REPRODUCIBILITY OF EXTRA-ORAL TONGUE MOTION IN A NORMAL COHORT USING A 3D MOTION CAPTURE SYSTEM

by

NOOR ALHUDA AL-HADI

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Abstract

Aim: The aim of this study was to determine the magnitude of reproducible tongue motion in a normal cohort of healthy individuals using a 3D motion capture system.

Design: Single centre, case-controlled study.

Materials and methods: Thirty volunteers comprising of 15 female and 15 male staff and students at Birmingham Dental hospital were recruited with an age range of 21 to 44, and mean age of 27.5 years. Volunteers had to meet inclusion and exclusion criteria, namely to be aged 18-60 and be medically fit and well. Subjects were imaged using a markerless, high fidelity 3D facial motion capture system. Two sets of motions were captured per subject; up-down and right-left tongue movement at two different time points, T_1 and T_2, at least 30 minutes apart. Following capture the all 3D images were re-orientated to the principle planes. Four stabilising landmarks were placed on the forehead and one tracked landmark on the tip of the tongue was used. T_1 and T_2 sequences were superimposed on to one another and dynamic time warping was used to account for variability in speed. Mean and absolute mean differences between the maximum tongue tip position in the x, y and z directions were calculated for each of the two movements at both time points and subsequently analysed.

Results: The up and down range of motion (ROM) of the tongue was 48.3 ± 10.0mm (95% CI 45.7mm to 51.0mm) and for right to left ROM was 66.4 ± 7.8mm (95% CI 63.4mm to 69.4mm). Based on a paired *t*-test the mean displacement of the tongue tip in the x, y and z-direction, was not statistically significantly different between T_1 and T_2 for any of the tongue movements. The mean absolute differences of the tongue tip in the x, y and z-direction, at T_1 and T_2, were all statistically significantly less than

5.0mm. Apart from during tongue tip elevation in the z-direction which was not statistically significantly different to 5.0mm.

Conclusions: This study has shown that ROM of the tongue is reproducible in the x, y and z-directions for right to left tongue movement with all differences in mean and mean absolute measurements being less than 5.0mm. However, for up to down tongue movement, whilst ROM of the tongue was reproducible in the x, y and z-directions, the upper limit of the 95% confidence interval for the mean absolute difference was greater than 5.0mm when the tongue is in its most elevated position in the z-direction. The average ROM in the up and down direction was 48.3mm and from right to left was 66.4mm.

For interventional studies, differences in tongue tip position in the order of 6-7mm are likely to be due to a lack of reproducibility rather than treatment effect. This should be taken into account when designing future studies. It is vital to rehearse tongue motion to reduce the magnitude of the reproducibility error.

LIST OF FIGURES

List of Tables

Contents

PAGE

CHAPTER 1

LITERATURE REVIEW

1.1 INTRODUCTION

Speech and language therapists (SLTs) are often responsible for assessing vocal tract musculature and accompanying cranial nerve function. The tongue, in addition to the lips, palate and larynx are the oral-motor units assessed for range, rate, precision, strength and coordination of movements during speech and non-verbal communication (Lazarus et al., 2014). Tongue range of motion (ROM) is a commonly used parameter during the clinical evaluation.

By understanding the reproducibility and magnitude of “normal” tongue ROM, it is possible to create a normative database to which future intervention based research can be compared. Tongue dysfunction can result in numerous complications including obstructive sleep apnoea, dysphagia or aphasia (Sanders and Mu, 2013). Using the latest available technologies, this study aims to assess the reproducibility and magnitude of extra-oral tongue motion in four dimensions, i.e. changes in x, y and z directions over time.

1.2 DEVELOPMENT OF THE TONGUE

Developing embryos have a collection of tissues on their anterior surface called pharyngeal arches. The mandibular arch is classified as the first pharyngeal arch, the hyoid arch as the second followed by three additional arches. The anterior two thirds of the tongue arise from the first pharyngeal arch and the posterior third from the third pharyngeal arch, with a minor contribution from the fourth arch. The tongue begins its development as two lateral swellings arising from the pharyngeal arches during the late fourth week of development. Concurrently, a medial swelling develops between them, the tuberculum impar. The anterior two thirds of the tongue forms as the lateral lingual swellings rapidly expand and eventually fuse in the midline covering the tuberculum impar. The anterior portion of the tongue is covered by epithelia arising from the ectoderm whilst the posterior third develops from the endoderm (Brand and Isselhard, 2019). The taste buds begin formation from around the seventh week as the 8th and 9th visceral afferent nerves interact with the epithelium of the tongue (Kharbanda, 2011).

1.3 ANATOMY OF THE TONGUE

1.3.1 Musculature of the tongue

The muscles in the human tongue differ in position and size compared to other mammals, yet it remains unclear how these differences may be significant (Sanders et al., 2013). The tongue is comprised of several muscles, which in turn can be classified as intrinsic or extrinsic, Figure 1.1. The extrinsic muscles are those whereby one end inserts into the tongue itself whilst the other end is attached to bone. The intrinsic muscles however are not attached to bone at either end, with both ends originating and attaching within the tongue itself (Sanders and Mu, 2013). The main extrinsic muscles are the genioglossus, hyoglossus and styloglossus muscles. The genioglossus muscle is fan-shaped and forms the bulk of the posterior tongue with most of its fibres radiating medio-laterally (Abd-El-Malek, 1939). It has been found that many patients with obstructive sleep apnoea have increased genioglossus activity prior to opening the airway (Loewen et al., 2011). The main function of the genioglossus is protrusion of the tongue but it is also involved in depression, ventroflexion and retrusion. The hyoglossus muscle arises from the anterior surface

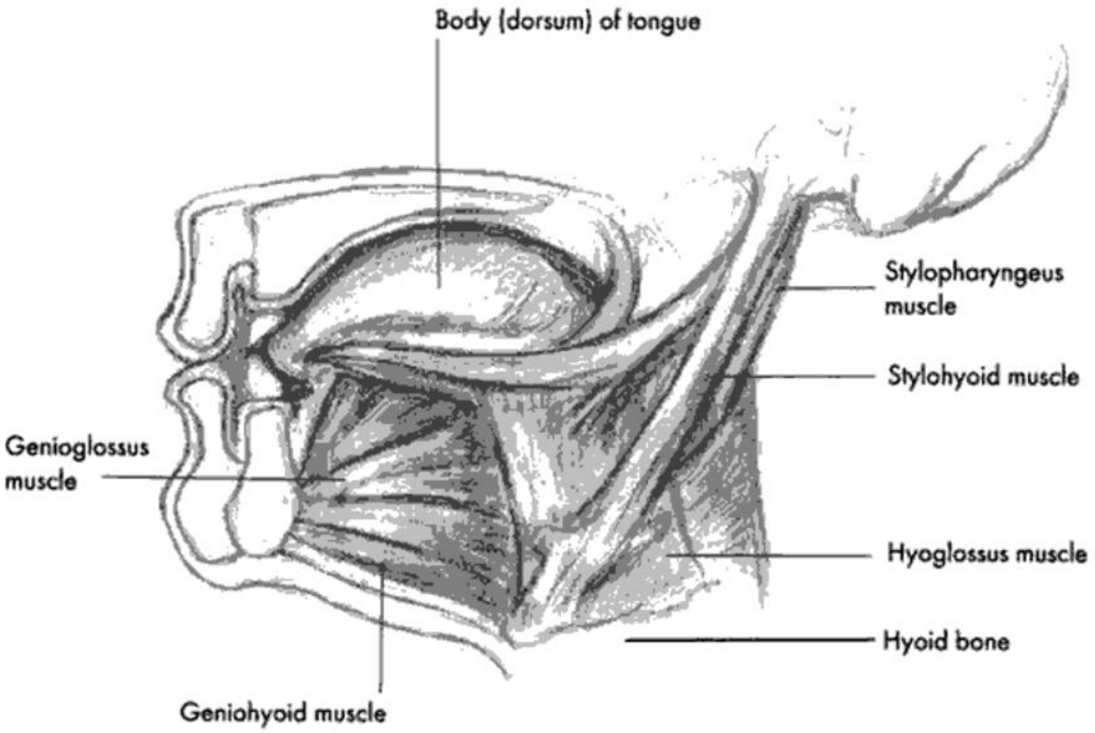


Figure 1.1. The intrinsic and extrinsic tongue muscles. Image courtesy of (Gray, 1918)

and the greater cornu of the hyoid bone. This muscle is responsible for depression and retrusion of the lateral margin of the tongue. The styloglossus muscle originates towards the apex of the styloid process as well as the stylomandibular. This muscle is mainly responsible for aiding elevation and retrusion of the tongue. In addition, there are three smaller muscles; palatoglossus, chondroglossus and glossopharyngeus which insert into the tongue at its lateral margin and do not play a major role in facilitating tongue movement. The intrinsic muscles of the tongue comprise of the superior and inferior longitudinal muscles, the transverse and vertical muscles. The superior longitudinal muscle covers the entire tongue's length and consists of a high amount of connective tissue; it aids in dorsiflexion and shortening of the tongue. The inferior longitudinal is a narrow muscle originating near the tongue base and enables its retroflexion. The transverse muscle extends more posteriorly and anteriorly than the vertical muscle, starting from the median septum and results in elongation and narrowing of the tongue. The final intrinsic muscle, the vertical muscle, functions to flatten and subsequently widen the tongue. Comprised of many vertically directed fibres, the vertical muscle intersects the transverse muscle to form a considerable portion of the mid-tongue.

1.3.2 Innervation of the tongue

The motor supply of the tongue arises from the twelfth cranial nerve; the hypoglossal nerve. This nerve comprises of many fibre bundles in varying levels of thickness which are traced to motor endplates and tend to finish on blood vessels (Weddell et al., 1940). The hypoglossal nerve initially runs between the hyoglossus muscle and submaxillary gland then towards adjacent muscles such as the geniohyoid, styloglossus and genioglossus muscles (Abd-El-Malek, 1939). The sensory innervation of the anterior and posterior part of the tongue is supplied separately and originates from the first pharyngeal arch. The anterior two thirds of the tongue runs anterior from the vallate papillae. Taste is supplied via the chorda tympani branch of the facial nerve whereas sensation is supplied via the lingual branch of the mandibular division of the trigeminal nerve (Frisdal and Trainor, 2014). With regards to the posterior third of the tongue, taste and sensation is supplied by the glossopharyngeal nerve (Sakamoto et al., 2010).

