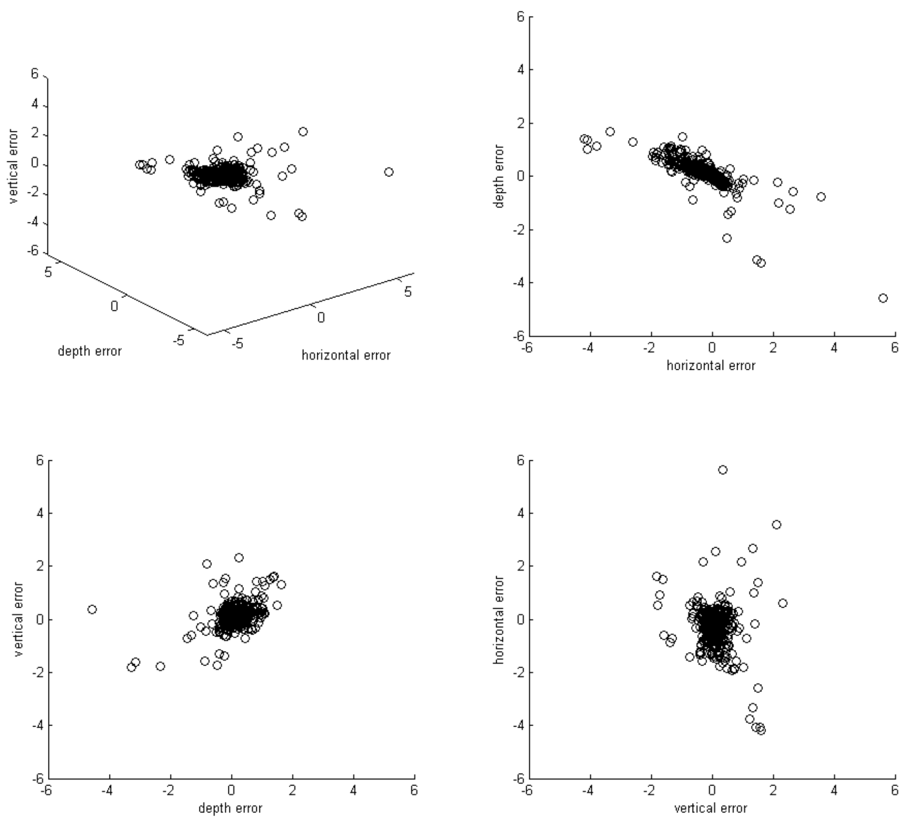

Figure 5.10 Plots showing the differences in distance (mm) between the manual and automatically tracked landmark, for Landmark number 5 on a 3D plot (top left) and in the individual planes, for all expressions.

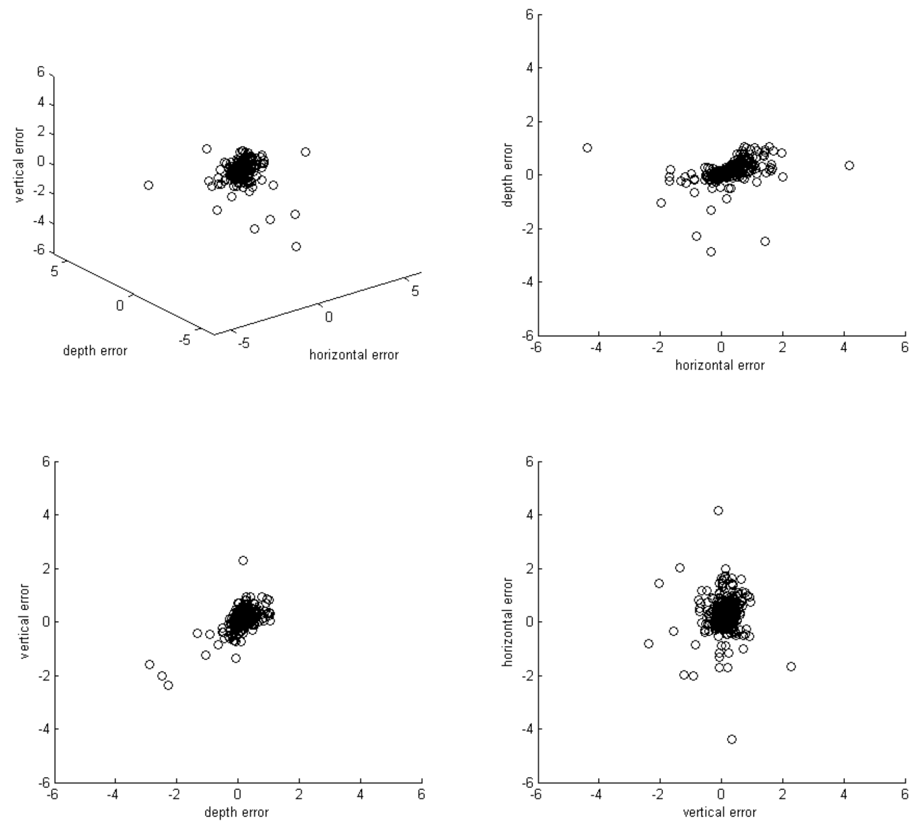

Figure 5.11 Plots showing the differences in distance (mm) between the manual and automatically tracked landmark, for Landmark number 6 on a 3D plot (top left) and in the individual planes, for all expressions.

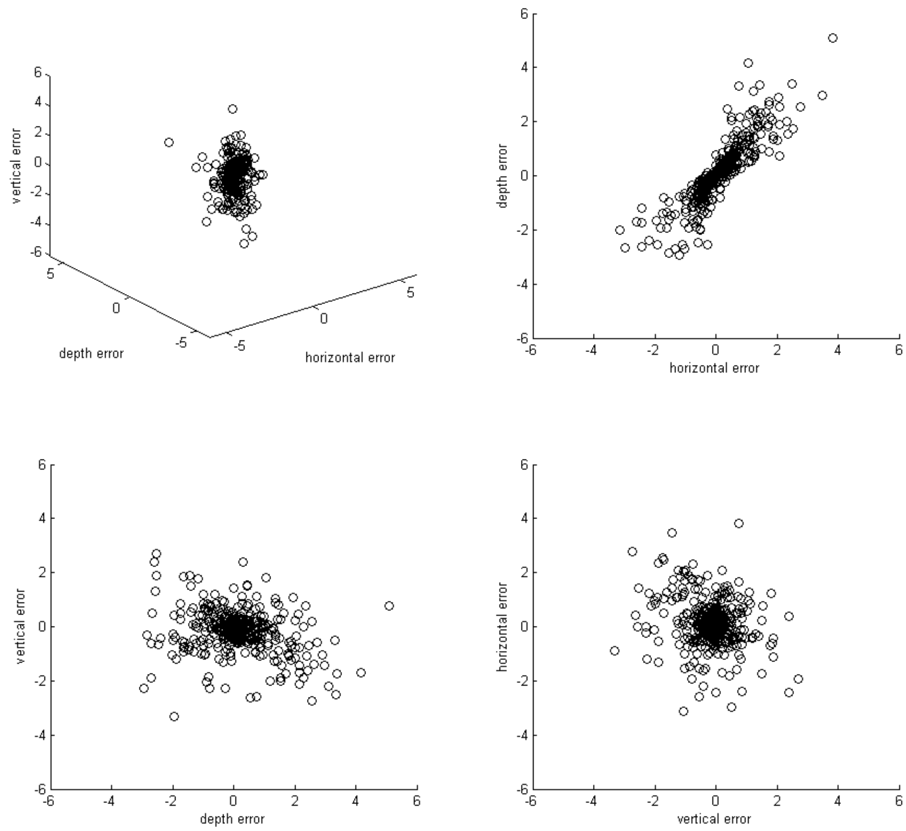

Figure 5.12 Plots showing the differences in distance (mm) between the manual and automatically tracked landmark, for Landmark number 7 on a 3D plot (top left) and in the individual planes, for all expressions.

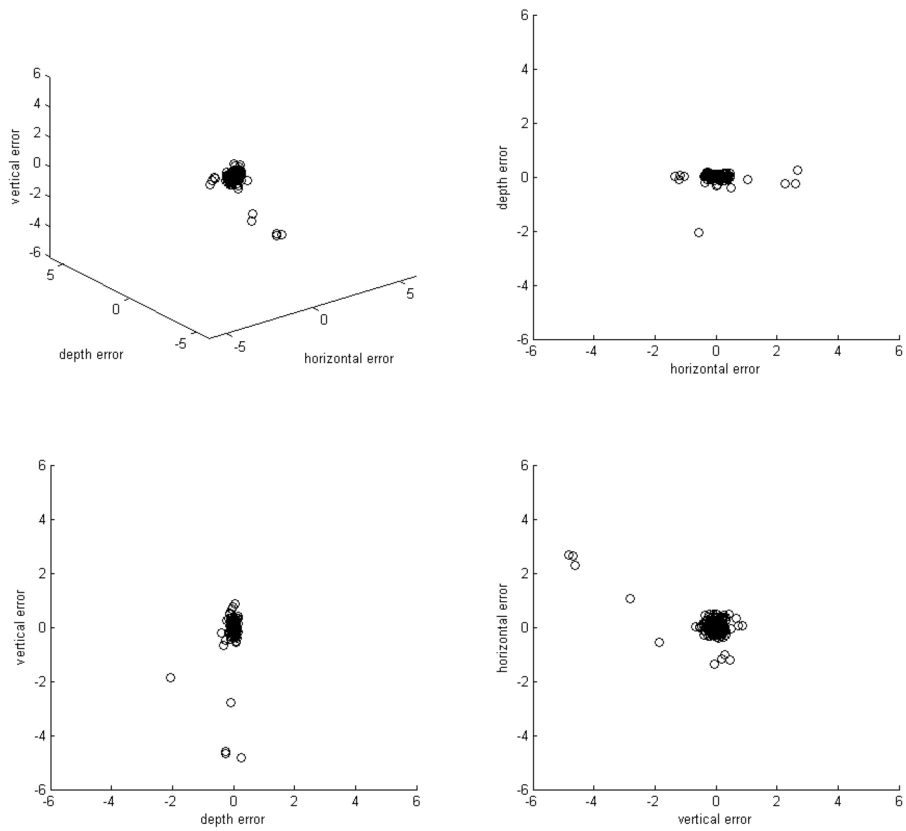

Figure 5.13 Plots showing the differences in distance (mm) between the manual and automatically tracked landmark, for Landmark number 8 on a 3D plot (top left) and in the individual planes, for all expressions.

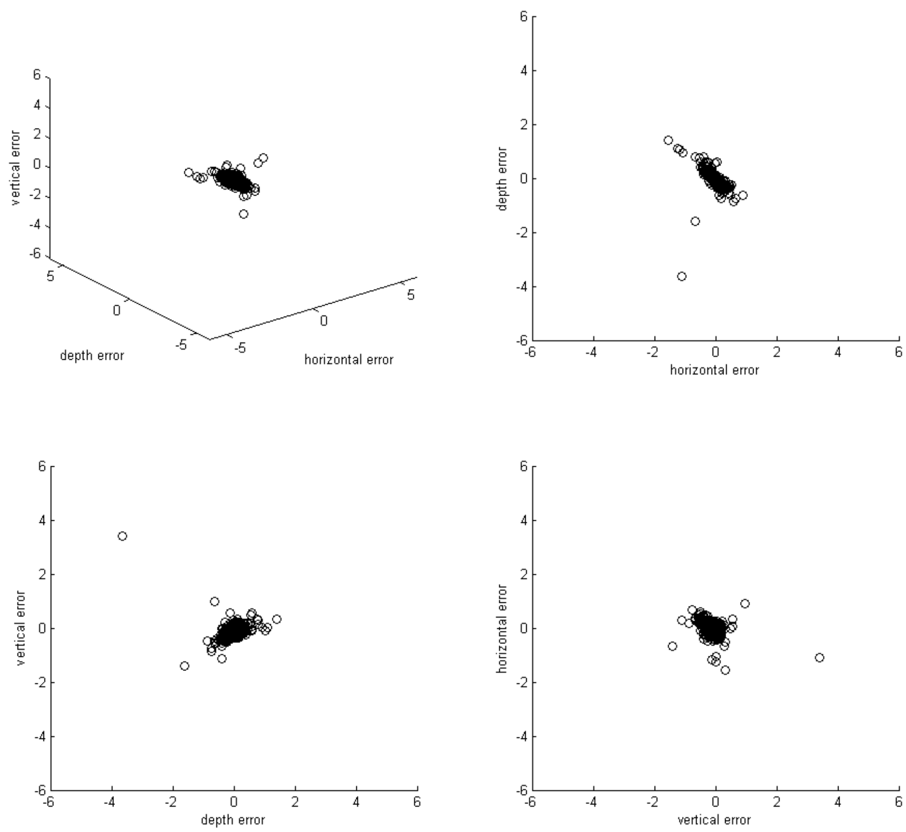

Figure 5.14 Plots showing the differences in distance (mm) between the manual and automatically tracked landmark, for Landmark number 9 on a 3D plot (top left) and in the individual planes, for all expressions.