1.3.3 Blood supply to the tongue

Essentially, the main blood supply to the tongue is via the lingual artery (Parada et al., 2012). The lingual artery originates from the external carotid artery; its main blood supply to the tongue is via the deep lingual artery branch (Seki et al., 2017). The lingual artery has been seen to gradually deepen as it edges towards the tongue base and no anastomosis has been found between the right and left sides of the artery (Mun et al., 2016), Figure 1.2.

1.4 CONDITIONS AFFECTING TONGUE RANGE OF MOTION

1.4.1 Oral cancer and tongue resection

Cancer of the head and neck is currently the eighth most common form of cancer in the United Kingdom with 3% of all new cancer cases falling in to this category (Cancer Research UK, 2018). However, on a global scale, head and neck cancer has been stated as the sixth most common form of cancer in the World (Warnakulasuriya, 2009) although this varies amongst the literature. The tongue has consistently been

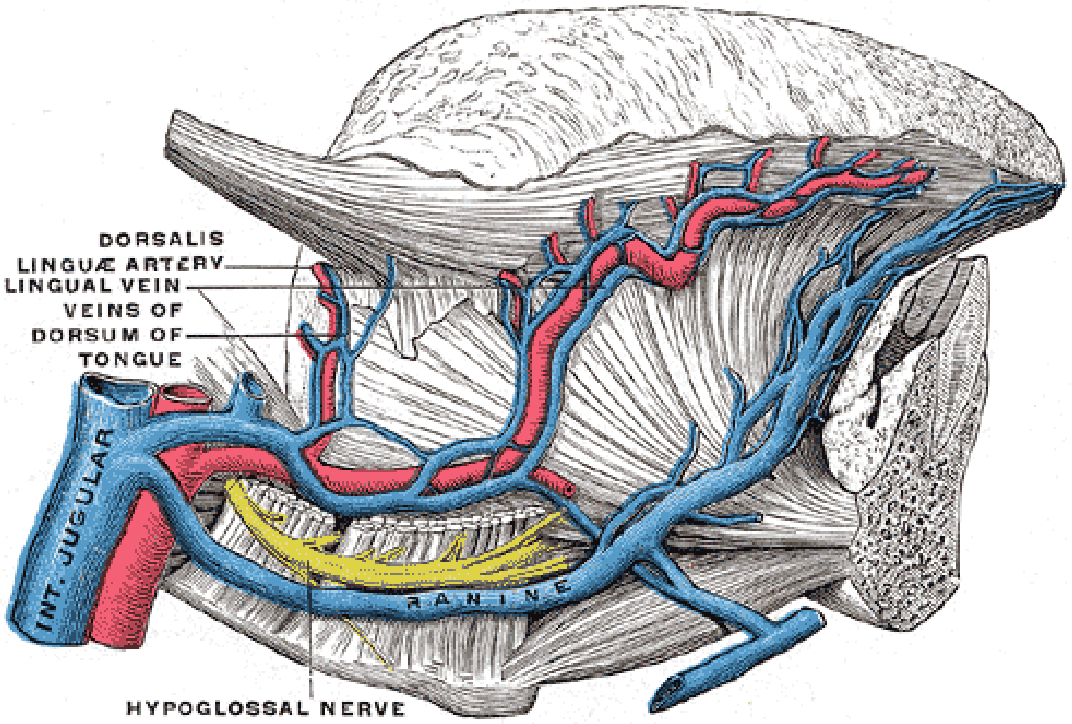


Figure 1.2 Main blood supply to the tongue. Image courtesy of (Gray, 1918)

classified as one of the highest risk sites for head and neck cancer and accounts for almost half of oral cancer cases within the European and American populations (Gupta et al., 2016). Treatment of oral squamous cell carcinoma may include surgery for resectable tumours, radiotherapy and chemotherapy (Rivera, 2015). Following tongue resection patients often report difficulty in swallowing, aesthetic disfigurement, reduced control of salivary secretion, compromised speech articulation and mandibular deviation during functional movements (Andersson et al., 2011). More specifically, it has been reported that bolus formation, as well as normal deglutition, are often impaired following tongue resection (Kolokythas, 2010). A reduction in the quality of life following tongue resection has also been reported with psychological distress, social and psychological disability having the lowest scoring Oral Health Impact Profile (OHIP) domains (Wang et al., 2013). With regards to range of motion, this understandably is also disrupted with tongue resection procedures or as a result of reconstruction or fibrosis caused by radiotherapy (Pauloski, 2008).

Improved tongue mobility has been shown to be associated with better speech (Bressmann, 2007). Furia et al. (2001) used “a therapeutic program aimed at maximizing the residual tongue tissue movements” in patients following total, subtotal and partial glossectomy. The study concluded as a result of increased tongue movement, there was an improvement of intelligibility of speech. In a later multicentre study investigating the factors influencing postoperative speech function of tongue cancer patients following reconstruction with fasciocutaneous or myocutaneous flaps it was reported that surgeons should use surgical techniques which maintain the mobility of the tongue. This was supported by the fact that tongue mobility was highly correlated with the Speech Intelligibility Test (SIT) and the Conversational Understandability Test (CUT) (Matsui et al., 2007). This was confirmed in an earlier study investigating the articulatory function and tongue mobility after surgery followed by radiotherapy for tongue and floor of the mouth cancer patients in which tongue mobility and shape were influential factor in speech (Konstantinovic and Dimic, 1998).

1.4.2 Neurological defects

Parkinson's disease (PD) is a neurodegenerative disorder of complex aetiology including genetic and environmental elements that factor into its pathophysiology (Schapira, 2010). Impaired tongue control, reduction in the strength and breadth of tongue motion during bolus production as well as extended oral transit are all common features of PD (Van Lieshout, et al., 2011). The study used Electromagnetic Midsagittal Articulography (EMMA) for dynamic tracking of the tongue intra-orally, taking measurements in the midsagittal plane. EMMA utilises low strength electromagnetic fields to measure tongue movement. Subjects wore a helmet containing transmitter coils with tiny sensors placed on the surface of the tongue. A computer tracked these as they passed through the electromagnetic field. This technique, although routine practice, must be cumbersome and intrusive to some degree and in itself hinder tongue movement. The study found that PD sufferers expressed smaller and more variable tongue movements in the horizontal plane which could increase the difficulty of swallowing liquids safely.

Furthermore, patients who have experienced a stroke or transient ischaemic attack may present with tongue dysfunction. Following motor cortex impairment, the hypoglossal nerve innervating the musculature of the tongue maybe be defective leading to deviation away from the midline towards the side of the lesion (Wei et al., 2012). This clinical presentation of tongue deviation has been suggested as a method of early detection of a cerebral event (transient ischaemic attack or full stroke). This was investigated using a photograph of the protruded tongue and determining the "tongue deviation angle". There was a reported 3.2 degrees difference between the stroke / TIA group and a normal control group. This technique even though simple, captured static tongue motion rather than full dynamic tongue motion.

1.4.3 Degenerative disease

Amyotrophic lateral sclerosis (ALS) also referred to as Lou Gehrig's disease, is a type of motor neuron disease that causes rapidly progressive muscle weakness due to a loss of motor nerve cells (Miller et al., 2005). Studies have found that ALS patients can exhibit a reduction of up to two-thirds in tongue size in the sagittal plane and the position can be altered such that there is no contact with the palate (Cha and Patten, 1989). Tongue motion specifically has also been assessed in ALS patients. At the more severe stages of the disease, patients tend to exhibit smaller maximum speeds of tongue motion and larger movement duration when compared to healthy controls (Shellikeri et al., 2016). Similarly to the EMMA device an electromagnetic tracking device (the Wave Speech Research System) was used in these studies. A reference sensor was attached to a headband and securely positioned together with a sensor attached to the mid sagittal plane of the tongue. A head mounted sensor was used to subtract any involuntary head movements from the tongue movements. Again this device was cumbersome and may interfere with tongue motion.

1.4.4 Endogenous tongue thrust

Tongue thrusts have been described as a forward motion of the tongue tip between the teeth to meet the lower lip during swallowing and speech so that the tongue is interdental (Tulley, 1969). Tongue thrusts may be habitual, endogenous or adaptive. There has been wide speculation and debate whether endogenous tongue thrusts play a role in malocclusion and whether they contribute to poor occlusal intercuspation both during and post orthodontic treatment (Chawla, 2006). Understanding the reproducibility of tongue range of motion may assist in predicting the stability of orthodontic treatment for these patients.

1.4.5 Abnormal tongue size

Macroglossia refers to a painless, long-term enlargement of the tongue. True macroglossia is associated with definitive histopathology and has been linked to various diseases including hemangioma and lymphangioma (Murthy and Laing, 1994). Although some patients may not experience any signs or symptoms, others may present with dysphagia, dysphonia, sialorrhea, open bite malocclusion and mandibular prognathism (Neville, 2016). In contrast, microglossia is characterized by an abnormally small tongue and aglossia refers to missing the entire tongue. Microglossia may present in patients with hypodactylia or hypomelia, with concurrent hypoplasia of the mandible (Neville, 2016).

1.4.6 Ankyloglossia

Ankyloglossia, more commonly referred to as ‘tongue tie’ presents with a shortened lingual frenulum connecting the tongue to the floor of month thus restricting lingual movement (Rowan-Legg, 2015). Patients may encounter difficulties eating, speaking and swallowing. A lingual frenectomy, to increase the range of motion of the tongue, may be indicated (Lamba et al., 2015).

1.5 CURRENTS METHODS OF ASSESSING TONGUE MOTION

The tongue is a complex structure made up of both intrinsic and extrinsic muscle groups. The arrangement of the muscles enables the complex movements that are required by the tongue in order for it to fulfil its functions. The intra-oral environment is harsh and any methods of assessing tongue motion must record its activity without any restrictions. In addition tongue motion can be assessed both intra and extra-orally and therefore many different techniques have been reported which are either subjective or objective.

1.5.1 Subjective Grading Systems

In order to quantify the tongue's range of movement, various different grading systems have been developed (Konstantinovic and Dimic, 1998; Bressmann et al., 2004; Matsui et al., 2007; Lazarus et al., 2014). A Tongue Mobility Test, comprising of a three point scale to measure four extra-oral and two intra-oral motions, has previously been used (Konstantinovic and Dimic, 1998). Subjects were asked to perform each tongue movement, for instance 'tongue to soft palate' and the mobility was then scored as either 'poor' 'fair' or 'good'. For this approach, 'poor' was considered when tongue motion was almost or completely impossible. A score of 'fair' was given when the tongue was restricted to the middle of the alveolar ridge or to the lingual side of the teeth. A 'good' rating was given when the tongue was able to move beyond the middle of the alveolar ridge or lingual side of the teeth. The rating could be classified as subjective and not easily amenable to statistical analysis.

Another three-point scale has previously been used called the Tongue Motility Assessment (Bressmann et al., 2004). Nine tongue motions were assessed including ‘elevation’ or ‘retroflexion’; tongue motion and graded from normal (3), mild impairment (2) and marked impairment (1). However, there was no specific information given to differentiate between mild and marked impairment. Furthermore, the authors noted that it was not possible to determine the interrater reliability of the method as the assessment was made clinically without video recordings. This is suggestive of a subjective scale which may not be reproducible, lead to bias and reduce the validity of the results. In a further study looking at speech function of patient’s post-glossectomy, a different 3-point scale tongue mobility test was used (Matsui et al., 2007). Protrusion and elevation of the tip and dorsum of the tongue were assessed with a score of 0 indicating the tongue could not be elevated, a score of 1 meant the tongue could elevate but was unable to meet the palate and 2 meant the tip of the tongue could contact the palate. The sum of the scores were then determined and used in combination with objective and subjective functional observations of the patient’s speech. The disadvantage with this scale was that it only addresses two types of tongue movement (elevation and protrusion) and did not quantify lateral protrusions or other dynamic motions. In addition the sum of the individual scores may not be clinically meaningful.

Lazarus et al. (2014) developed an objective tool to assess tongue ROM in oral cancer. The technique recorded protrusion, elevation and right and left lateral movements of the tongue using a “TheraBite” jaw ROM device. The device was designed for physiotherapy purposes extending the range of mandibular opening. However the measurement discs, which have a millimetre ruler, were also used to assess tongue range of movement. To attain a collective score for tongue ROM, the measurements for the four different motions were added then divided by 4 to create a score between 0-100. Whilst described as objective, positioning / angulation error of the TheraBite devise could result inaccurate readings which would reduce the validity of the results.

1.5.2 Imaging systems

1.5.2.1 Magnetic Resonance Imagining (MRI)

The majority of research on tongue motion has focused on recording intra-oral motion using technological advances, of which MRI is the commonest modality. Magnetic Resonance Imaging uses a strong magnetic field to forcibly align hydrogen protons in the body’s tissues. The patient is exposed to a pulsating radiofrequency current, which causes the protons to be taken out of their spin equilibrium, pulling them against the already established magnetic field. When the radiofrequency is stopped the protons release energy as they realign, and the MRI sensors detect this release of energy. The amount of energy released as the protons return to equilibrium, and the time taken, produces a “signature” for that tissue type, which can then be read to produce an image. The faster the protons realign, the brighter the image produced. MRI scanning is predominately used for soft tissue imaging given the high content of water and number of hydrogen protons in soft tissues.

The images produced by early conventional MRI scanners were static but can now be combined over time to produce a dynamic “cine” image. Cine MRI allows data collection by identifying a mid-sagittal time frame for each subject whilst performing specific vowel sounds. Changes in the morphology of the tongue and adaption of speech pronunciation in patients undergoing glossectomies (n=13) to a control group (n=23) have recently reported using cine MRI (Ha et al., 2016). Participants were positioned supine in a dental chair to imitate the MRI recording position then an audio recording was taken. This was then followed by a second audio recording whilst the patient was in the MRI scanner with a fibreoptic subtraction microphone used to reduce MRI noise. The MRI and speech recordings were used to compare the changes in tongue motion after surgery. Two-dimensional measurements were made of the interlip distance, tongue-palate distance, tongue position, tongue height and pharynx size. Following surgery, complex adaptation motions of the tongue to preserve the acoustic integrity of the vowels ‘u’ and ‘i’ were maintained. However, the authors highlighted that they had a heterogeneous surgical group with two patients having reconstruction with a radial forearm free flap and the remaining eleven patients having had primary closure. Unfortunately this meant there were not enough free flap patients (n=2) to conclusively determine differences in the effects of the closure procedure on tongue motion outcome. Another study used tagged cine MRI (tMRI) to investigate the motion of the internal features of the tongue when producing the syllable ‘ka’ (Stone et al., 2001). In this case, the ‘ka’ syllable was repeated 32 times per slice or 96 times in total. The study concluded that tMRI was able to determine deformation of tissue points within the tongue and identify regions of strain, compression and extension. However, the results of the paper could not be generalised as it was carried out on a single individual and simplified speech material was used.

Alternatively, some studies use a harmonic phase (HARP) algorithm, a form of tagged MRI using a special pulse sequence, to assess tongue motion for varying objectives. Initially, this was developed in cardiac motion tracking by producing myocardial markers (Axel, 2002). This method has since been used in several studies to track internal tissue motion of the tongue (Parthasarathy et al., 2007). Literature comparing different motion tracking modalities during speech is available which found advantages and disadvantages to the different methods. Deformable registration methods applied to cine MRI showed non-systematic tracking errors across and within participants whilst the HARP method exhibited tag pattern fading which inadvertently produced mis-tracking of some points (Woo et al., 2014). The authors concluded that a hybrid of the different MRI modalities is under exploration. There has also been research in adapting the use of MRI, such as by using a semi-automatic segmentation method, to analyse 3D motion of the tongue to decrease segmentation load (Lee et al., 2014). In this approach, a few slices are seeded one frame at a time then seeds are disseminated to the same slices at different points in time with the use of deformable registration. The proposed advantage of this method is that it requires limited user interaction in the first stages to guide the algorithm thus reducing the burden compared to manual segmentation. Whilst there is reasonable literature available on the different MRI methodologies on assessing intra-oral tongue motion, mostly in relation to speech. There is currently no evidence on the reproducibility of tongue motion. Furthermore sample sizes tend to be very small which can affect the validity and generalisability of the results.

1.5.2.2 Ultrasound

Ultrasound imaging relies on the generation of ultrasonic waves. These are generally produced by high frequency piezoelectric crystals enclosed within a transducer. The ultrasound is focused into a narrow beam and reflected back from the different tissue types. These reflections or echoes are reflected back to the same transducer and visualised into an image.

Ultrasound imaging of the tongue uses an extra-oral transducer generally positioned submentally to capture the base of the tongue, the intrinsic muscles of the tongue and the air / soft tissue boundary. Quantitative shape and movement of the tongue using ultrasound imaging has previously been described in detail (Bressmann, 2007). The midsagittal plane is the most common for ultrasound imaging as it is most comparable between different speakers. Research has been conducted into the motion of the tongue base comparing control participants with those with Obstructive Sleep Apnoea (OSA) (Chien et al., 2017). The authors developed a new tracking algorithm using ultrasound imaging and found the control group had a greater tongue base displacement than the OSA group whilst performing the Müller manoeuvre designed to collapse the airway. The study concluded that using ultrasound to assess tongue motion was easily accessible and provided a less intrusive approach. Other researchers have used ultrasound to compare tongue motion between different age groups. It has been found that elevation and depression tongue motions were more irregular in elderly patients than young adult patients (Hirai et al., 1991). In this study, a 5 MHz ultrasound convex transducer with motion-mode observation was used to capture the sagittal plane whilst participants elevated and depressed their tongues. There have also been several studies on the tongue in relation to speech using ultrasound. Zharkova (2013) found that ultrasound can be used as an effective way for analysing tongue function in subjects with cleft palate both pre- and post-therapy. Other researchers have found that some subjects with neurological deficits had significant differences whilst articulating ‘a’ ‘l’ and ‘k’ sounds compared to a control group (Shawker and Sonies, 1984). Interestingly, the same paper found that of the 10 control subjects with no neurological disease, tongue motion was consistent, particularly during ‘l’ and ‘k’ sounds. The use of ultrasound in tongue motion tracking has progressed and there are various different methods being employed to improve its accuracy. For instance, tracking the tongue using a highly flexible active contour whilst simultaneously using a particle filtering algorithm (Laporte and Menard, 2018). The authors found that this method did not require a large or diverse training set and had improved accuracy over other tongue tracking techniques. However, research papers utilising ultrasound have not specifically investigated the reproducibility of the tongue range of motion. The use of ultrasound for this purpose would be limited to intra-oral movements.

1.5.2.3 Electromyographic (EMG) Activity

Electromyographic **(**EMG) activity is related to both the amount of muscle contraction and the number of contracted muscle groups. The greater the number of activated muscles and the stronger the muscle contraction, the higher the EMG value. The method involved using non-invasive bipolar electrodes attached to the surface of the tongue to assess the activity of the genioglossus muscle during mastication (Takada et al., 1996). One of the findings from this study was that the largest genioglossus activity was seen just before the maximum jaw opening position. The problems with this methodology are that it is time consuming, costly and soft tissue / electrode contact can easily be altered which would cause artefacts in the EMG recordings. Furthermore, saliva can be exposed to the electrodes which could cause short-circuiting. In addition the placement of the electrodes on the tongue surface will interfere with the tongue motion that is being evaluated.

1.5.2.4 Electromagnetic Articulography (EMA)

Electromagnetic articulography (EMA) measures the position and movement of the tongue, over time, using a sensor coil placed on the surface of the tongue. Induction coils placed around the head produce an electromagnetic field that creates a current in the sensors coils placed on the tongue. The magnitude of the current various with distance from the external coil and this can be used to determine the sensor coils location in space.

Electromagnetic articulograph devices have been used to assess tongue motion during speech research (Yunusova et al., 2009). The electromagnetic device consisted of six transmitter coils each driven at a different frequency ranging from 7.5 to 13.75 kHz. The subjects were placed in an optimised position within the EMA cube to reduce recording errors. The system was found to be adequate for speech movement acquisition but several specific steps need to be taken to reduce chances of error.