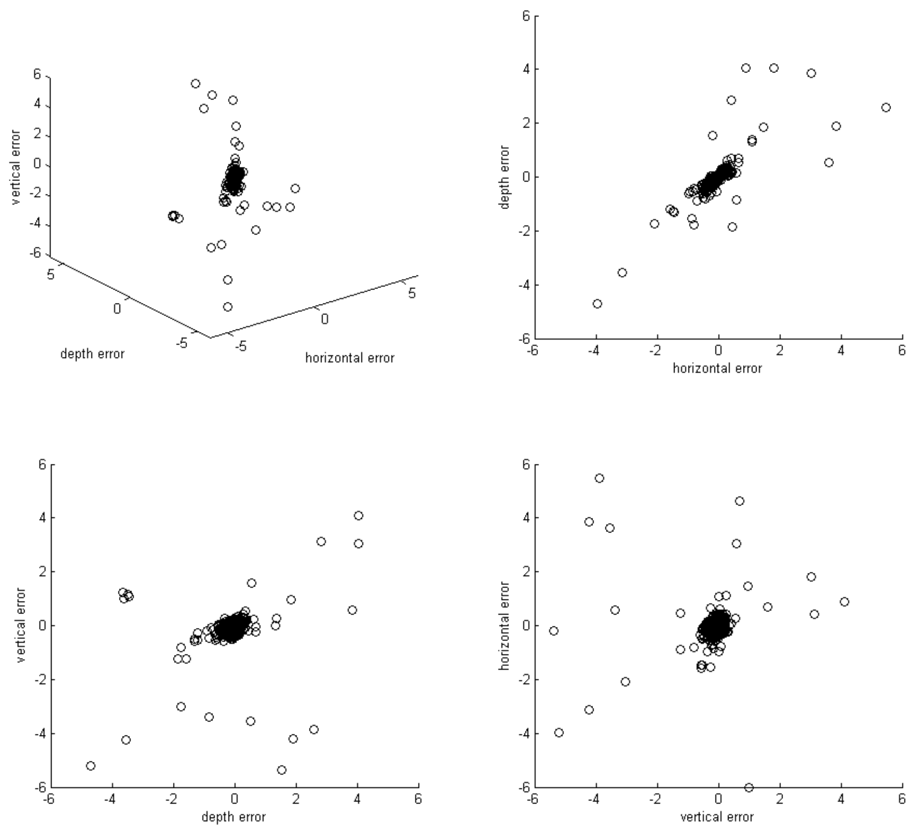

Figure 5.15 Plots showing the differences in distance (mm) between the manual and automatically tracked landmark, for Landmark number 10 on a 3D plot (top left) and in the individual planes, for all expressions.

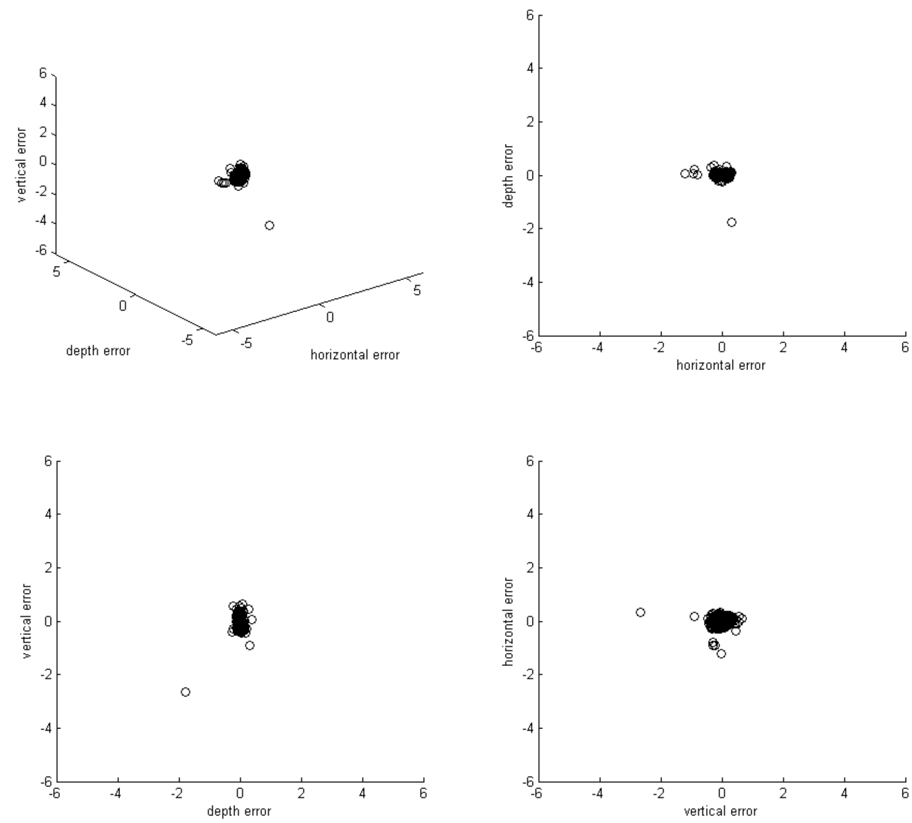

Figure 5.16 Plots showing the differences in distance (mm) between the manual and automatically tracked landmark, for Landmark number 11 on a 3D plot (top left) and in the individual planes, for all expressions.

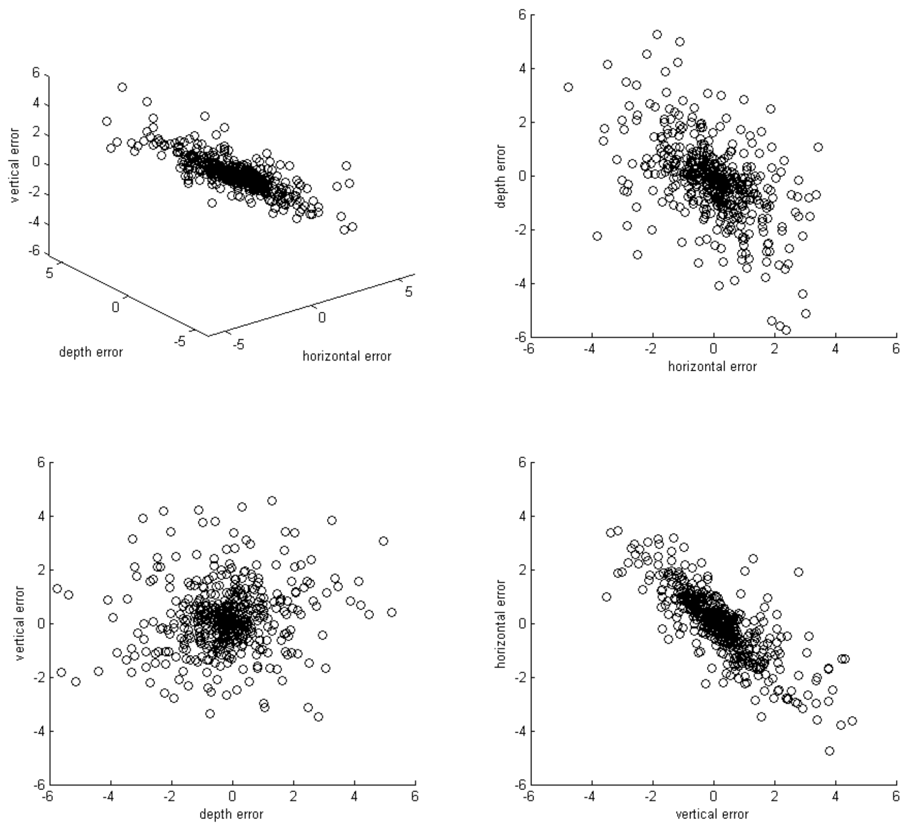

Figure 5.17 Plots showing the differences in distance (mm) between the manual and automatically tracked landmark, for Landmark number 12 on a 3D plot (top left) and in the individual planes, for all expressions.

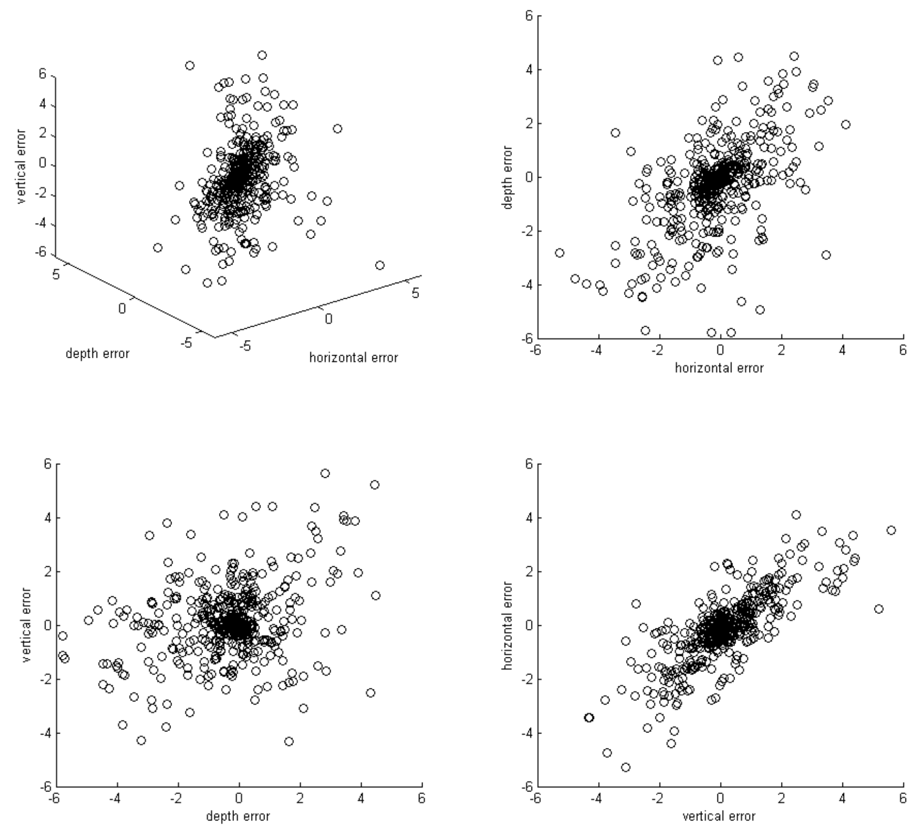

Figure 5.18 Plots showing the differences in distance (mm) between the manual and automatically tracked landmark, for Landmark number 13 on a 3D plot (top left) and in the individual planes, for all expressions.

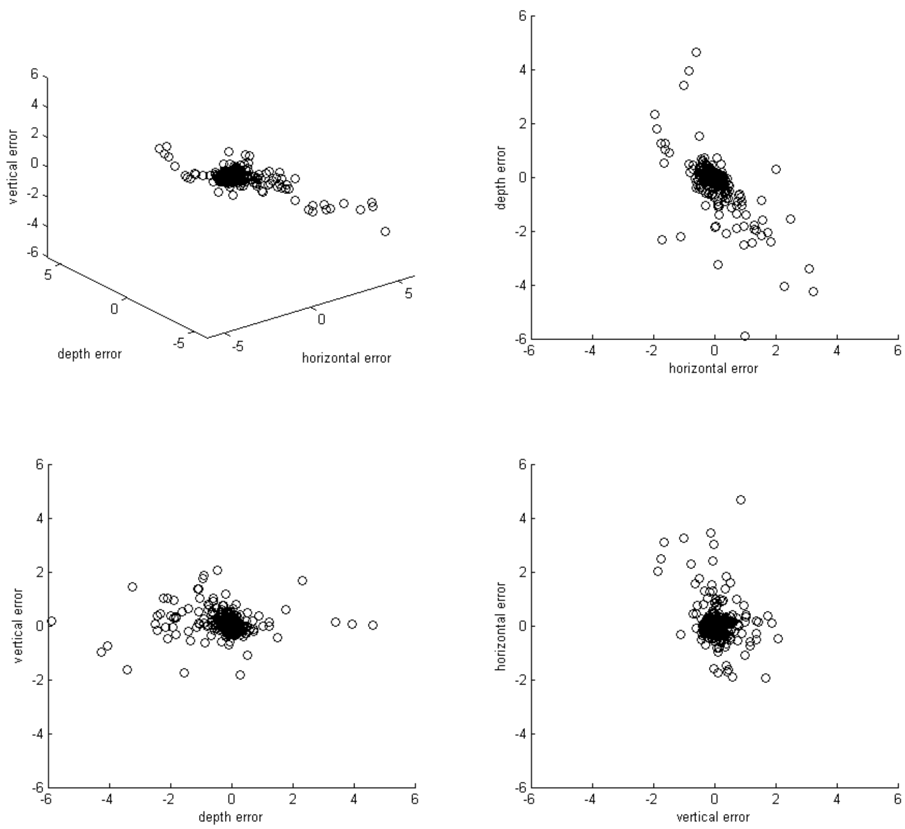

Figure 5.19 Plots showing the differences in distance (mm) between the manual and automatically tracked landmark, for Landmark number 14 on a 3D plot (top left) and in the individual planes, for all expressions.