Identifying errors in the tongue and lip movement was found to be exceedingly difficult compared to data from sensors connected to rigid objects such as the head. Again, this method does not appear to be refined for use with the tongue and is more cumbersome and complicated than other available systems. In addition the system is obtrusive and will again ultimately interfere with tongue motion.

1.5.2.5 3D imaging stereophotogrammetry

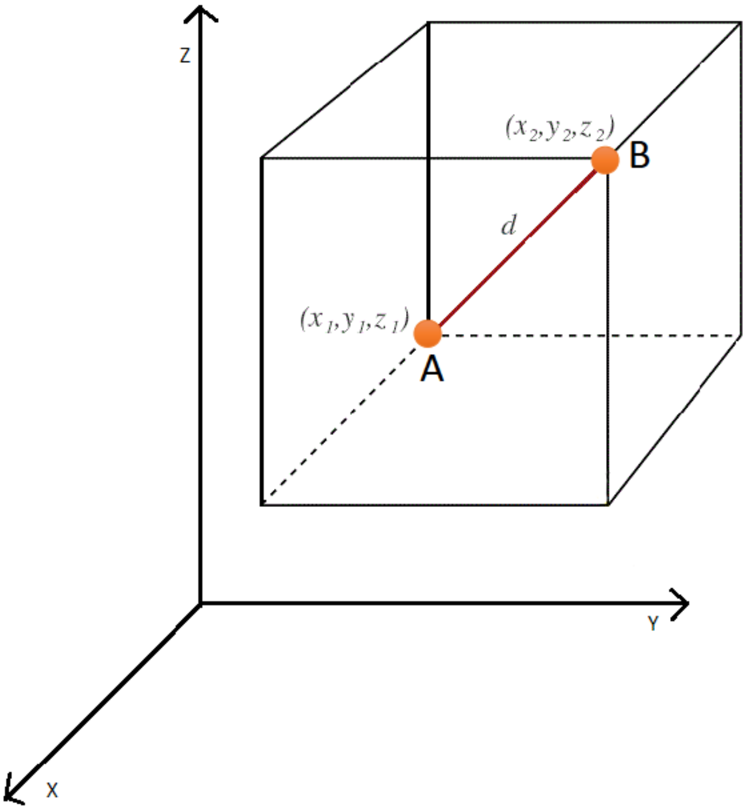
A triple camera setup has found a symmetrical range of tongue motion in five standardised positions for healthy individuals (van Dijk et al., 2016). In this method, the three video cameras were set at a fixed position with a frame rate of 100 frames per second. Two reference points were used on the tongue and four points on the face to account for unwanted head movement whilst analysing the tongue motion. The study was actually conducted to compare the ROM of the tongue of a control group of healthy individuals to a group of partial glossectomy patients. The ROM of the tongue was based on measuring the maximum displacement of the tongue tip relative to the interdental papilla of the maxillary midline on a single 3D image. Interestingly, an intrarater and interrater measurement error was performed but the reproducibility of the range of tongue motion by subjects on two separate occasions was not assessed. The results detected a statistically significant difference ($p<0.001$) in lateral tongue movement (left and right) between side of resection (42.2 ± 5.8mm) and the contralateral side (42.2 ± 7.0mm). There was no statistically significant difference ($p<0.001$) in lateral tongue movement (left and right) in the control group. With reference to the control group, the sample size of 15 subjects was not justified i.e. there was no sample size calculation. Secondly, the study could have been carried out using a static 3D system, as the dynamic element of tongue movement was not assessed; only the extremes of ROM were assessed not the path or trajectory of the tongue tip. Finally the intra-rater and inter-rater reproducibility was assessed using the intra-class correlation coefficient. This analysis assesses the relationship of correlation and agreement between repeated measures, but not the magnitude of the error measurement. When measuring a variable such as tongue ROM the size of the difference between recordings is clinically relevant but still remains unknown.

1.5.2.6 3D Motion Capture Technology

Motion capture is an imaging technology whereby a live motion event is recorded and translated into mathematical terms by tracking defined key points in space over time to create a single three dimensional representation of the performance (Menache, 2011). A recent study has reported on the use of a “3D camera system” to track extra-oral tongue motion in a group of healthy subjects, post-chemotherapy and post-surgical patients (Kappert et al., 2019). A custom-made 3D camera system consisting of three horizontally aligned video cameras was used to track a visible marker (3D paper cube) placed on the tongue tip. Additional markers were placed on glabella, apex of the nose and mental region for image stabilisation. The study reported ROM for the three group’s i.e. healthy subjects, post-chemotherapy and post-surgical patients. The findings of the study should be viewed with caution as there was lack of a clear sample size calculation, which places doubt on the validity of the results. Furthermore, the dynamic motion of the tongue was not assessed and the trajectory of the tongue from one point to another was not considered. The advantage of 3D motion capture technology is that the x, y and z changes of the tongue tip, for instance, can be recorded over the range of motion of the tongue i.e. time. In addition the reproducibility of the outcomes measures, maximal deviation of the tongue tip in the x-direction, while performing the left to right protrusion was assessed by “measuring and processing a single healthy participant five times under the same conditions”. It remains unclear if the subject was re-imaged performing the motion or the measurements retaken on the same image five times. Based on the single patient elevation of the tongue tip could not be reproduced as well as the other movements.

1.5.3 Measurements used to describe range of tongue motion

Previous papers investigating tongue motion have used the Euclidean distance as their outcome measure (Kappert et al., 2019; van Dijk et al., 2016). The Euclidean distance relates to the ‘ordinary’ straight-line distance measured between two separate points, in either 2D or 3D space. The Euclidean distance is made of all the distances in the x, y and z direction, this means that the Euclidean distance based on 3D co-ordinates is overestimated, Figure 1.3. Another disadvantage with relying on Euclidian distance alone, is that it does not reflect direction of displacement but is a one-dimensional reading. For instance the tongue tip could move 20mm from rest downwards on one occasion, and then on the second occasion 20mm to the left. In



$$\Rightarrow d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2}.$$

Figure 1.3 Euclidean distance is made of all the distances in the x, y and z direction.

d = Euclidean distance between point A and point B both instances the tongue tip has displaced 20mm. In this example, tongue displacement, based on the Euclidian distance, was 20mm and therefore would be reported as reproducible, Figure 1.4. However this is clearly incorrect with respect to direction and therefore is not clinically reproducible. The Euclidean distance, taken in isolation, is therefore not a clinically valid measure of range of tongue motion. In fact for tongue ROM reproducibility the motion of the tongue tip can be said to be reproducible based on three assumptions,

1. The tip of the tongue needs to move the same amount (magnitude) in the x, y and z direction, not just the Euclidean distance, for the reasons discussed above.
2. The path followed by the tip of the tongue needs to be the same. For instance the tongue tip may reach the same final position (maximum ROM), on two separate occasions, but may have followed two different paths. This would be reproducible for displacement but not path of motion.
3. The speed of tongue motion should be reproducible, but this is more difficult to control.

The Euclidean distance can provide a snapshot of expected tongue movement that may be useful for a quick reference measurement, performed clinically for instance using a ruler. The alternative analysis of assessing differences in 3D co-ordinates, similarity in tongue tip path and speed measurement would be more clinically valid for comparing individuals and their dynamic range of tongue motion. For example, it could be used to quantify the extent of the residual deformity following a partial

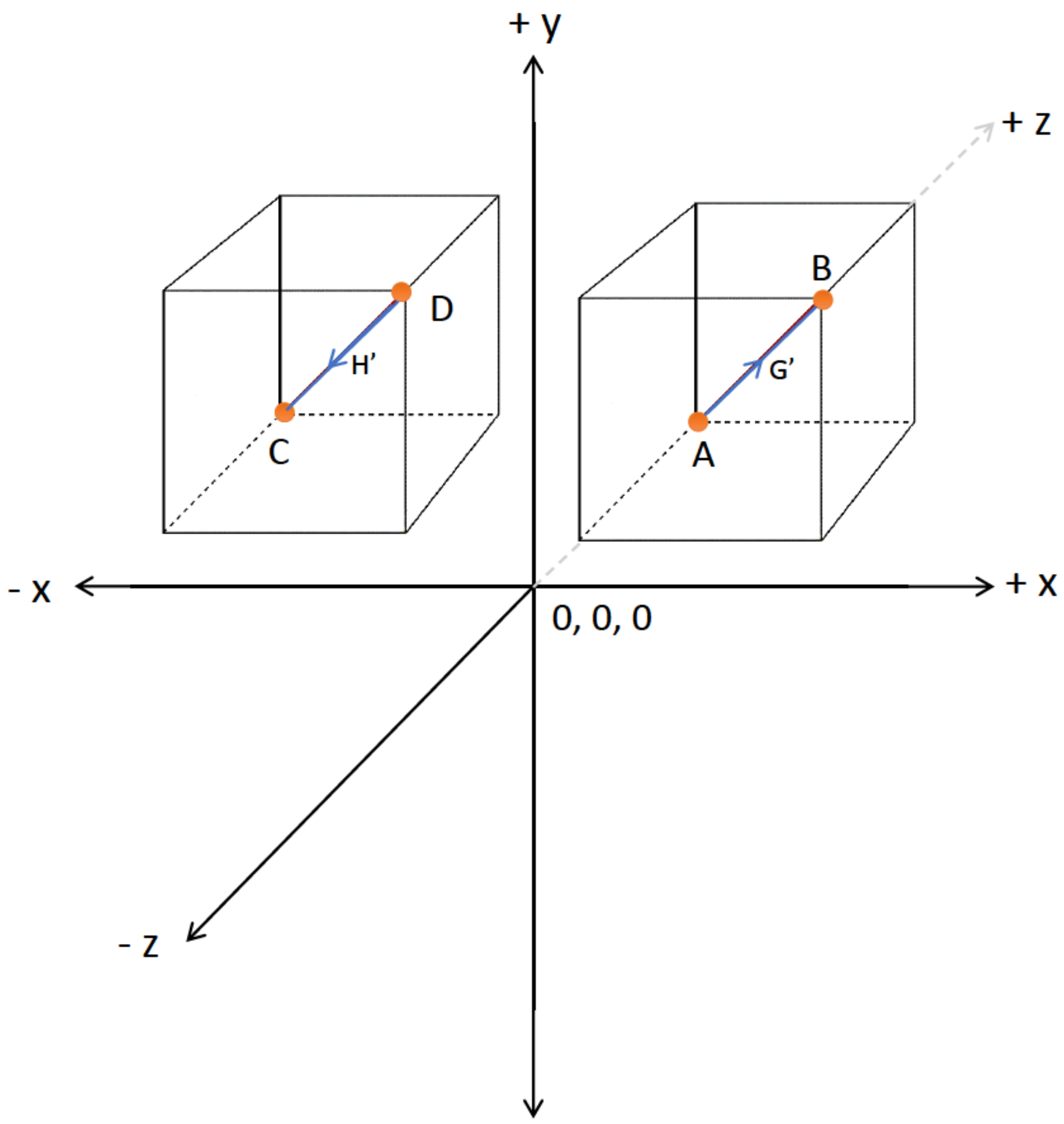


Figure 1.4 Euclidean distance from A to B = G’ (top right)
Euclidean distance from D to C = H’ (top left)

G’ distance =H’ distance in magnitude but NOT direction of motion or final position in 3D space.

glossectomy in comparison to a healthy control. This may provide an object valid tool which could then be used to direct patient-specific physiotherapy.

1.6 THREE DIMENSIONAL MOTION CAPTURE TECHNOLOGY AND ITS CLINICAL APPLICATIONS

1.6.1 Marker-Based and Markerless Technologies

Currently there are two main technology types available for recording 3D motion capture; marker-based or markerless. The marker-based technology traditionally used up to 350 retro-reflective markers to track full-body movement with high-resolution cameras. However other forms of markers can be used such as paper markers composed of a 3D paper cube to enable visibility of the marker at every angle (Kappert et al., 2019). Other marker-based research applications include analysing the kinematics of violinists using spherical surface markers on anatomical landmarks (Wolf et al., 2019). Another more recent advancement involves the use of active LED markers to provide real-time feedback of facial animation. However the markers need to be secured to the individuals face and are in the order of 2mm diameter (Trotman, 2011; Sidequersky et al., 2016). These markers may be lost during capture or potentially restrict facial movement. In addition only the markers are captured and not the facial topography between the markers.

The markerless system, as suggested by the name, does not rely on physical markers but instead track landmarks that are “digitally” placed on the captured image. These can be placed on anatomical points, such as the commissures of the lips or the tip of the tongue. These points can be tracked frame by frame which means they are far more convenient and allow greater expression for the individual being tracked. Problems with this approach have previously included issues with frame rates and resolution; however this problem has reduced with the advancement of camera technologies. Markerless systems have been used to capture facial expressions in cleft patients (Al-Rudainy et al., 2018), oncology patients (Shujaat et al., 2014), facial palsy patients (Alagha et al., 2018), control groups (Lowney et al., 2018) and following orthognathic surgery (Popat et al., 2010).

Markerless technologies are similar to those used in facial recognition systems which identify or verify a person from either a digital image or video frame using a video source. This type of biometric artificial intelligence has been utilised in government security operations, social media and even modern ‘Face ID’ applications on handheld mobile devices. Markerless systems can be further be classified into subcategories including 2D versus 3D tracking, real-time performance, person specific or others where human supervision is needed. The use of markerless 3D motion capture technology has been reported in gait recognition (Sandau, 2016) and in Parkinson’s Disease (Martinez et al., 2018). In addition, studies have compared markerless and marker-based motion capture systems when assessing the kinetics of human movement using knee flexion and leg squat (Perrott et al., 2017). The study reported that both markerless and marker-based motion capture systems can capture a similar range of change and that a markerless system adequately describes squat motion.

1.6.2 The science behind three-dimensional imaging

3D imaging approaches can be classified in to three categories. The first would be ‘slice imaging’ such as CT axial data to create 2D reconstructed images. The second is ‘projective imaging’ such as surface layer scanning and the third category is ‘volume imaging’ such as holography (Udupa and Herman, 1991). Whilst projective imaging is the most popular approach, volume imaging provides a more true 3D mode of visualisation (Hajeer et al., 2004).

It is important to establish that unlike 2D imaging, where there are two main axis (x = horizontal and y = vertical), 3D imaging incorporates a third dimension i.e. the z-axis which relates to depth. The x, y and z coordinates therefore define the three dimensional space in which multidimensional data is represented (Hajeer et al., 2004). Digital stereophotogrammetry can be useful in acquiring data from a 3D object using the principle of triangulation. By pre-calibrating the system and taking photographs from at least two different positions, it is possible to extract and analyse 3D coordinates. A 3D model can then formed into a ‘point cloud’ and a mesh created consisting of polygons or triangles, aid visualisation (Deli et al., 2013). A textured surface is then added to the modelled subject to produce a pixeled layer known as ‘texture mapping’. Light and shade is subsequently added to enhance the realism (Seeram, 1997). The benefit of photogrammetry is that you can obtain large visual and angular field data considerably faster than other methods (Deli et al., 2013).

1.6.3 Applications of 3D motion capture systems

Motion capture has been used most commonly in the film industry. It originated with a two dimensional approach using a rotoscope, a device designed by Fleischer in 1915 to help automate cartoon films. This was utilised by Walt Disney Studios in 1937 in the creation of the film Snow White but later became replaced by three dimensional animation and the birth of motion capture (Menache, 2011). Other than the film and television industry, motion capture is also commonly used in computer animation and video games. Video game character actors wear special outfits that allow computers to translate their motion into three dimensional animation using reflective markers for motion capture (Menolotto, 2020). In more recent years, motion capture has been utilised by researchers to enhance evidence-based medicine. For example, the use of a 3D motion capture system to assess shoulder dysfunction during bilateral arm abduction (Rettig et al., 2015).

1.6.4 Facial imaging using 3D Motion Capture

As outlined above, the shift from the entertainment industry to medical research using motion capture is a recent exploration. Since then, several studies have utilised 3D motion capture for facial imaging research. In 2013, a study was carried out to assess whether such system could be valid in automatically tracking facial landmarks (Al-Anezi et al., 2013). In this investigation, subjects performed three facial expressions which were both manually digitised and automatically tracked using the DI4D system. 23 facial landmarks were marked on each participant's face using an ink pen and particular facial motions such as 'maximal smile' were carried out. The findings were that automatic tracking had a clinically satisfactory level of accuracy (within 0.55mm) to facilitate analysis of dynamic facial movements. The significance of these findings has allowed for later studies to be carried out using automatic tracking as opposed to manual digitisation (Kappert et al., 2019; van Dijk et al., 2016).

A pilot study was performed to assess dynamic facial movements in head and neck oncology patients using the Di4D motion capture system (Shujaat et al., 2014). Each movement was recorded with a frame rate of 60 per second and soft tissues were landmarked and tracked over sequential frames. The researchers reported that the Di4D capture system can be implemented as an objective tool when looking at facial soft tissue movements and can be used for assessing impacts such as surgical interventions. They noted that previous attempts at video based tracking of facial soft tissue movements required physical retro-reflective markers or infrared signal markers to be applied to the area of interest (Hontanilla and Auba, 2008; Kohn et al., 1995). With this technology using retro-reflective markers, motion data is analysed by identifying the same distance between two landmarks which is referred to as the ‘interlandmark distance’. The facial landmarks are then scaled to the same size and changes over the interlandmark distance are calculated (Trotman, 2011). A similar approach was used but with an automatic optical 3D motion capture system called ‘FACIAL CLIMA’ (Hontanilla and Auba, 2008). This system also used reflective markers on subjects faces followed by three infra-red light cameras to track various facial motions with the use of capture algorithms. The positioning of the three cameras was particularly important to ensure that all reflective markers were translated to 3D. Another study reported on lip shape during speech using a motion capture system called 3DMDFace^{TM} (Popat et al., 2013). In this approach, six landmarks were manually placed around the lips and geometric morphometrics was used to extract three dimensional coordinate data for participants' lip shapes as they spoke specific words. With all these studies involving markers, the process involved is time consuming and difficult for the operator to place in the correct position, but it could also affect the spontaneous movements that were intended to be recorded. In addition, markers can be difficult to place in younger subjects, particularly infants or toddlers. Other authors have also suggested further problems such as marker occlusion and or slippage (Begg and Palaniswami, 2006). Given the moist surface of the tongue it would be difficult to secure or adhere markers to the tip.

As a result of these short comings, the introduction of marker-less systems have become increasingly popular. One such set-up was introduced utilising a calibration of four cameras (three infrared and one colour digital camera) whilst subjects wore a sun-visor with a checkerboard print. An infrared pattern was then projected onto them and the points of intersection of the checkerboard pattern were manually designated with a computer mouse (Mishima et al., 2006). In this way, physical markers were not required but instead the immobile points obtained from this checkerboard pattern were tracked across the image sequence using a specific algorithm. The accuracy of the obtained range image was also analysed using a positioning actuator which found the differences from known values ranged from 0.53 to 0.73mm in length and 0.14 to 0.44mm in width.

It is worth noting that even with the newer systems such as Di4D, there are challenges that need to be addressed. The investigator is still required to reliably landmark the appropriate structures manually over the digital interface for the first frame. This is then automatically tracked over subsequent frames which reduces manual landmark placement error. However, to initially identify the chosen landmarks, standardisation and inter / intra-rater reliability needs to be carried out to ensure validity and reliability of the results. Based on this technology further work has also been done on assessing the reproducibility of nonverbal facial expressions using Di4D motion capture (Ju et al., 2016). The study reported no statistical difference in magnitude and speed for three nonverbal facial expressions over two captures. For this particular study, the investigators pre-marked the landmarks on the subjects faces prior to testing to reduce errors in digitization. However, as discussed by the authors themselves, pre-marking is not a pre-requisite or obligate step in using this system and may not be possible in the real world. A more recent study has reported a normative dataset of dynamic nasolabial complex motions during maximal smiles (Lowney et al., 2018). The authors explain the importance of assessing dynamic motions in four dimensions as opposed to measuring Euclidian distances which underestimates differential movements over the x, y and z axis. It is clear from the current studies undertaken using this technology that there are wider applications then just facial movements, in particular identifying normative baselines of motion.