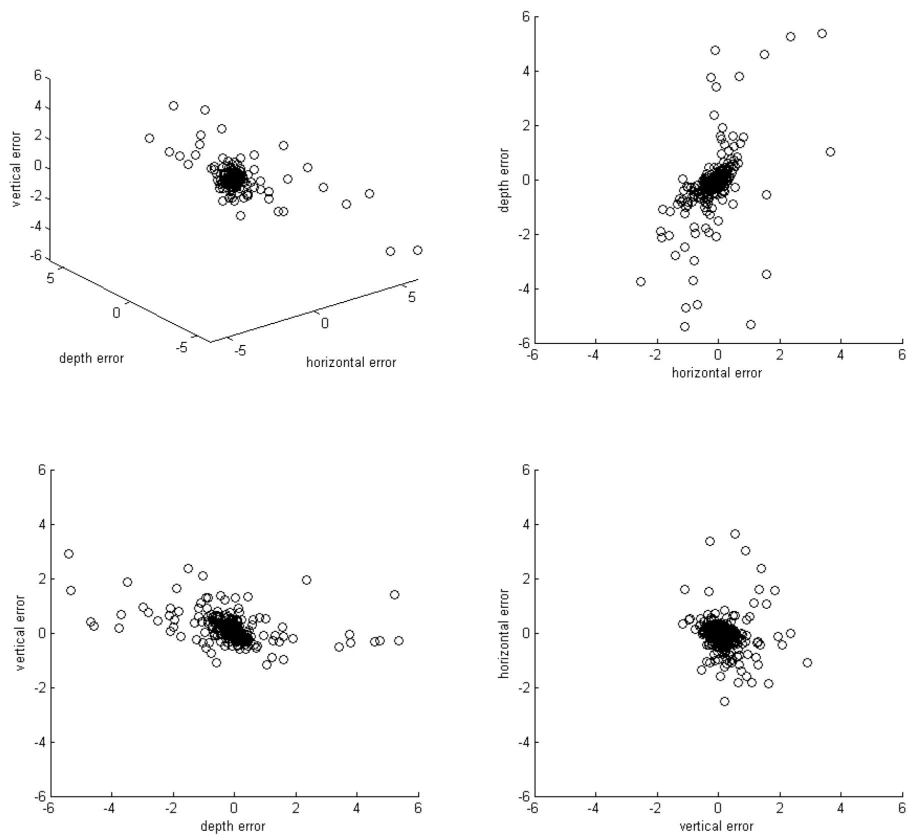

Figure 5.20 Plots showing the differences in distance (mm) between the manual and automatically tracked landmark, for Landmark number 15 on a 3D plot (top left) and in the individual planes, for all expressions.

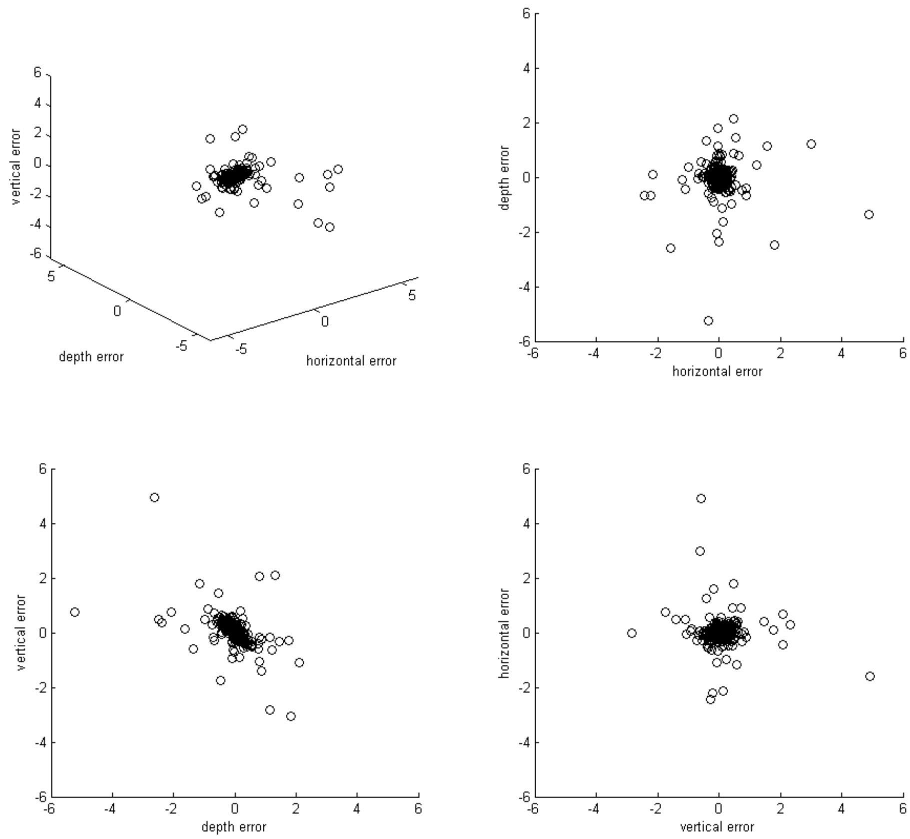

Figure 5.21 Plots showing the differences in distance (mm) between the manual and automatically tracked landmark, for Landmark number 16 on a 3D plot (top left) and in the individual planes, for all expressions.

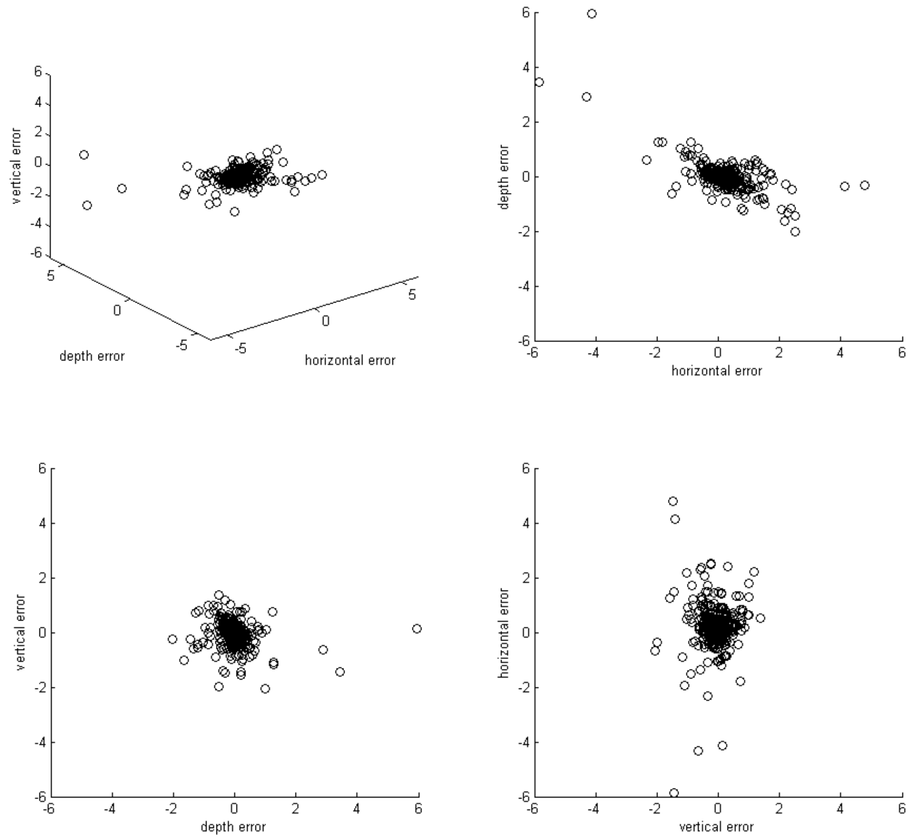

Figure 5.22 Plots showing the differences in distance (mm) between the manual and automatically tracked landmark, for Landmark number 17 on a 3D plot (top left) and in the individual planes, for all expressions.

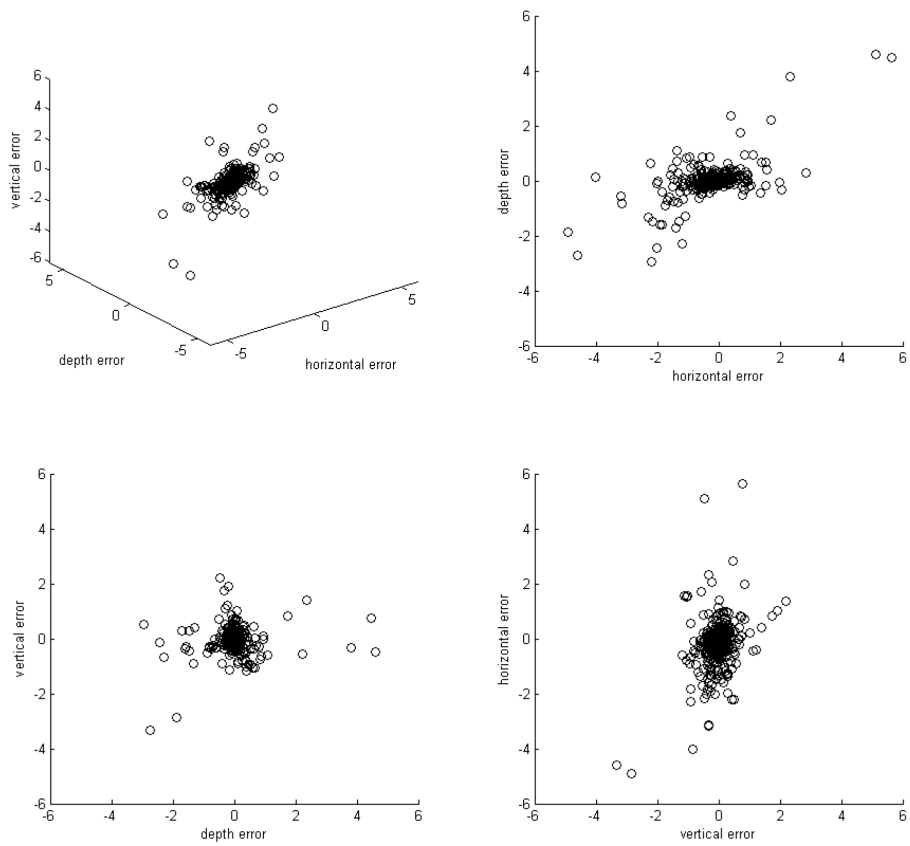

Figure 5.23 Plots showing the differences in distance (mm) between the manual and automatically tracked landmark, for Landmark number 18 on a 3D plot (top left) and in the individual planes, for all expressions.

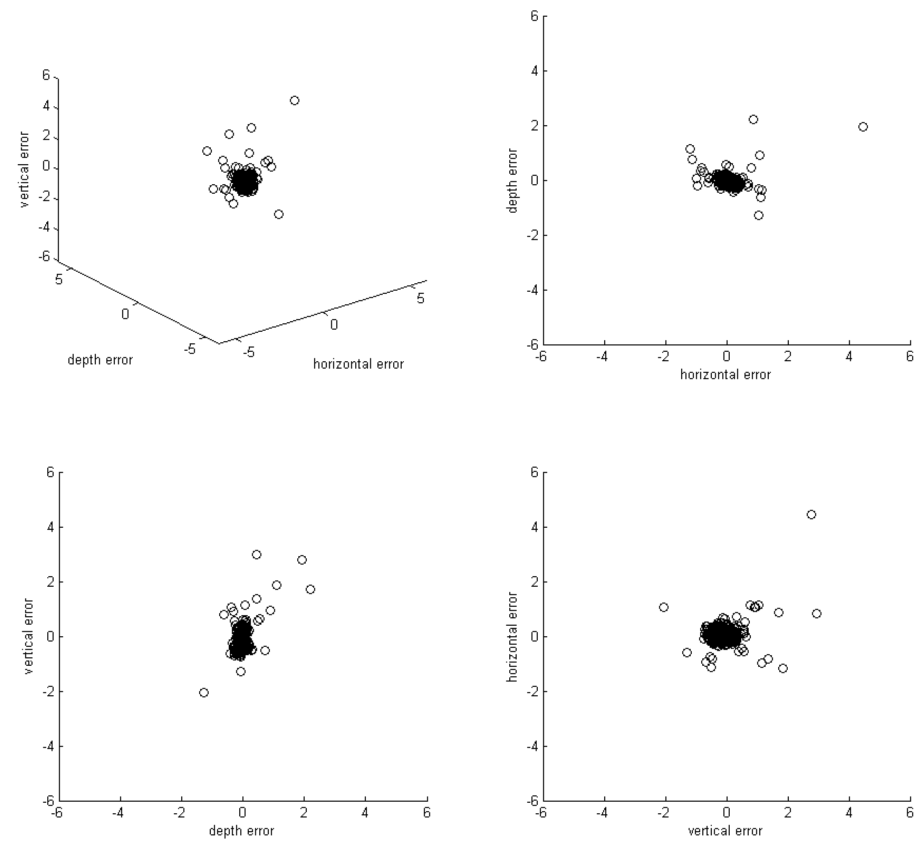

Figure 5.24 Plots showing the differences in distance (mm) between the manual and automatically tracked landmark, for Landmark number 19 on a 3D plot (top left) and in the individual planes, for all expressions.

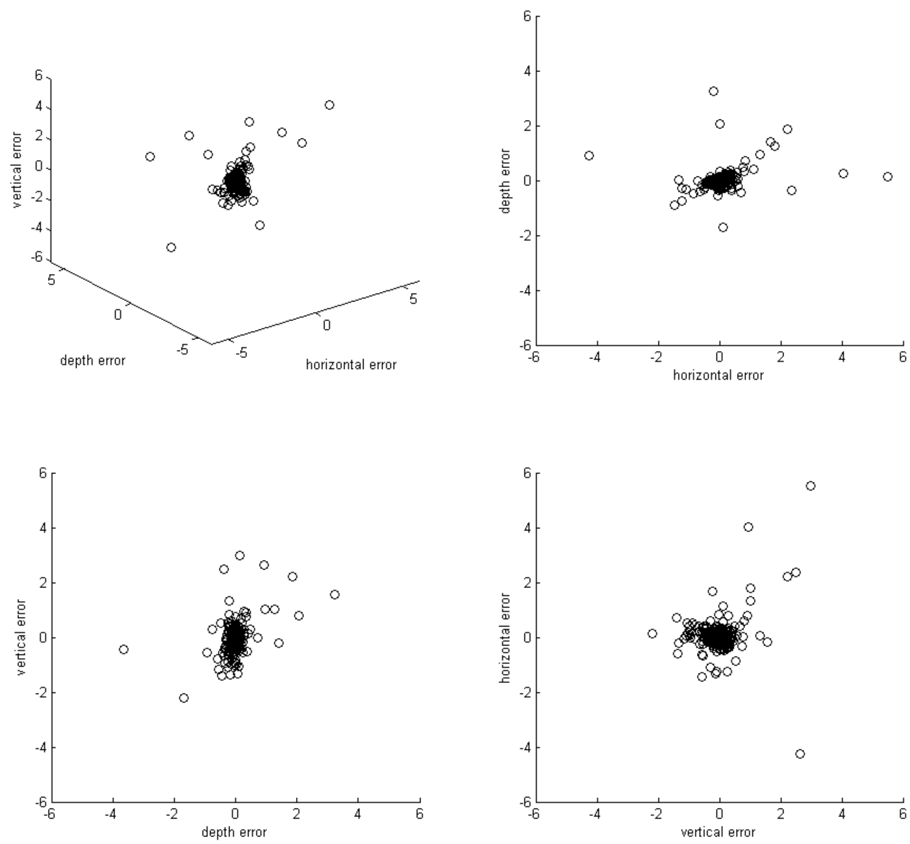

Figure 5.25 Plots showing the differences in distance (mm) between the manual and automatically tracked landmark, for Landmark number 20 on a 3D plot (top left) and in the individual planes, for all expressions.

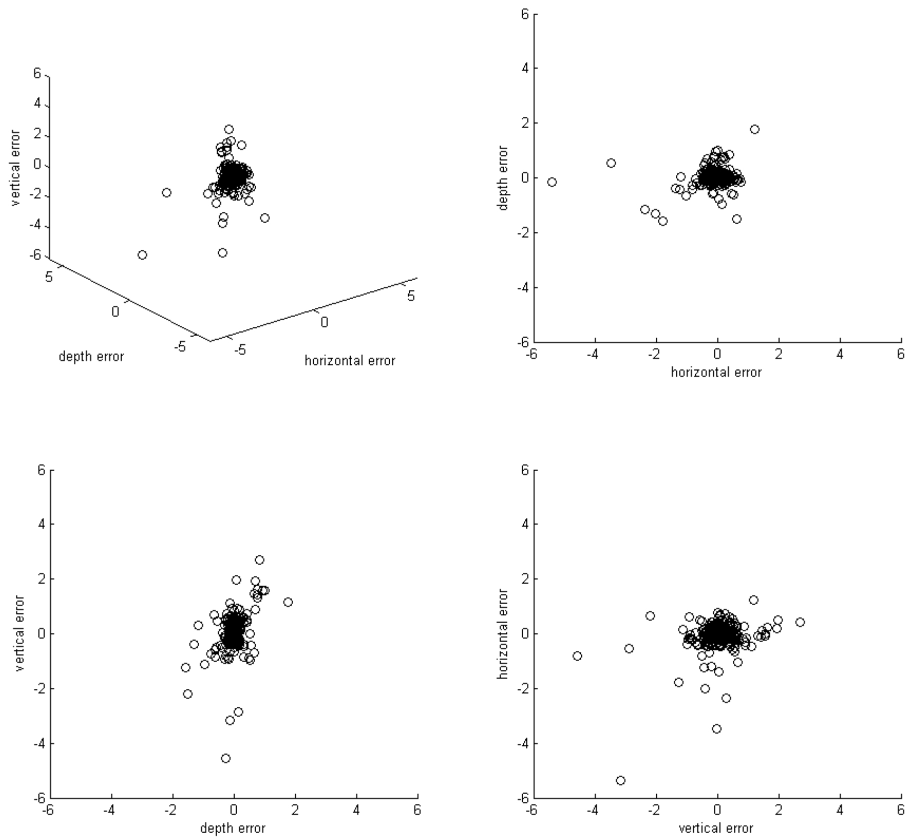

Figure 5.26 Plots showing the differences in distance (mm) between the manual and automatically tracked landmark, for Landmark number 21 on a 3D plot (top left) and in the individual planes, for all expressions.

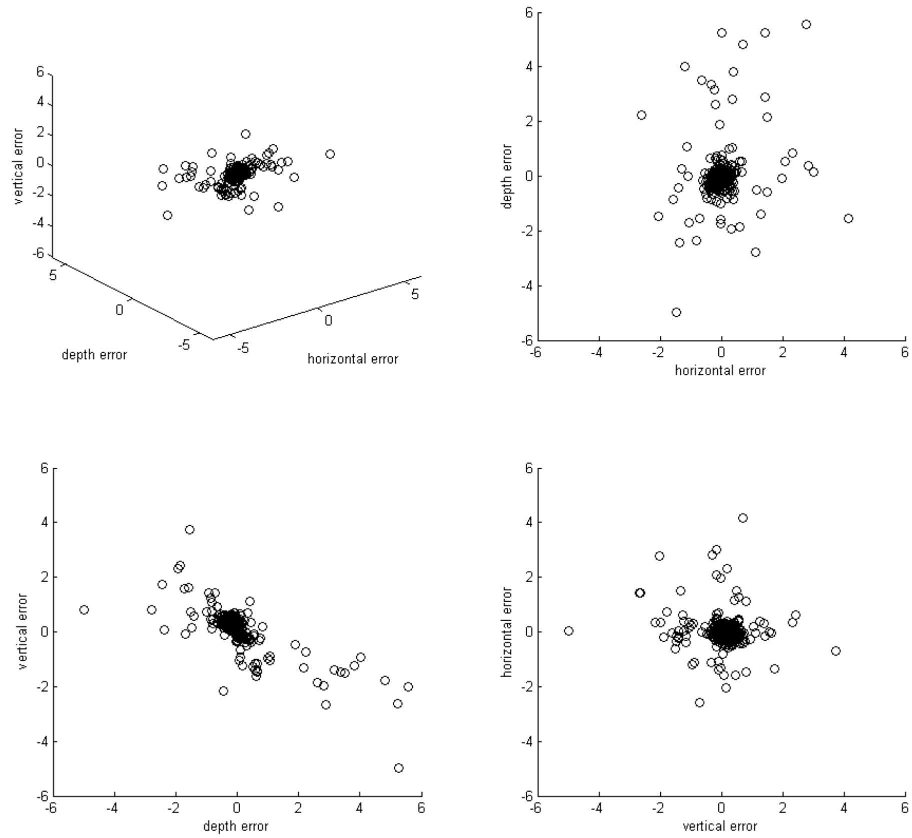

Figure 5.27 Plots showing the differences in distance (mm) between the manual and automatically tracked landmark, for Landmark number 22 on a 3D plot (top left) and in the individual planes, for all expressions.

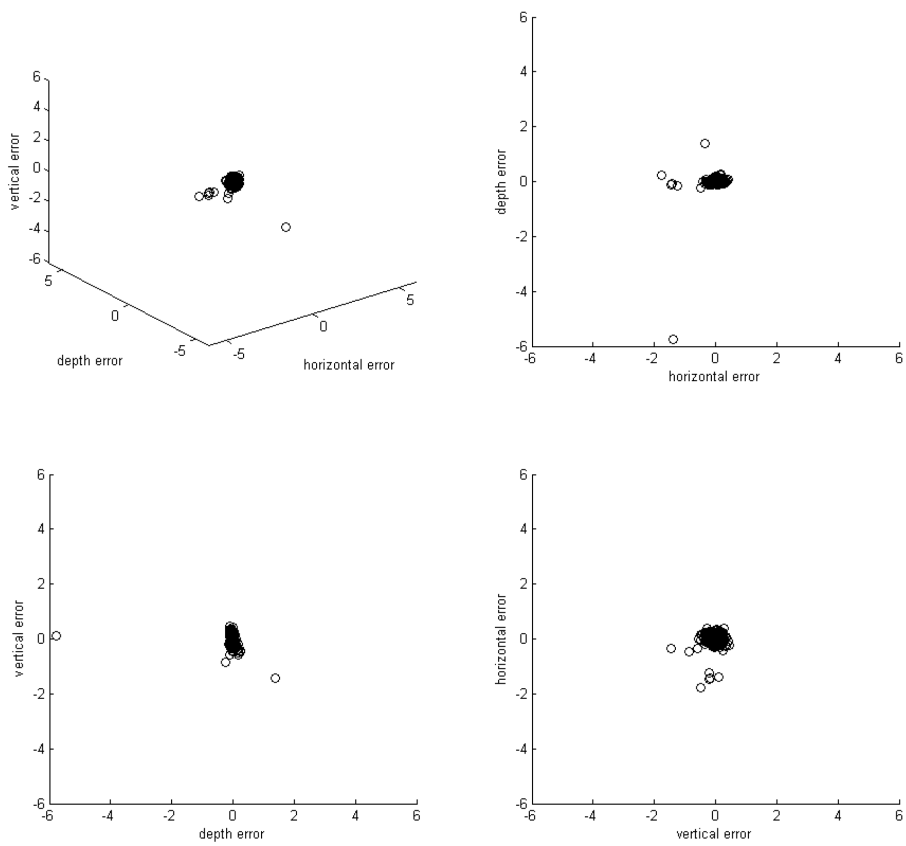

Figure 5.28 Plots showing the differences in distance (mm) between the manual and automatically tracked landmark, for Landmark number 23 on a 3D plot (top left) and in the individual planes, for all expressions.

	Mean difference(mm)	SD (mm)	Median	Range	
				Min	Max
Females					
X direction	0.37	0.64	0.14	0.00	6.77
Y direction	0.35	0.77	0.08	0.00	11.98
Z direction	0.32	0.54	0.15	0.00	5.62
Euclidian distance	0.69	1.09			
Males					
X direction	0.39	0.65	0.17	0.00	5.62
Y direction	0.48	1.09	0.10	0.00	13.02
Z direction	0.34	0.59	0.15	0.00	5.21
Euclidian distance	0.82	1.34			

Table 5.5 Differences in all landmarks for maximal smile animation of all frames in females and males separately.

	x direction	y direction	z direction	Euclidian distance
Mean (mm)	0.38	0.42	0.33	0.38
Standard Deviation (mm)	0.64	0.95	0.57	0.64
Median (mm)	0.15	0.09	0.15	0.15
Range				
Minimum (mm)	0.00	0.00	0.00	0.00
Maximum (mm)	6.77	13.02	5.62	6.77

Table 5.6 Mean discrepancy between landmarks for maximal smile animation for all animations in the combined female and male groups

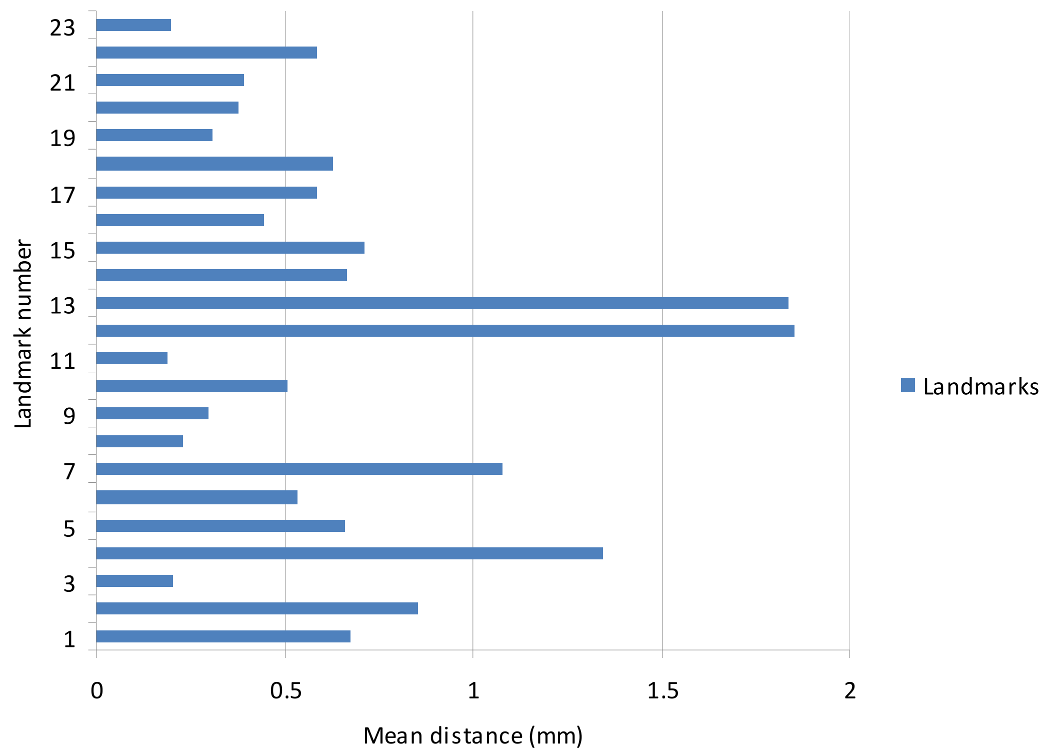

Figure 5.29 The mean distance between landmarks for maximal smile animation between the automatically tracked and manually located landmarks in the female group.