1.7 SUMMARY OF LITERATURE REVIEW

The development of the tongue arises from a series of lateral swellings from the pharyngeal arches during the late fourth week of development. The tongue has a complex anatomy comprised of intrinsic and extrinsic muscles. It is innervated by the hypoglossal and glossopharyngeal nerves and the lingual artery serves its blood supply.

Tongue dysfunction can result in numerous complications including obstructive sleep apnoea, dysphagia or aphasia (Sanders and Mu, 2013).. This can particularly be seen with patients with neurological or degenerative conditions as well as abnormal tongue anatomy. The tongue has also consistently been classified as one of the highest risk sites for head and neck cancer (Gupta et al., 2016). Resections of the tongue have been shown to cause numerous problems such as speech and swallowing difficulties and a reduced quality of life (Andersson et al., 2011). The importance of understanding normal and abnormal tongue function and range of motion can therefore be appreciated.

Tongue motion can be assessed both intra-orally and extra-orally with various grading systems and measurements being available. Various imaging systems have examined tongue motion in the literature, this includes but is not limited to magnetic resonance imaging, ultrasound, electromyographic activity, 3D imaging stereophotogrammetry and 3D motion capture. The latter offers the latest technology in assessing extra-oral tongue range of motion, with the development of both markerless and marker-based technologies available. The science behind 3D motion capture focuses on three categories; slice imaging, projective imaging and volume imaging (Udupa and Herman, 1991). This technology has many different applications both in the health and science industries as well as in the film, computing and gaming sectors. It is only within the last decade or so that 3D motion capture has been readily utilised for facial imaging research, including a limited number of papers looking at tongue range of motion. Unfortunately, these papers have their associated shortcomings including issues with sample sizes or downfalls within their methodology. As a result, a more robust study would need to be undertaken to address these issues and be able to definitively address the question of tongue reproducibility.

CHAPTER 2

AIMS AND NULL HYPOTHESIS

2.1 AIMS OF THE STUDY

The aim of this study was to determine the reproducibility of extra-oral tongue motion using a markerless 3D motion capture system. Reproducibility, in this study, is defined as the ability of individuals to move their tongue tip to the same position in 3D space (x, y and z directions), whilst following the same path of motion, on two separate occasions. Tongue tip reproducibility when performing right to left and up and down movement was assessed. Differences (mm) in the x, y and z co-ordinates of the tongue tip between the two occasions provided the outcome measure of reproducibility. Differences in tongue tip position 5.0mm and above, were deemed to be clinically significant.

2.2 NULL HYPOTHESES

- There were no statistically significant differences ($p<0.05$) in tongue tip position (x, y and z-direction and Euclidian distance) for right to left tongue motion, on two different occasions. In addition, any differences were not 5.0mm or greater.

- There were no statistically significant differences ($p<0.05$) in tongue tip position (x, y and z-direction and Euclidian distance) for up and down tongue motion, on two different occasions. In addition, any differences were not 5.0mm or greater.

The normative range of tongue movement right to left and up and down was also determined.

CHAPTER 3

MATERIALS AND METHODS

3.1 ETHICAL APPROVAL

Ethical approval was granted by the Science, Technology, Engineering and Mathematics Ethical Review Committee, the University of Birmingham, (REC reference number ERN_17-0823R).

3.2 STUDY PARTICIPANTS

This was a prospective investigation of healthy adult volunteers. All participants were recruited from October 2018 to March 2019. Volunteers were selected by identifying staff members and students who worked at the Birmingham Dental Hospital who satisfied the inclusion criteria. The individuals were approached to participate in the study and those who were interested were then asked specific questions to identify whether they met the inclusion and exclusion criteria. The inclusion criteria for the study were as follows:

- Males or females aged 18 to 60.
- Medically fit and well.
- Willing to participate in the study.
- English speaking.
- Forehead uncovered and clearly visible.

The exclusion criteria for in the study were as follows:

- Historical or existing oral cancer.
- Participants who have undergone a glossectomy procedure.
- Participants receiving care from speech and language therapists.

- Historical or existing neurological defects that may alter function e.g. Parkinson’s disease, stroke, or epilepsy.
- Presence of tongue piercing(s).
- Participants with a tongue tie.

3.3 SAMPLE SIZE CALCULATION

The sample size calculation determined a minimum of 30 individuals would be necessary to detect a difference of 5mm in tongue motion between the same individual on repeat occasions. Van Dijk et al., (2016) reported a difference of 5.3mm in tongue motion between the ‘healthy’ group and post-glossectomy patient group. The same authors reported varying standard deviations from 5.2mm to 10.9mm depending on the different tongue movements in the healthy group. For this calculation, a standard deviation of 10mm was used to give a reasonable sample size. Power was set at the 80% level with $\alpha=0.05$.

3.4 MATERIALS AND METHODS

3.4.1 Participant recruitment and training

The study was explained verbally to each volunteer and through written information sheets (Chapter 8) which were handed to participants prior to conducting the investigation. If the volunteer was happy to participate in the study and met the criteria, written consent was obtained (Chapter 8). The following demographic details were recorded: age and gender, for epidemiological purposes.

Volunteers were allocated an appointment time to meet the principal researcher (NA) in order to conduct the investigation. The volunteers were shown a short video clip of an individual making the tongue movements that were required. The volunteers were asked to practice the two tongue movements (up and down and right to left) using a handheld mirror, in accordance with verbal instructions by the principle researcher and video clip. The participants were asked to make the tongue motion with minimal movement of the mandible.

3.4.2 Tongue motion capture system

All data collection was conducted in the Birmingham Dental Hospital using 4D imaging system, DI4D Pro (Dimensional Imaging Ltd, Hillington, Glasgow, U.K.), a markerless high fidelity facial motion capture system, Figure 3.1. The motion capture system was made up two banks of camera; each bank was made up of two black and white cameras and a central colour video camera. For left to right tongue motion capture both banks of cameras were required as tongue motion transversed the left and right sides of the face, Figure 3.2. For up and down tongue motion, only one bank of cameras was required as tongue motion was in one plane i.e. vertical, Figure 3.3.

3.4.3 Calibration

Prior to image capture the 4D motion capture system was calibrated according to the manufactures instructions. The purpose of the calibration was to record the internal and external camera perimeters that would be used by the software to reconstruct the 3D depth of the image. Calibrating the two camera banks for recording left and

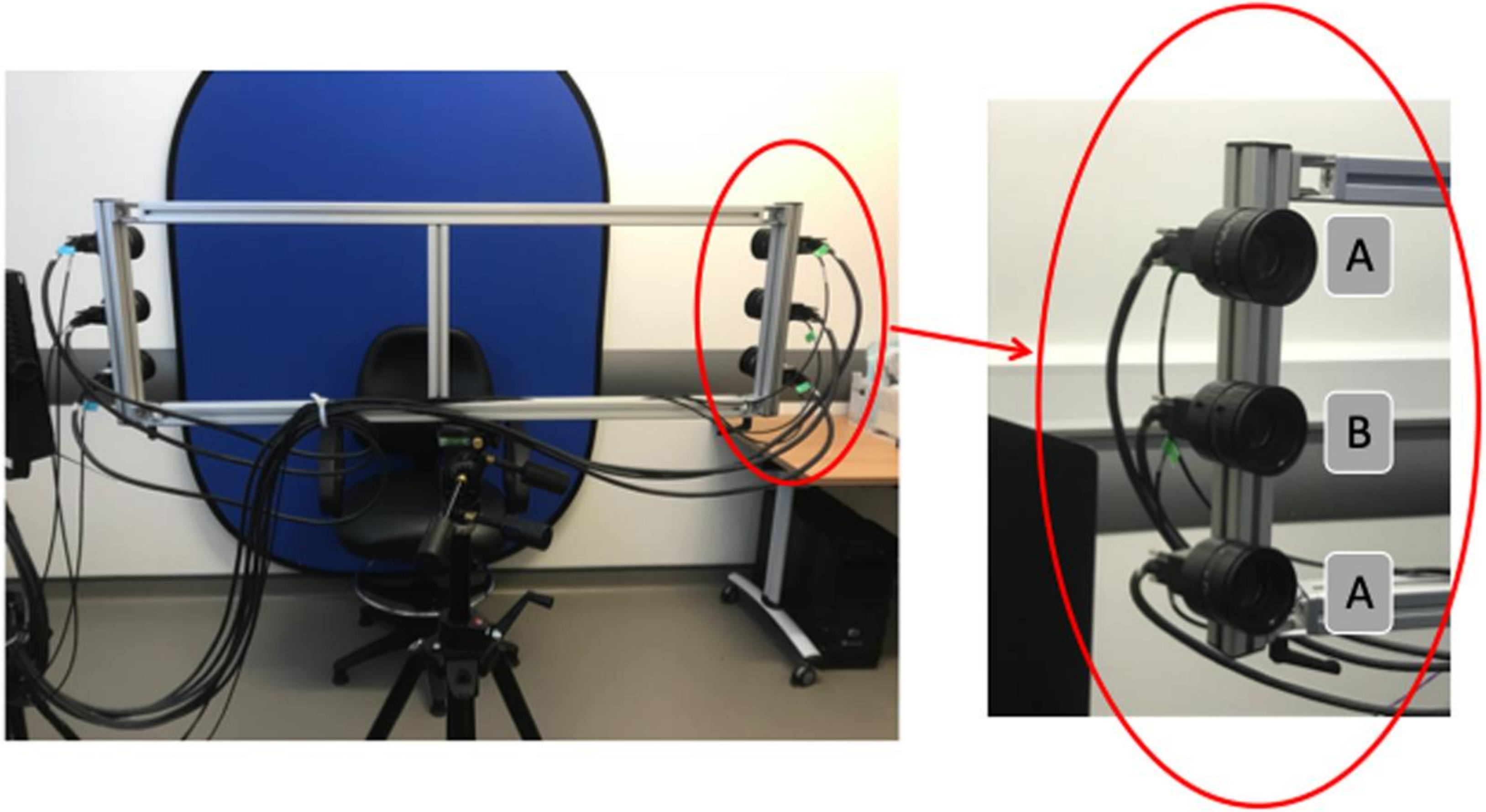


Figure 3.1 DI4D Pro Facial motion capture system. Two banks of camera; each made up of two black and white cameras [A] and a central colour video camera [B].