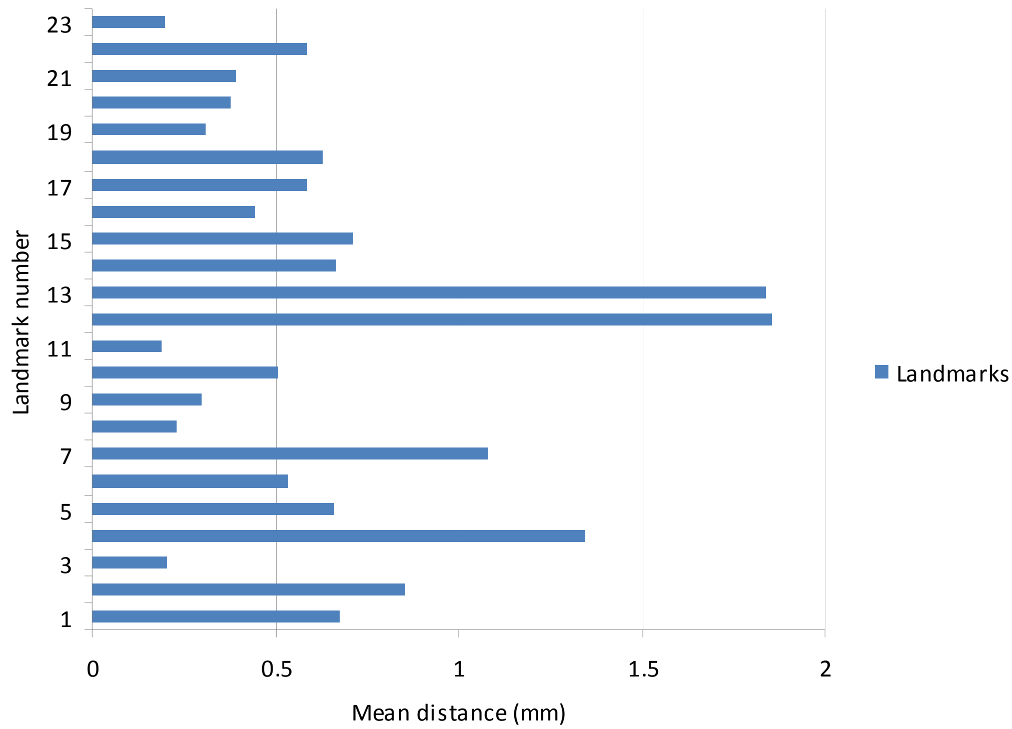

Figure 5.30 The mean distance between landmarks for maximal smile animation between the automatically tracked and manually located landmarks in the male group.

5.5 LIP PURSE

5.5.1 Differences in all landmarks for lip purse animation of all frames in males and females separately

Table 5.7 shows the differences regarding the discrepancies in the x, y and z coordinates between manually digitised and the automatically tracked landmarks for females and males separately. All were less than 0.4 mm. As previously, there was a slightly larger standard deviation of the y coordinates. The maximum difference between the two methods was similar in the x, y and z direction (6.24mm, 6.64mm and 5.36mm respectively) The overall mean distance between the manually digitised and automatically tracked landmarks was 0.64 ± 0.93mm for females and 0.58 ± 0.88mm for males.

5.5.2 The mean discrepancy between landmarks for lip purse animation for all animations in the combined female and male groups

The overall mean distance between the manually digitised and automatically tracked landmarks was 0.61 ± 0.89mm, Table 5.8. A t-test comparing the female group to the male group for all the animations showed no statistical difference (P=0.029) at a significance level of 0.01.

The mean distance between the manual and automatically tracked landmarks is shown in Figure 5.31 and 5.32. The majority of difference between the landmarks is less than 1.0mm apart from landmarks 12 and 13 which are between 1.5mm and 2.0mm. This is similar for females and males.

5.6 CHEEK PUFF

5.6.1 Differences in all landmarks for cheek puff animation of all frames in males and females separately

Table 5.9 shows the differences in the x, y and z coordinates between the manually digitised and the automatically tracked landmarks for females and males separately. All were less than 0.4 mm. The

	Mean difference(mm)	SD (mm)	Median	Range	
				Min	Max
Females					
X direction	0.37	0.62	0.15	0.00	6.24
Y direction	0.32	0.64	0.08	0.00	6.64
Z direction	0.28	0.41	0.14	0.00	4.30
Euclidian distance	0.64	0.93			
Males					
X direction	0.31	0.50	0.15	0.00	5.86
Y direction	0.29	0.59	0.08	0.00	5.55
Z direction	0.28	0.47	0.14	0.00	5.36
Euclidian distance	0.58	0.86			

Table 5.7 Differences in all landmarks for lip purse animation of all frames in females and males separately.

	x direction	y direction	z direction	Euclidian distance
Mean (mm)	0.34	0.30	0.28	0.61
Standard Deviation (mm)	0.56	0.61	0.44	0.89
Median (mm)	0.15	0.08	0.14	0.29
Range				
Minimum (mm)	0.00	0.00	0.00	0.00
Maximum (mm)	6.24	6.64	5.36	7.33

Table 5.8 Mean discrepancy between landmarks for lip purse animation for all animations in the combined female and male groups.

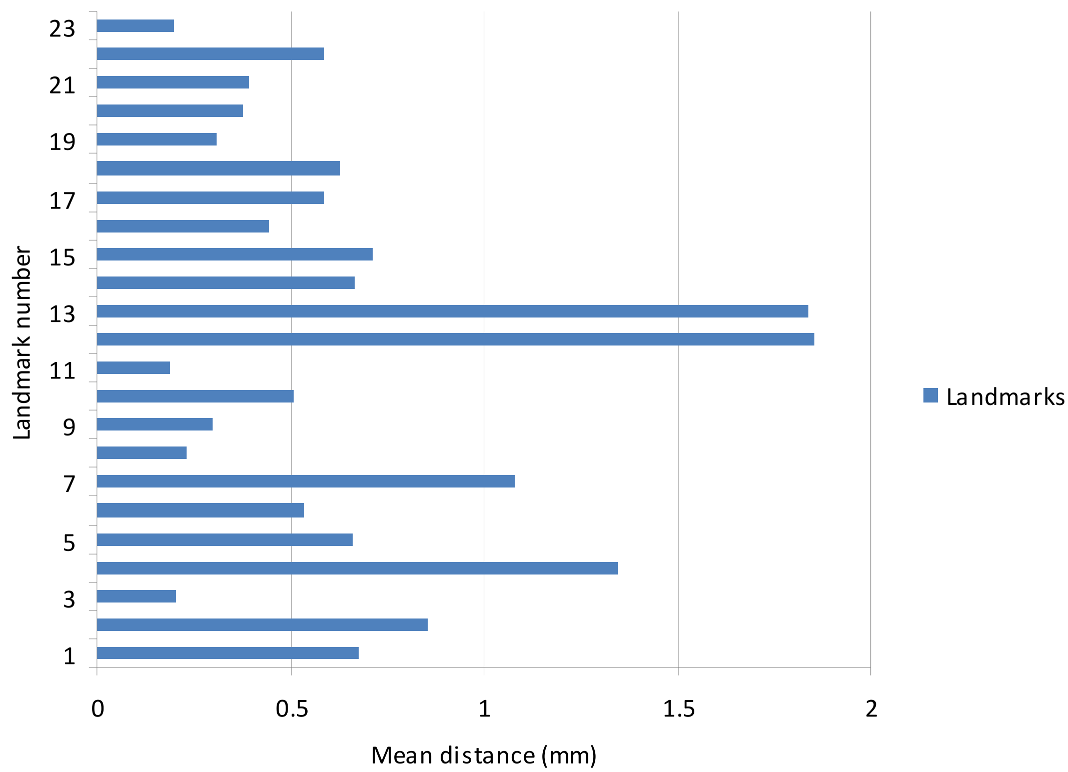

Figure 5.31 The mean distance between landmarks for lip purse animation between the automatically tracked and manually located landmarks in the female group.

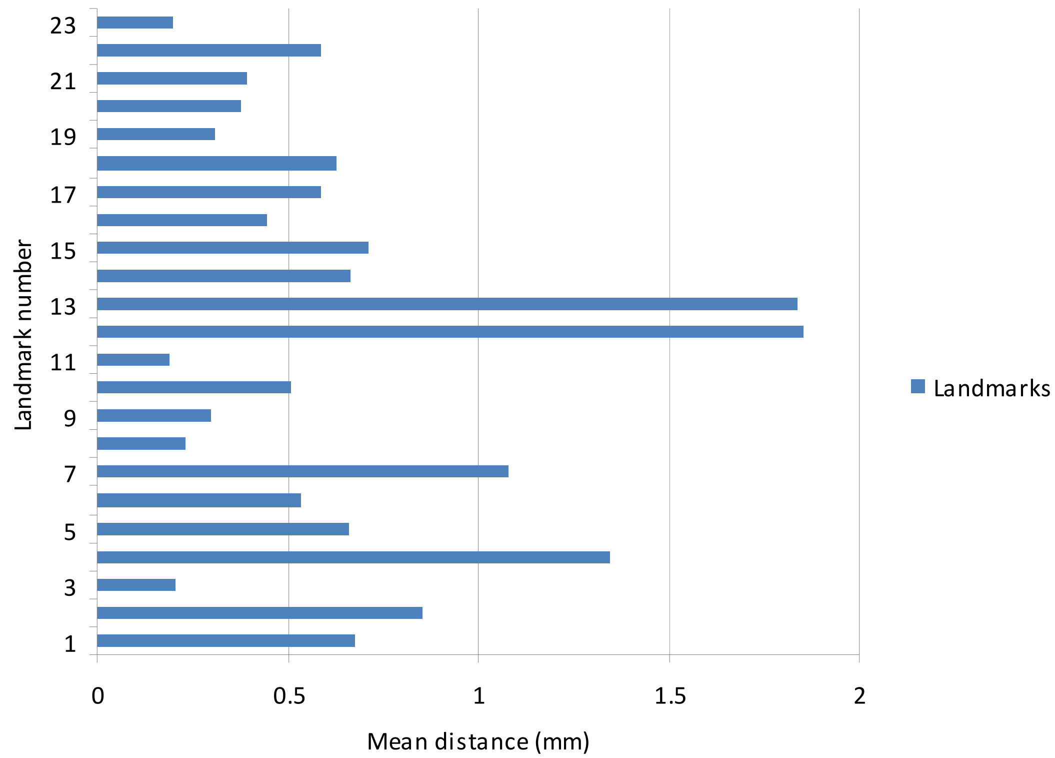

Figure 5.32 The mean distance between landmarks for lip purse animation between the automatically tracked and manually located landmarks in the male group.

	Mean difference(mm)	SD (mm)	Median	Range	
				Min	Max
Females					
X direction	0.32	0.55	0.12	0.00	6.51
Y direction	0.29	0.68	0.07	0.00	10.34
Z direction	0.28	0.43	0.14	0.00	4.22
Euclidian distance	0.59	0.93			
Males					
X direction	0.35	0.59	0.15	0.00	5.50
Y direction	0.30	0.59	0.09	0.00	6.74
Z direction	0.30	0.46	0.16	0.00	4.99
Euclidian distance	0.63	0.90			

Table 5.9 Differences in all landmarks for cheek puff animation of all frames in females and males separately.

maximum difference between the two methods was similar in the x, y and z direction (6.51mm, 10.34mm and 4.99mm respectively) The overall mean distance between the manually digitised and automatically tracked landmarks was 0.59 ± 0.93mm for females and 0.63 ± 0.90mm for males.

5.6.2 The mean discrepancy between landmarks for cheek puff animation for all animations in the combined female and male groups

The overall mean distance between the manually digitised and automatically tracked landmarks was 0.61 ± 0.92mm, Table 5.10. A t-test comparing the female group to the male group for all the animations showed no statistical difference (P=0.148) at a significance level of 0.01.

The mean distance between the manual and automatically tracked landmarks is shown in Figure 5.33 and 5.34. Again, the majority of difference between the landmarks is less than 1.0mm except for landmarks 12 and 13 which are between 1.5mm and 2.0mm. This is similar for females and males.

5.7 Summary

In summary, the overall discrepancies between the coordinates of most of manually located and automatically tracked landmarks during facial animations were within one millimetre with a high correlation coefficient between the two methods. Landmarks 12 and 13, alar cartilage right and alar cartilage left, were associated with the largest discrepancies. Apart from maximum smile there were no statistical significant differences in the discrepancies of automatic tracking of facial landmarks between males and females. The operator's digitisation errors of the pre-labelled facial landmarks were negligible.

	x direction	y direction	z direction	Euclidian distance
Mean (mm)	0.33	0.30	0.29	0.61
Standard Deviation (mm)	0.57	0.63	0.45	0.92
Median (mm)	0.14	0.08	0.15	0.29
Range				
Minimum (mm)	0.00	0.00	0.00	0.00
Maximum (mm)	6.51	10.34	4.99	10.41

Table 5.10 Mean discrepancy between landmarks for cheek puff animation for all animations in the combined female and male groups.

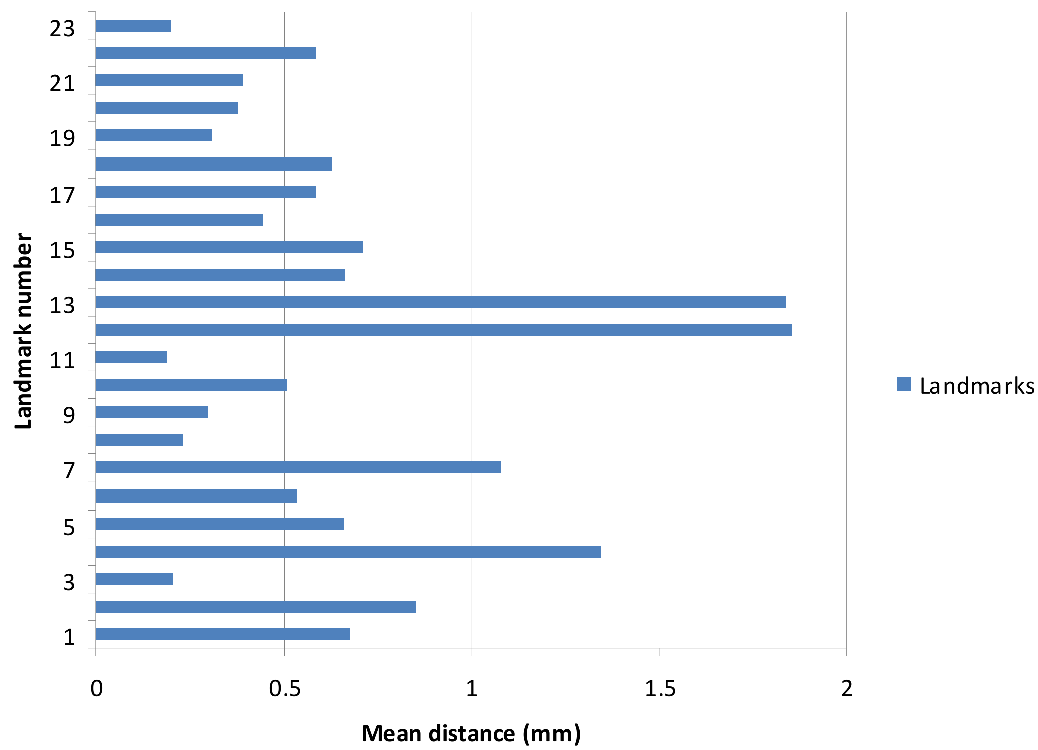

Figure 5.33 The mean distance between landmarks for cheek puff animation between the automatically tracked and manually located landmarks in the female group.

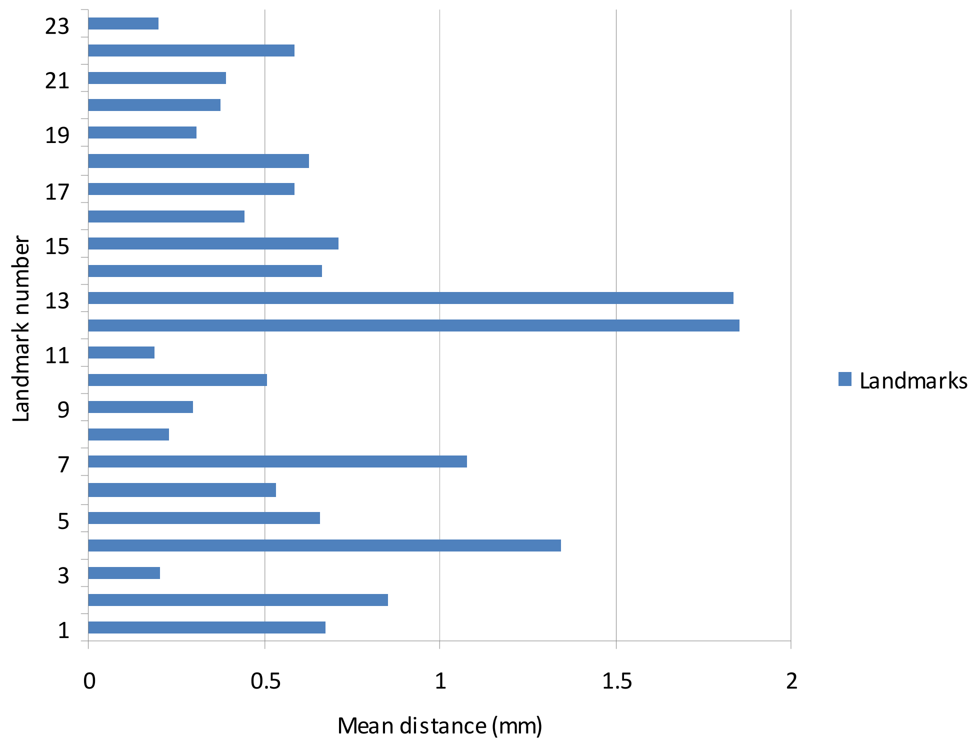

Figure 5.34 The mean distance between landmarks for cheek puff animation between the automatically tracked and manually located landmarks in the male group.

Chapter Six

Discussion

6 Discussion

The evaluation of facial animation is crucial for the diagnosis of cranio-facial anomalies that cause facial nerve damage. Quantifying the functional deficient would facilitate planning, surgical management and measuring surgical outcome. This applies to the diagnosis and management of patients with cleft lip and palate, neurological deficient and malignant tumours which affect the movement of facial muscles.

Despite the fact that the correction of facial deformities is three dimensional in nature, diagnosis and prediction planning is usually carried out using 2D computer programs which combines the skeletal and soft tissue components of the face. Facial morphology is usually captured using a lateral cephalometric radiograph and profile photograph. These methods do not address facial depth and shape and do not allow the accurate recording and analysis of facial animations. This requires 3D capture facilities and the application of sophisticated programmes for analysis (Honrado *et al.*, 2004).

Three-dimensional imaging system has wide application in clinical practice. It has been used to assess the facial growth in children (Nute *et al.*, 2000) and evaluate facial appearance following the surgical repair of cleft lip and palate (Ayoub *et al.*, 2003). Facial expressions can also be captured using 3D recording systems. It has been reported that males showed larger facial movements than women in a study of 24 subjects (Giovanoli *et al.*, 2003). Changes that occurred during facial expressions have been recorded to compare right and left facial displacements during 3D movement (Coulson *et al.*, 2002).
Evaluation of facial animations is usually achieved by an observer or an operator subjectively. The best known method and widely used system for grading facial nerve paralysis was the House Brackmann system, which assigned patients to 1-6 categories on the basis of their facial function (House *et al.*, 1983). The main drawback of the subjective evaluation is bias and the inherent deficiency of accurate measurements for decision making in clinical practice. It has been shown that the reliability of the House Brakmann system is doubtful with a wide variation in scoring facial animations between trained observers (Coulson *el at.*,

1995). Furthermore, the scoring system was labour intensive and time consuming.

An objective analysis of facial animations was developed to overcome the limitations of the subjective analyses. Photography and video systems were the main methods used for facial measurements. Animations were analysed by recording the amplitude of motions of facial landmarks during facial expressions at rest animation and at maximal animations using standardised photographs (Johnsons *et al.*, 1994). Video camera systems have been used to measure movements of landmarks around the lips and record both the amplitude and direction of the landmark motions (Platez *et al.*, 1994). These video recording systems were easier to use and allowed better understanding of facial movements.

The 2D assessment methods do not provide sufficient information to specify the 3D configuration of the face accurately and realistically neither it does they represent the actual path of motion of the facial landmarks. The 2D amplitude of animations may underestimate the 3D movement of facial muscles by as much as 43% (Gross *et al.*, 1996).
The use of 3D imaging opens new dimensions to evaluate and quantify facial morphology and muscle movements. Not only can the magnitude and direction of animations be measured in 3D but also the dynamics of motion can be traced. Laser scanning can provide an efficient, valid and reproducible method of measuring facial morphology with an accuracy within 1 mm (Kau *et al.*, 2005). However, laser scanning of the face is slow and it may take up to 30 seconds. Any change in facial animation during scanning will distort the recorded image (Yamad *et al.*, 1998). Therefore, the use of this method to record facial animations may not be ideal. Stereophotogrammetry systems have the advantages of fast capture time (less than 1 millisecond) and a reported accuracy to 0.5 mm recording facial morphology (Ayoub *et al.*, 2007). The method has also been used to study 3D static facial animation (Johnston *et al.*, 2003).

Several studies have investigated lip motion (dynamic movement) during facial animation using three video cameras (Mishema *et al.*, 2006; Popat *et al.*, 2011).

The main drawback of these systems is the limited information that is obtained regarding the course of animation from rest to the maximal movement. Also the process of validating the software used was not provided.

Analysis of facial animations has been previously reported using markers which were attached to surface of the subject's face. Retro reflective spherical markers with a diameter of 4 mm have been used (Trotman *et al.*, 1998), together with light reflective markers (Frey *et al.*, 1994) and retro reflective markers of 2 mm (Ferrario *et al.*, 2005). Movements of the marker are recorded three-dimensionally. The use of a physical marker in measuring facial animation was time consuming for both the operator and the subjects and there presence may inhibit spontaneous facial motion. The application of facial markers may also cause some inconvenience to patients and may also be impractical to apply to children. Depending on the size of the markers the surrounding areas may be obscured, therefore, no information could be obtained from areas beyond or adjacent to the applied area. On the other hand, Watchman *et al.*, (2001) analysed facial motion without markers using optical flow to calculate the whole surface of the face, and facial movements were analysed in detail. However, this study was limited to 2D analysis and did not describe the full characteristics of facial animations.

Retro reflective markers and a special lighting system, which consisting of 4 infra-red video cameras was reported to measure of the circumoral area in 16 cleft lip and palate patients. The capture rate was 60 frames per second and six facial animations were recorded(Trotman *et al.*, 2005). The Motion Analysis system was used to track the motion of flat and circular reflective markers of 2 mm diameter which were placed on selected facial landmarks. The operator digitised the marked points to extract the x, y and z coordinates of the landmarks. However, the study was insufficient to address the method of landmarks tracking. Also, the system did not record the dynamic motion of facial animation

Linstrom *et al.*, (2002) analysed facial motion using a video-computer interactive system, the Peak Motus Motion Measurement System, PEAK™. The authors studied the liner displacement of preselected light reflective facial landmarks in normal and abnormal faces. The landmarks were manually digitised at the first frame, the Peak Motus software then tracked the landmarks through all the rest of frames. The software derived the x and y coordinates for each marker's location. Despite the fact that information regarding dynamic facial animation was obtained, and information about facial motion, the study was limited to the 2D analysis of muscle movements.

In a recent study, Popat *et al.*, (2011) used the 3dMD Face Dynamic System to analyse the movement of 6 landmarks around the lips at 48 frames per second. The motions of the facial landmarks were tracked manually using the x, y and z coordinates after each facial "shell" had been manually aligned on a common 3D plane system using Rapidform™ software. The study did not give sufficient information regarding system validation. Analysis of facial muscle movements was limited to the rest and at maximal animations. Information regarding the path of dynamic movement between the first and the last animations was not provided. This information would help in quantifying the possible defects of facial animation in patients with cleft deformities before and after surgical repair.

A comprehensive facial motion analysis should generate useful information for the diagnosis of facial impairments due to neuro-facial deficits and quantifying surgical outcome. An ideal system should provide a reliable capture of the face and allow objective analysis of facial movements. The system should be non-invasive and capture the facial animation in high fidelity and accuracy. This would facilitate multi-centre studies and data sharing. There is also a need for reliable software to track facial landmarks automatically without human intervention in a relatively short time to be used in routine clinical practice.

The present study was undertaken to validate a new system produced to track the landmarks automatically during facial animation in dynamic motion using "optical flow". The commercially available system Di4D (Dimensional Imaging Ltd, Glasgow, UK) was used for facial capture. It consisted of 2 greyscale video cameras and a single colour camera. The system captured the movements of facial landmarks at 60 frames per second which allowed facial animations to be recorded more comprehensively than other systems which capture the face at a rate of 48 frames per second (Popat *et al.*, 2011). However, the clinical significance of the number of frames/second requires further investigation which is beyond the scope of this study. The calibration of the system was not time consuming and could be easily calibrated by a single operator, which was much simpler than other systems. The Di4D viewer software allowed the operator to view, magnify the 3D dynamic image and track the landmarks automatically across the frames. The system used in this study required a strong lighting source to illuminate the face which allowed the recording of fine detail during animation. However the bright light could be uncomfortable to patients and may distract their attention during animation especially for children. One of the main disadvantages of the 4D capture is the volume of data generated for analysis, the time required to process and reconstruct the dynamic 3D sequences. More storage, faster computer processors, and an optimum frame rate capture would facilitate this process.

The sample size of this study compares favourably with other investigations on the same topic. Mashima *et al.*, (2006) conducted their investigation on 6 subjects. Sixteen patient with cleft lip and palate and 8 control subject were recruited in investigation by Trotman *et al.*, (2005) to analyses lip motion. Ayoub *et al.*, (2003) validated the 3D facial imaging system on 21 infants with cleft lip and palate. Popat *et al.*, (2011) recruited 150 subjects in their study on facial animations.

There are considerable variations in the literature regarding which facial animations are essential to capture and analyse. In this study, 3 facial animations were evaluated; maximal smile, lips purse and cheek puff. These were selected to cover a broad group of facial muscles and include extreme movements of facial landmarks. Trotman *et al.*, (2000) found grimace to be the most reproducible expression followed by maximal smile, lip purse and cheek puff (rest position was not assessed in this study). Frey *et al.*, (1994) found maximal expressions to be more reproducible than sub-maximal ones. Johnson *et al.*, (2003) found that the rest position to be the most reproducible animation followed by maximum smile.

For the purposes of this study, the landmarks used by Hajeer *et al.*,(2002) and Gwilliam *et al.*,(2006) were combined with the points defined by Farkas (1994) to produce a total list of 23 landmarks. These points were directly marked on the subjects face, landmarks covered more than one area of the face to measure the facial motion in different direction; this was more comprehensive than previous studies (Mishema *et al.*, 2006; Popat *et al.*, 2011). For this study direct marking of the face was advantageous, it minimised the digitisation errors of the 3D models which was necessary to evaluate the accuracy of the automatic tracking software. This may not be ideal for other studies as pre- marking of the face induces bias in facial measurements. Bush *et al.*, (1996) compared the accuracy of points' identification using a 3D laser scanned image of dummy head with and without pre-labelled landmarks. Identification with pre-labelled landmarks achieved an accuracy of about 0.6 mm for most points (maximum error 1.8 mm). Identification without landmarks achieved an accuracy of about 2.5 mm for most points (maximum error 4 mm). Aynchi *et al.*, (2011) reported a high level of precision especially when facial landmarks were labelled.

In a few cases some landmarks could not be identified because of the dark skin colour or the presence of freckles which mimic the colour of the landmarks even when the image was magnified. This was noted for landmarks at the supercilliary and zygomatic regions. Some landmarks were difficult to identify on the screen due to skin creases produced by facial expressions. This was a particular problem for exocanthion landmarks during maximal smile and subalare points during cheek puff.

6.1 Automated landmark tracking

Facial animations were captured using the Di4D imaging capture system. Di4D captured a sequence of stereo images of facial animation, then reconstructed sequential 3D facial shapes from the captured stereo images and also established the corresponding points between frames. Any point in one frame will find its corresponding point in the other frames. Automatic landmark tracking was achieved by extracting corresponding locations in all frames for the landmarks manually defined in the first frame of all image sequence using the process of "optical flow".