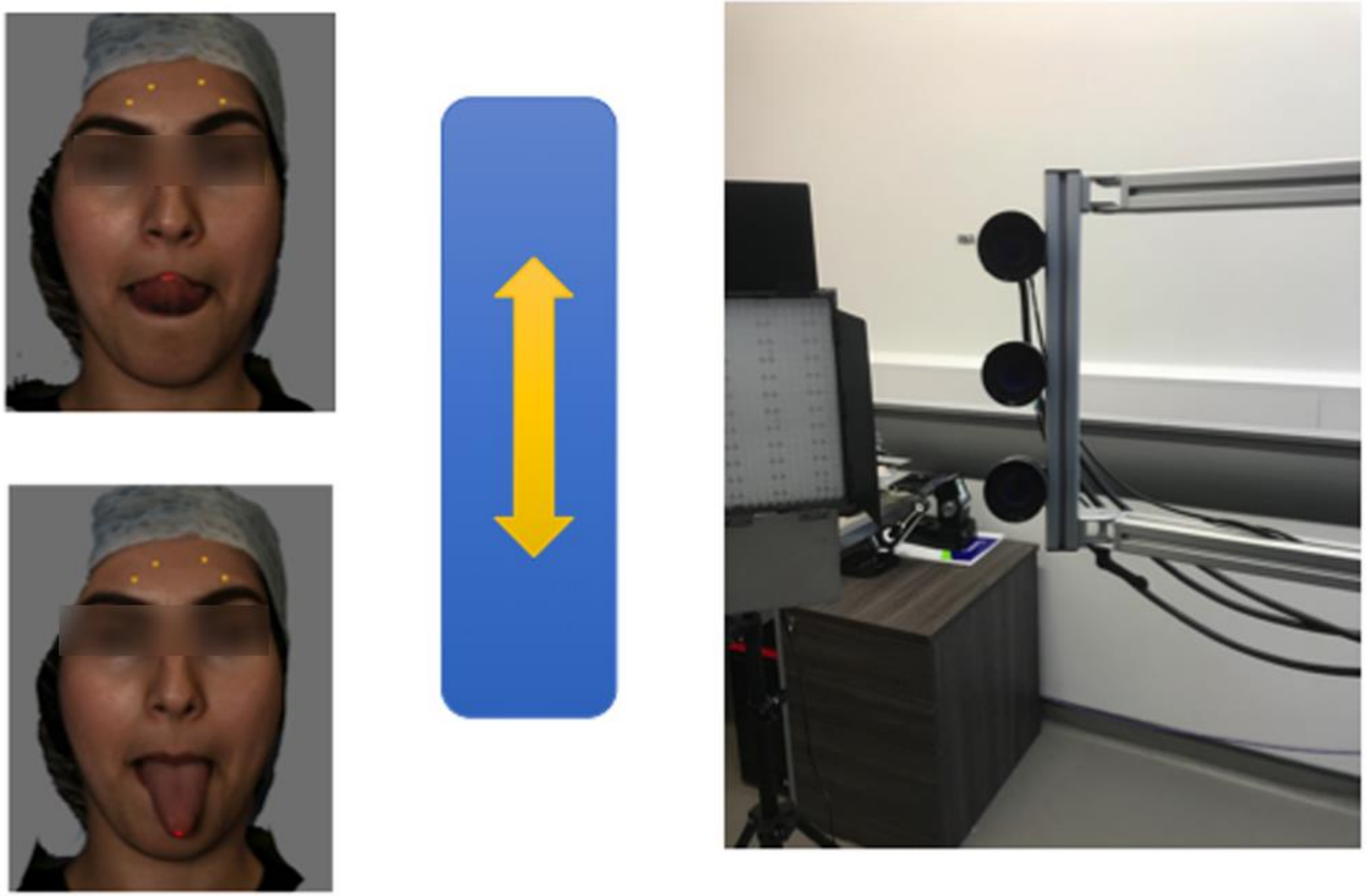


Figure 3.2 For left to right tongue motion capture both banks of cameras were required as tongue motion transversed the left and right sides of the face.

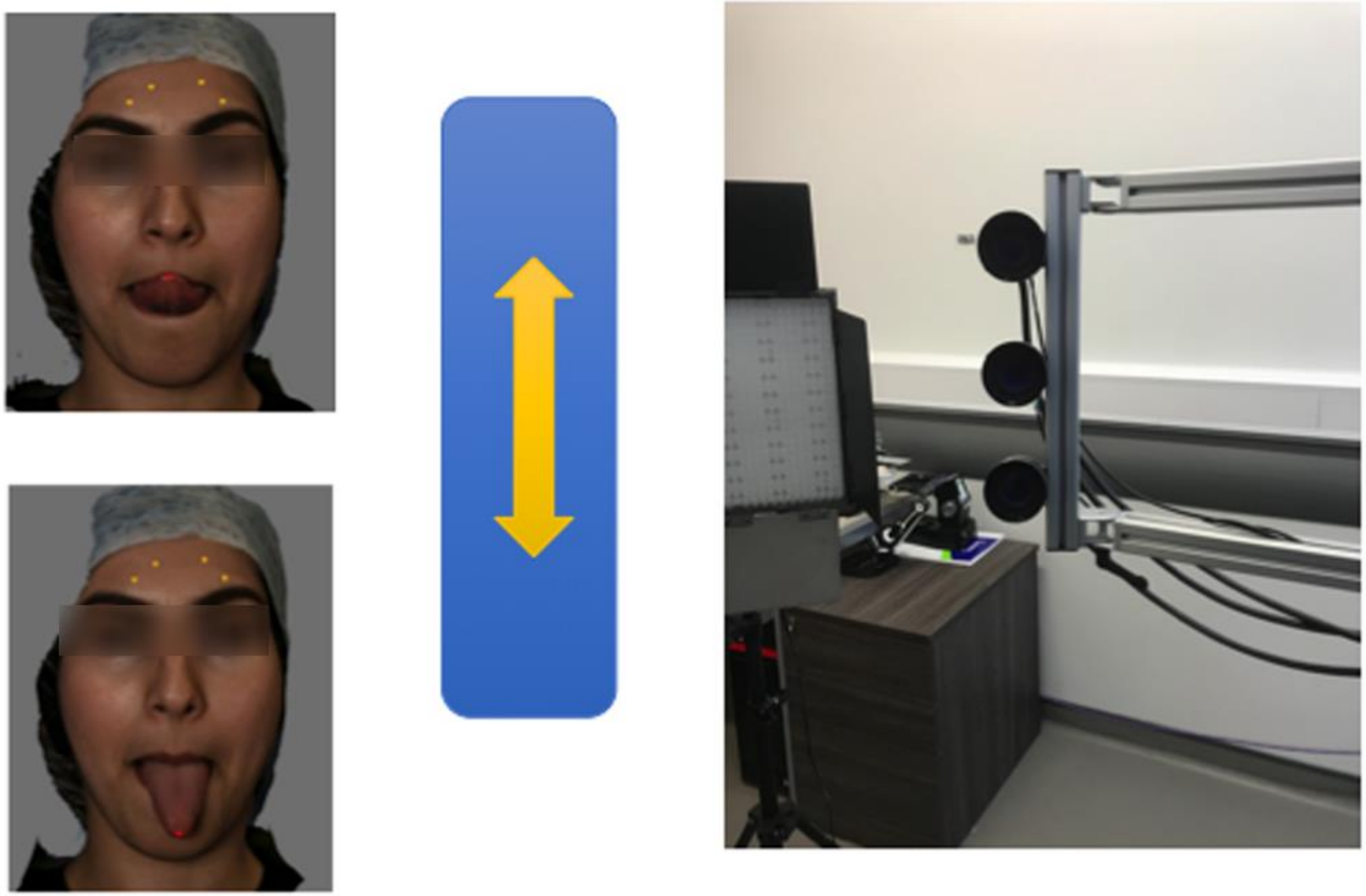


Figure 3.3 For up & down tongue motion, one bank of cameras was required as tongue motion was in one plane i.e. vertical.

right tongue motion required the capture of a calibration target, supplied with the system, in a minimum of six different positions. All the images of the calibration target needed to be captured by all six cameras. For capturing up and down tongue motion only one bank of cameras (three cameras) needed to be calibrated. Again this involved capturing the calibration target in a minimum of six different positions. This time the calibration target needed to be seen in all three cameras within the one bank of cameras. The images for each calibration were stored and uploaded into DiHydra (Dimensional Imagining Ltd, Hillington, Glasgow, UK), which then produced a calibration file containing the internal, and external camera parameters.

3.4.4 Participant capture

Each participant was positioned directly in front of the 4D capture system, in between the two camera banks, at the required distance. A head cap or hair band was used to make sure the forehead was clearly visible. Prior to image capture, the participant's head was orientated so Frankfort Plane was parallel to the floor. They were then asked to perform a right to left tongue motion, repeated 2-3 times, during which the sequence was recorded at 60 frames per second (60 fps) based on the previously rehearsed tongue movements.

For up and down tongue motion recording, the participant was rotated to face one of the camera banks and asked to perform an up to down tongue motion, repeated 2-3 times, again the video sequence was recorded at 60 frames per second (60 fps). The right to left and up and down video sequences for each participant was saved based on unique identification number at $T_{1,}$ for processing at a later time. Each participant was asked to wait for a minimum of 15 to 30 minutes, in which time they were free to leave the room, prior to returning to record the same tongue motions for a second time (T_2).

3.4.5 4D motion capture sequence build

For each participant the video sequence at T_1 was viewed in its entirety and the frame number with the tongue tip furthest over to the right was noted as well as the frame number with the tongue tip furthest to the left. This portion of video sequence together with the appropriate calibration file (2 camera bank) was loaded into DiHydra. Using the “build” function in DiHydra the 3D motion capture sequence was produced. This was a series of 3D images, one taken every 1/60th of second, from the frame with the tongue tip to the extreme right to the tongue tip over to the extreme left. This was repeated for the video sequence, right to left tongue motion, at T_2. In addition the up and down extreme frames at T_1 were chosen, imported in DiHydra together with the calibration (one camera bank) and a sequence of 3D images build. This was also repeated for T_2 up and down tongue motion. In total for each participant four 4D motion sequences were produced and saved for further processing. Each 4D motion sequence was around 20 Gigabytes in size.