The area based normalised cross-correction (NCC) technique was used to establish corresponding points in an image sequence. In order to establish the correspondences for individual points in the images sequence, two image windows were selected automatically in two different image frames. NCC calculated the cross-correlation coefficient defining corresponding locations between these two frames. The differences between landmark locations in different frames were caused by facial animation and head/body movements.

There are several factors that affect the accuracy of the automatic landmark tracking:

a) Due to object occlusion, body hairs and repeated patterns, the stereo matching gives false stereo matching which can lead to false 3D coordinates in occluded regions. The coordinates of a landmark selected in the region will not be accurate.
b) Due to lack of correct texture information in the image sequences captured, such as the image motion blurring or image distortions, NCC will lead to find the incorrect corresponding points in frame.

The accuracy of manual landmarking will be affected by these two factors as well.

6.2 Validation of the tracking system

In this study, the discrepancies in x, y and z coordinates between manual and automatic digitisation of facial landmarks was within 0.5 mm and the mean absolute Euclidian distance between manual digitisation and automatic location of corresponding landmarks using the tracking software was within 0.7 mm, which reflects the accuracy of the method. The majority of these distances were within 1 mm.

This study showed no statistical differences between male and female regarding the discrepancies in the x, y and z coordinates between manually digitised and automatically tracked landmarks (P=0.068). However during maximal smile the mean distance between manual digitisation and automatically tracked landmarks in females was within 0.7 mm and in males was within 0.8 mm (P=0.0016). However, this difference was minimal and within the author's digitisation error. Weeden *et al*., (2001) found that males have greater movement than female in maximal facial expressions. This may have been the case in this study; nevertheless, it did not impact on the accuracy of tracking facial landmarks. Analysis of the magnitude of facial animations and evaluating gender differences were beyond the scope of this study.

Points 12 and 13 were associated with the largest discrepancies in the antero-posterior direction which was represented by the y coordinates. Despite the fact these points were pre-marked, there were difficulties in identifying the depth of these points on the 3D facial morphology. Another possible explanation for the difficulties in digitising these particular landmarks was the inability of the camera system to capture the base of the nose. These points were obliterated by the surrounding structures which are known in computing science as “occlusion”. The points were on a blind spot to the cameras which affects the accuracy of capturing, building a 3D model and digitising the landmarks. This would affect the accuracy of the automated landmark tracking system which provides insufficient data for the normalised cross-correlation (NCC) to establish corresponding points in image sequences. Ayoub *et al.*, (2003) reported that the right nostril point was difficult to digitise possibly because of inadequate lighting at base of the nose. To improve the quality of capturing the base of nose, the head should be slightly elevated to ensure an adequate view of the nasolabial and submental regions (Wong *et al.*, 2008). The addition of another camera to the capturing system may improve the accuracy of the inferior surface of the nose of the tracking. However, this would require further investigation.

The operator errors in the x, y and z coordinates of all subjects for all animation in repeated digitisation was within 0.09 mm. The mean distance between corresponding landmarks of repeated digitisation was 0.21 mm. In this study it is not surprising to find out that the digitisation errors were minimal. The operator digitised the pre-labelled landmarks which facilities the process and reduced random errors. Khambay *et al.*, (2008), also using pre-labelling, found the error in placement of landmarks on 3D model using Di3D system to be 0.07 mm and ranged from 0.02 mm to 0.11 mm. Using a laser scanner system, Popat *et al.*, (2011) reported the range in landmark distance’s error for both intra- and inter-examiner assessments to be 0.59 mm and 1.32 mm respectively. Toma *et al.*, (2009) reported the accuracy of landmark identification ranged from 0.39 to

1.49 mm. Ayoub *et al*., (1997) have reported a precision of 0.2 mm in digitising landmarks using the C3D capture system and custom designed software for landmark location. Using a laser scanner, Moss *et al.*, (1987& 1994) found the accuracy of the capture system to be 0.5 mm, while using stereophotogrammetry, a value of 0.53 mm was reported by Trotman *et al*., (1996). In other study the reliability of 3D laser system was found to be within 0.85 mm (Kau *et al*., 2005). Ma *et al*., (2009) reported on the reproducibility of a 3D facial scanning system based on structured light technique to be within 0.93 mm.

Statistical analysis using a one-sample student *t*-test for the mean distance between the manually digitised and automatically located landmarks for all animations for male and female against the mean operator error at 0.17mm was $P<0.01$, which confirms there is a statistically significant differences between the automatically tracked landmarks and those identified manually. Therefore the first null hypothesis was rejected.

However the mean discrepancy between manually digitised and automatically tracked x, y and z coordinates of landmarks were all with in 0.4mm, Table 5.3. This is below the recognised and widely accepted clinical threshold of 0.5mm for clinical significance of differences in landmark's location. Therefore the second null hypothesis was accepted (failed to reject).

CHAPTER SEVEN

CONCLUSIONS AND FUTURE WORK

7 Conclusion & Future work

Advances in the field of stereophotogrammetry have led to the development of a 4D motion analysis system that allows non-invasive capture of facial animation. The developed software allowed automatic tracking of landmarks with a sufficient accuracy for clinical application.

Future work

The study confirmed the accuracy and the reliability of the Di4D software for automatic tracking of facial landmarks.This facilitate the capture and the analysis of the dynamic movements of facial expressions.

The study highlighted a number of problems associated with the tracking system of the Di4D imaging system, which could be improved. The first was related to occlusion at the base of the nose. This may be improved by adding another camera that captured the face from an inferior position. Tilting the head slightly upward may improve the quality of capture. These variables would require further investigation

The 4D capture system generated enormous amounts of data which causes some difficulties in the manipulation and storage of the images. This requires further refinement. The use of faster processors, data compressor and rationalization of the number of captured frames/second would overcome this difficulty.

Automatic tracking of facial landmarks with satisfactory accuracy facilitate the analysis of dynamic motion during facial animations and answers the question of the reproducibility and the symmetry of facial expressions. An important application for the 4D imaging technology is to measure neuro-facial deficits and their impact on facial animations.

There is a considerable debate in the literature regarding facial animation following the surgical repair of cleft lip and palate. Lip scarring may affect the quality, symmetry and magnitude of facial animations. The availability of a reliable 4D capture system and validated software to track facial anatomical landmarks facilitate further investigation on surgically managed cleft cases.

Facial paralysis is one of the most difficult anomalies to be quantified. The 4D capture system and the automatic tracking would help in objectively grading this paralysis and quantifying the degree of improvement following surgical or medical treatment.

Improvement in the accuracy of the tracking system would put an end to subjective assessments of facial animation; it would improve our understanding of the dynamics of facial expressions and facilitate multi-centre investigations and comparisons.

CHAPTER EIGHT

REFERENCES

8 References

ALDRIDGE, K., BOYADJIEV, S. A., CAPONE, G. T., DELEON, V. B. & RICHTSMEIER, J. T. 2005. Precision and error of three dimensional phenotypic measures acquired from 3dMD photogrammetric images. *American Journal of Medical Genetics Part A,* 138, 247-253.

AYNECHI, N., LARSON, B. E., LEON-SALAZAR, V. & BEIRAGHI, S. 2011. Accuracy and precision of a 3D anthropometric facial analysis with and without landmark labeling before image acquisition. *The Angle Orthodontist,* 81, 245-252.

AYOUB, A., GARRAHY, A., HOOD, C., WHITE, J., BOCK, M., SIEBERT, J., SPENCER, R. & RAY, A. 2003. Validation of a vision-based, three-dimensional facial imaging system. *The Cleft Palate-Craniofacial Journal,* 40, 523-529.

AYOUB, A., SIEBERT, P., MOOS, K., WRAY, D., URQUHART, C. & NIBLETT, T. 1998. A vision-based three-dimensional capture system for maxillofacial assessment and surgical planning. *British Journal of Oral and Maxillofacial Surgery,* 36, 353-357.

AYOUB, A., WRAY, D., MOOS, K., JIN, J., NIBLETT, T., URQUHART, C., MOWFORTH, P. & SIEBERT, P. 1997. A three-dimensional imaging system for archiving dental study casts: a preliminary report. *The International journal of adult orthodontics and orthognathic surgery,* 12, 79.

AYOUB, A., XIAO, Y., KHAMBAY, B., SIEBERT, J. & HADLEY, D. 2007. Towards building a photo-realistic virtual human face for craniomaxillofacial diagnosis and treatment planning. *International journal of oral and maxillofacial surgery,* 36, 423-428.

BURRES, S. & FISCH, U. 1986. The comparison of facial grading systems. *Archives of Otolaryngology- Head and Neck Surgery,* 112, 755.

BUSH, K. & ANTONYSHYN, O. 1996. Three-dimensional facial anthropometry using a laser surface scanner: validation of the technique. *Plastic and Reconstructive Surgery,* 98, 226.

COULSON, S. & CROXSON, G. 1995. Assessing physiotherapy rehabilitation outcomes following facial nerve paralysis. *Aust J Otolaryngol,* 2, 20-24.

COULSON, S. E., CROXSON, G. R. & GILLEARD, W. L. 2002. Three-dimensional quantification of the symmetry of normal facial movement. *Otology & Neurotology,* 23, 999.

DE MENEZES, M., ROSATI, R., ALLIEVI, C. & SFORZA, C. 2009. A Photographic System for the Three-Dimensional Study of Facial Morphology. *The Angle Orthodontist,* 79, 1070-1077.

DEAN, D., HANS, M. G., BOOKSTEIN, F. L. & SUBRAMANYAN, K. 2000. Three-dimensional Bolton-Brush Growth Study landmark data: ontogeny and sexual dimorphism of the Bolton standards cohort. *The Cleft Palate-Craniofacial Journal,* 37, 145-156.

DELI, R., DI GIOIA, E., GALANTUCCI, L. M. & PERCOCO, G. 2010. Automated landmark extraction for orthodontic measurement of faces using the 3-camera photogrammetry methodology. *Journal of Craniofacial Surgery,* 21, 87.

DRYDEN, I. L. & MARDIA, K. V. 1998. *Statistical shape analysis*, John Wiley & Sons Chichester, UK.

EKMAN, P., FREISEN, W. V. & ANCOLI, S. 1980. Facial signs of emotional experience. *Journal of Personality and Social Psychology,* 39, 1125.

FARKAS, L. G. 1994. *Anthropometry of the Head and Face*, Raven Press New York.

FARKAS, L. G., BRYSON, W. & KLOTZ, J. 1980. Is photogrammetry of the face reliable? *Plastic and Reconstructive Surgery,* 66, 346.

FERRARIO, V. F., SFORZA, C., LOVECCHIO, N. & MIAN, F. 2005. Quantification of translational and gliding components in human temporomandibular joint during mouth opening. *Archives of oral biology,* 50, 507-515.

FERRARIO, V. F., SFORZA, C., POGGIO, C. E., D'ADDONA, A. & TARONI, A. 1996. Fourier analysis of cephalometric shapes. *The Cleft Palate-Craniofacial Journal,* 33, 206-212.

FERRARIO, V. F., SFORZA,C.,PIZZINI., VOGEL,G.,MIANI,A 1994. sexual dimorphisn in the human face assessed by euclidean distance matrix analysis. *Cleft Palate Craniofac J,* 29, 32-38.

FREY, M., JENNY, A., GIOVANOLI, P. & STUSSI, E. 1994. Development of a new documentation system for facial movements as a basis for the international registry for neuromuscular reconstruction in the face. *Plast Reconstr Surg,* 93, 1334-49.

GIOVANOLI, P., TZOU, C. H. J., PLONER, M. & FREY, M. 2003. Three-dimensional video-analysis of facial movements in healthy volunteers* 1. *British journal of plastic surgery,* 56, 644-652.

GROSS, M. M., TROTMAN, C.-A. & MOFFATT, K. S. 1996. A comparison of three-dimensional and two-dimensional analyses of facial motion. *The Angle Orthodontist,* 66, 189-194.

GWILLIAM, J. R., CUNNINGHAM, S. J. & HUTTON, T. 2006. Reproducibility of soft tissue landmarks on three-dimensional facial scans. *The European Journal of Orthodontics,* 28, 408.

HAJEER, M. Y., AYOUB, A. F., MILLETT, D., BOCK, M. & SIEBERT, J. 2002. Three-dimensional imaging in orthognathic surgery: the clinical application of a new method. *The International journal of adult orthodontics and orthognathic surgery,* 17, 318.

HAY, A., AYOUB, A., MOOS, K. & SINGH, G. 2000. Euclidean distance matrix analysis of surgical changes in prepubertal craniofacial microsomia patients treated with an inverted L osteotomy. *The Cleft Palate-Craniofacial Journal,* 37, 497-502.

HONRADO, C. P. & LARRABEE JR, W. F. 2004. Update in three-dimensional imaging in facial plastic surgery. *Current opinion in otolaryngology & head and neck surgery,* 12, 327.

HOUSE, J. W. 1983. Facial nerve grading systems. *Laryngoscope,* 93, 1056-69.

JOHNSON, P. C. M. D., BROWN, H., KUZON, W. M. J. M. D. P., BALLIET, R. P., GARRISON, J. L. M. D. & CAMPBELL, J. M. D. 1994. Simultaneous Quantitation of Facial Movements: The Maximal Static Response Assay of Facial Nerve Function. *Annals of Plastic Surgery February,* 32, 171-179.

JOHNSTON, D. J., MILLETT, D., AYOUB, A. & BOCK, M. 2003. Are facial expressions reproducible? *The Cleft Palate-Craniofacial Journal,* 40, 291-296.

JONES, M., HICKMAN, J., MIDDLETON, J., KNOX, J. & VOLP, C. 2001. A validated finite element method study of orthodontic tooth movement in the human subject. *Journal of Orthodontics,* 28, 29.

KANG, T. S., VRABEC, J. T., GIDDINGS, N. & TERRIS, D. J. 2002. Facial nerve grading systems (1985-2002): beyond the House-Brackmann scale. *Otology & Neurotology,* 23, 767.

KAU, C. H., RICHMOND, S., ZHUROV, A. I., KNOX, J., CHESTNUTT, I., HARTLES, F. & PLAYLE, R. 2005. Reliability of measuring facial morphology with a 3-dimensional laser scanning system. *American journal of orthodontics and dentofacial orthopedics,* 128, 424-430.

KHAMBAY, B., NAIRN, N., BELL, A., MILLER, J., BOWMAN, A. & AYOUB, A. 2008. Validation and reproducibility of a high-resolution three-dimensional facial imaging system. *British Journal of Oral and Maxillofacial Surgery,* 46, 27-32.

KNOX, J., KRALJ, B., HÜBSCH, P. F., MIDDLETON, J. & JONES, M. L. 2001. An evaluation of the influence of orthodontic adhesive on the stresses generated in a bonded bracket finite element model* 1. *American journal of orthodontics and dentofacial orthopedics,* 119, 43-53.

LINSTROM, C. J. 2002. Objective facial motion analysis in patients with facial nerve dysfunction. *The Laryngoscope,* 112, 1129-1147.

MA, L., XU, T. & LIN, J. 2009. Validation of a three-dimensional facial scanning system based on structured light techniques. *Computer methods and programs in biomedicine,* 94, 290-298.

MANKTELOW, R. T., ZUKER, R. M. & TOMAT, L. R. 2008. Facial Paralysis Measurement with a Handheld Ruler. *Plastic and Reconstructive Surgery,* 121, 435-442.

MISHIMA, K., YAMADA, T., MATSUMURA, T. & MORITANI, N. 2010. Analysis of lip motion using principal component analyses. *Journal of Cranio-Maxillofacial Surgery*.

MISHIMA, K., YAMADA, T., OHURA, A. & SUGAHARA, T. 2006. Production of a range image for facial motion analysis: a method for analyzing lip motion. *Computerized Medical Imaging and Graphics,* 30, 53-59.

MONTEGI N, T. S., WAKATSUKI E. 1996. A facial growth analysis based on FEM employing three dimensional surface mesurmenet by a rapid laser device. *Okajimas Folia Anat Jpn,* 72.

MOSS, J., MCCANCE, A., FRIGHT, W., LINNEY, A. & JAMES, D. 1994. A three-dimensional soft tissue analysis of fifteen patients with class II, division 1 malocclusions after bimaxillary surgery. *American journal of orthodontics and dentofacial orthopedics,* 105, 430-437.

MOSS, J. P., LINNEY, A.D., GRINDROD, S.R., ARRIDGE, S.R., CLIFTON, J.S. 1987. Three-dimensional visualization of face and skull using comuterized tomography and laser sacnning techniques. *europen Journal of orthodontics,* 9, 247-253.

MURTY, G. E., DIVER, J. P., KELLY, P. J., O'DONOGHUE, G. M. & BRADLEY, P. J. 1994. The Nottingham System: objective assessment of facial nerve function in the clinic. *Otolaryngol Head Neck Surg,* 110, 156-61.

NUTE, S. J. & MOSS, J. P. 2000. Three-dimensional facial growth studied by optical surface scanning. *Journal of Orthodontics,* 27, 31.

OZSOY, U., DEMIREL, B. M., YILDIRIM, F. B., TOSUN, O. & SARIKCIOGLU, L. 2009. Method selection in craniofacial measurements: advantages and disadvantages of 3D digitization method. *J Craniomaxillofac Surg,* 37, 285-90.

PALETZ, J. L., MANKTELOW, R. T. & CHABAN, R. 1994. THE SHAPE OF A NORMAL SMILE - IMPLICATIONS FOR FACIAL PARALYSIS RECONSTRUCTION. *Plastic and Reconstructive Surgery,* 93, 784-789.

POPAT, H., RICHMOND, S., BENEDIKT, L., MARSHALL, D. & ROSIN, P. 2009. Quantitative analysis of facial movement--A review of three-dimensional imaging techniques. *Computerized Medical Imaging and Graphics,* 33, 377-383.

POPAT, H., RICHMOND, S., MARSHALL, D., ROSIN, P.L. 2011. Facial Movement in 3 Dimensions: Average Templates of Lip Movement in Adults. *Otolaryngol Head Neck Surg,* 145, 24-29.

RICHTSMEIER, J. T., GRAUSZ HM,MORRIS GR,MARSH JL,VANNIER 1991. Growth of the cranial base in craniosynostosis. 28, 55-67.

RITTER, K., TROTMAN, C. A. & PHILLIPS, C. 2002. Validity of subjective evaluations for the assessment of lip scarring and impairment. *Cleft Palate-Craniofacial Journal,* 39, 587-596.

SHERIDAN, C., THOMAS, C. & CLEMENT, J. 1997. Quantification of ethnic differences in facial profile. *Australian orthodontic journal,* 14, 218.

TOMA, A., ZHUROV, A., PLAYLE, R., ONG, E. & RICHMOND, S. 2009. Reproducibility of facial soft tissue landmarks on 3D laser scanned facial images. *Orthodontics & craniofacial research,* 12, 33-42.

TROTMAN, C. A., FARAWAY, J. J. & ESSICK, G. K. 2000. Three-dimensional nasolabial displacement during movement in repaired cleft lip and palate patients. *Plastic and Reconstructive Surgery,* 105, 1273.

TROTMAN, C. A., FARAWAY, J. J. & PHILLIPS, C. 2005. Visual and statistical modeling of facial movement in patients with cleft lip and palate. *The Cleft Palate-Craniofacial Journal,* 42, 245-254.

TROTMAN, C. A., LONG, R. E., JR., ROSENSTEIN, S. W., MURPHY, C. & JOHNSTON, L. E., JR. 1996. Comparison of facial form in primary alveolar bone-grafted and nongrafted unilateral cleft lip and palate patients: intercenter retrospective study. *Cleft Palate Craniofac J,* 33, 91-5.

TROTMAN, C. A., STOHLER, C. S. & JOHNSTON JR, L. E. 1998. Measurement of facial soft tissue mobility in man. *The Cleft Palate-Craniofacial Journal,* 35, 16-25.

WACHTMAN, G. S., COHN, J. F., VANSWEARINGEN, J. M. & MANDERS, E. K. 2001. Automated tracking of facial features in patients with facial neuromuscular dysfunction. *Plastic and Reconstructive Surgery,* 107, 1124.

WEEDEN, J. C., TROTMAN, C. & FARAWAY, J. J. 2001. Three dimensional analysis of facial movement in normal adults: influence of sex and facial shape. *Angle Orthodontist,* 71, 132-140.

WEINBERG, S. M., SCOTT, N. M., NEISWANGER, K., BRANDON, C. A. & MARAZITA, M. L. 2004. Digital three-dimensional photogrammetry: evaluation of anthropometric precision and accuracy using a Genex 3D camera system. *The Cleft Palate-Craniofacial Journal,* 41, 507-518.

WONG, J. Y., OH, A. K., OHTA, E., HUNT, A. T., ROGERS, G. F., MULLIKEN, J. B. & DEUTSCH, C. K. 2008. Validity and Reliability of Craniofacial Anthropometric Measurement of 3D Digital Photogrammetric Images. *The Cleft Palate-Craniofacial Journal,* 45, 232-239.

YAMADA, T., SUGAHARA, T., MORI, Y. & SAKUDA, M. 1998. Rapid three-dimensional measuring system for facial surface structure. *Plastic and Reconstructive Surgery,* 102, 2108.

ZACHRISSON, B. U. 1998. Esthetic factors involved in anterior tooth display and the smile: vertical dimension. *Journal of Clinical Orthodontics,* 32, 432-445.

CHAPTER NINE

APPENDICES

Appendix 1 Study poster

You are invited to take part in a study

We are carrying out a study to see if different types of facial movement are reproducible over time i.e. smiling, frowning etc.

We are looking for female and clean-shaven male, adults aged between 18 and 35.

One of the reasons for collecting this information is to measure facial movements in males and femals between the ages of 18 and 35.

This will help us determine if patients with facial paralysis, for example after a stroke are getting better with time or treatment.

4D assessment of faces

We now have a way of recording the movement of the face in real time using 4D video capture. This takes less than ten seconds for each expression and you can see the picture of your face on the computer screen later.

4D Imaging Equipment

The video clips collected are confidential and no personal information will be identifiable in the study.

What are we asking you to do?

The cameras will be located in a research room at the Glasgow Dental Hospital & School. You will be asked to attend on a pre-agreed day. At the visit we will show you which facial expressions to make, you will practice them, we will record each one and repeat the process later. The whole visit will last approximately 1 hour.

If you wish to take part in this study please contact

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Appendix 2 Written explanations

Consent Form Version 1.0 BSK/EO

Patient Consent Form (Adult)

Pilot study: A study to determine the validity of a 4D imaging system and examine the reproducibility of facial movement.

Name of Researcher: Emer O'Leary, Orthodontic Registrar, Glasgow Dental Hospital

Patient's name: ______________________________

Date of birth: ______________________________

		Yes	No
1.	Have you read the information sheet?	☐	☐
2.	Do you understand the study?	☐	☐
3.	Did we answer all of your questions?	☐	☐
4.	Do you want to take part in this study?	☐	☐
5.	Do you understand participation is voluntary and that you are free to withdraw at any time, without giving any reason?	☐	☐

Who have you spoken to?

Dr/Mr/Mrs/Prof. ______________________________

Signed: ______________________________

Name (print): ______________________________

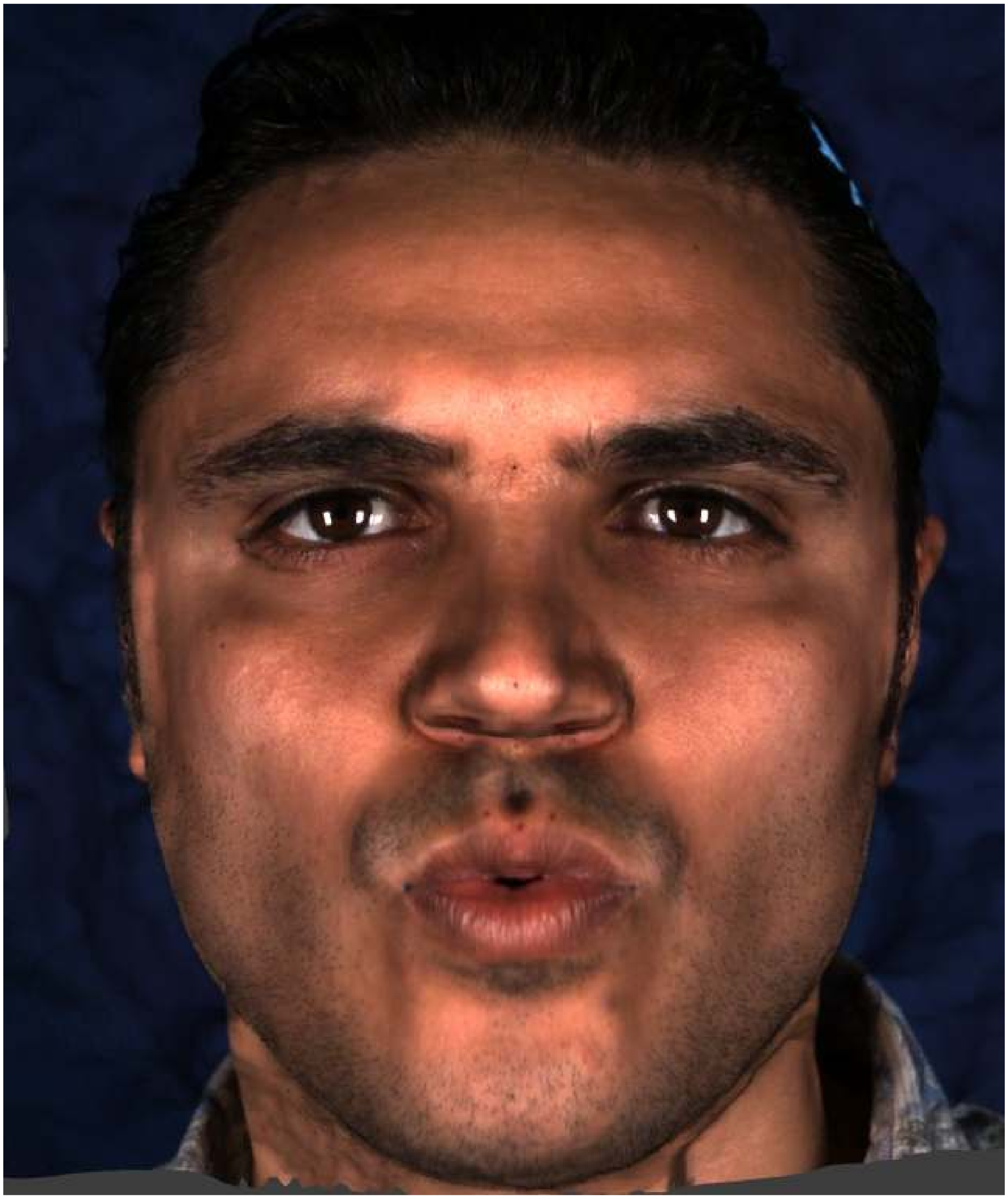
Signature of witness: ______________________________

Name (print): ______________________________

Appendix 3 Facial expressions

Maximal smile

Lip purse



Cheek puff