3.4.6 Image superimposition and alignment

The first frame / 3D image of the right to left motion capture sequence was loaded into Di3DView. The image was re-oriented so the intersection of the x, y and z planes (0, 0, 0) were at soft tissue nasion and the inter-canthal line (X-Z plane) and the Frankfort Plane were parallel to the axial plane. The sagittal plane (Y-Z plane) was down the middle clinical facial midline and the coronal plane (X-Y plane) was parallel to the facial plane, Figure 3.4. This frame was then saved as the "anchor" frame. The first frames of the remaining three sequences were superimposed onto the anchor frame using the forehead as a stable patch. This involved selecting a patch on the forehead of the anchor frame and aligning the next anchor frame to it, and saving it in the new location. The aim of this stage was to align all the first frames of each of the four sequences to the anchor frame so they all in the same orientation to the three planes and the intersection (0, 0, 0) at nasion. The software then realigned all the 3D images in the remaining sequences to the aligned anchor frame, thereby ensuring all four sequences were in the same 3D co-ordinate space.

3.4.7 Landmarking

For each participant the T_1 re-aligned video sequence for right to left tongue motion was imported into Di3DView (Dimensional Imagining Ltd, Hillington, Glasgow, UK). Five landmarks were placed on the first image of the sequence; four landmarks were placed on the forehead, for image stabilisation, and one on the tip of the tongue, to measure tongue motion, Figure 3.5. The image could be viewed from three different positions to ensure the tongue tip landmark could be accurately placed, Figure 3.6. Using the "automatic landmark tracking" function in Di3DView, which had been previously validated (Al-Anezi et al., 2013), the forehead landmarks were used to stabilise the image, whist the tongue tip landmark was automatically tracked through the remaining video sequence. Image stabilisation ensured any head movement was eliminated and did not contribute to "apparent" tongue motion. This procedure was repeated for the three remaining video sequences i.e. right to left tongue motion at T_1

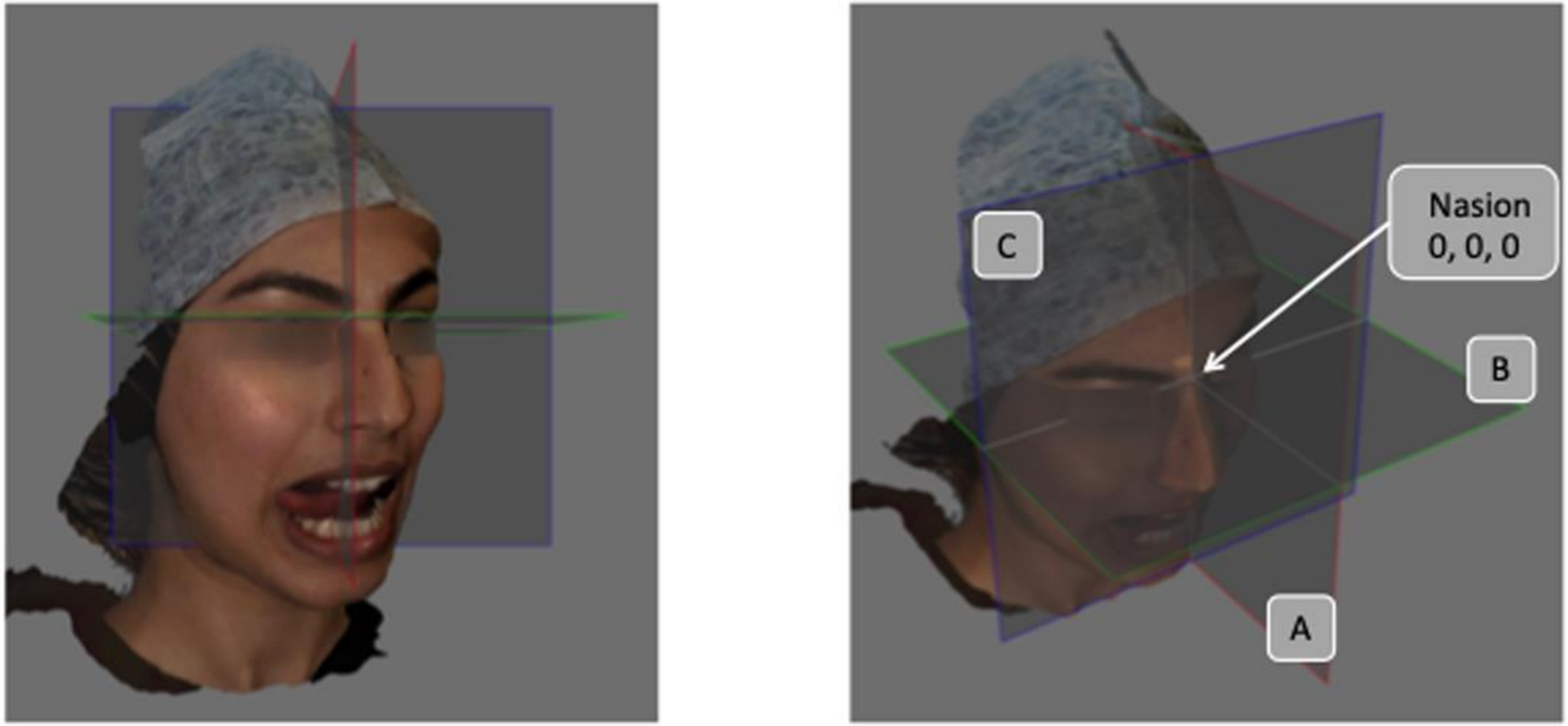


Figure 3.4 Re-orientation of first image to soft tissue nasion (0, 0, 0). The inter-canthal line (B) and the Frankfort Plane were parallel to the axial plane. The sagittal plane (A) was down the middle clinical facial midline and the coronal plane (C) was parallel to the facial plane.

Figure 3.5 Digitised landmarks - four landmarks on the forehead, for image stabilisation, and one on the tip of the tongue, to measure tongue motion.

Figure 3.6 Three different views to allow accurate placement of the tongue tip landmark.

and up and down tongue motion at T_1 and T_2. This produced a .PC2 file containing the x, y and z co-ordinate data for the tongue tip landmark, for each frame / 3D image. This file was saved and using in-house developed code (MATLAB software) and following data measurements were extracted for each tongue movement i.e. right and left and up and down,

1. The maximum range of motion (ROM) of the tip of the tongue (Euclidian distance).
2. Differences in the maximum range of motion (ROM) of the tip of the tongue between T_1 and T_2 for the Euclidian distance and in the x, y and z-direction (mean and absolute mean differences).
3. The Fréchet distance was used to quantify the difference in the path of tongue tip motion between T_1 and T_2. Given that tongue tip movement occurs over a different duration between T_1 and T_2, Figure 3.7a, the “displacement over time graphs” at T_1 and T_2 need to be “dilated” or “compressed” to a common timeline using a process of “dynamic time warping”, Figure 3.7b. Following this mathematical process the displacement over time graphs can be plotted and the distance between the curves calculated, Figure 3.7c. If the tongue tip path of motion were identical on both occasions then the Fréchet distance would be zero, the more dissimilar the paths of motion the greater the Fréchet distance. The Fréchet distance, between T_1 and T_2, in the x, y and z-directions and for the Euclidian distance, were calculated, Figure 3.7d.

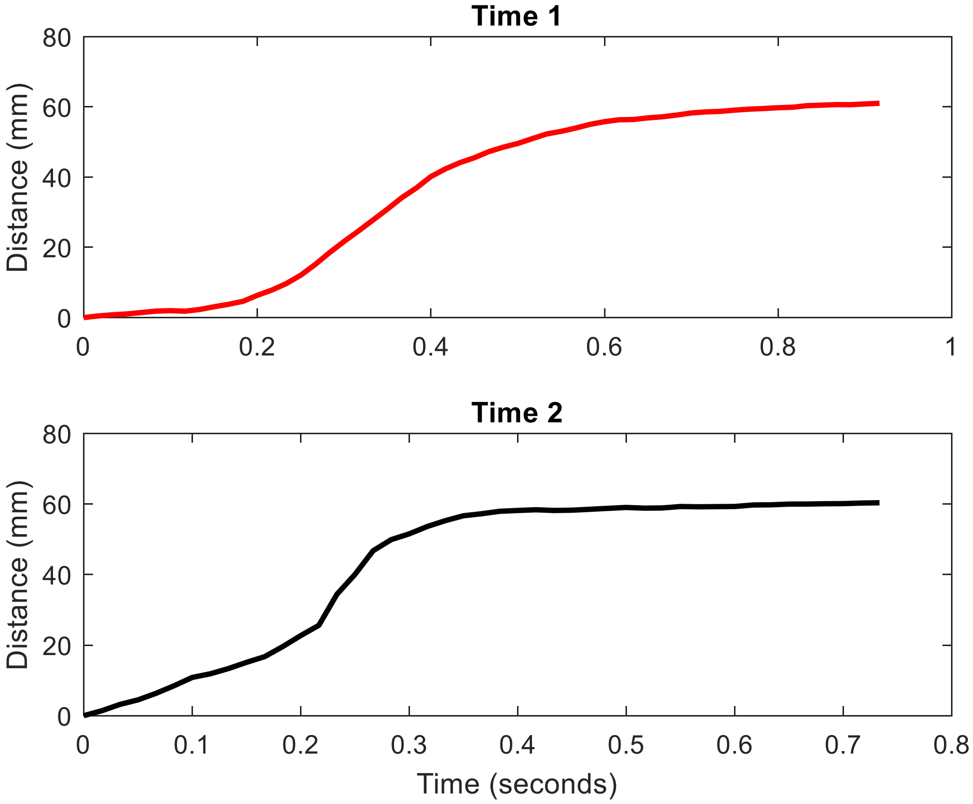


Figure 3.7a Right and left tongue tip displacement (Euclidian distance) over time at Time 1 (T_1) and Time 2 (T_2) – an example volunteer. Note the different duration of movement in the x-axis - Time

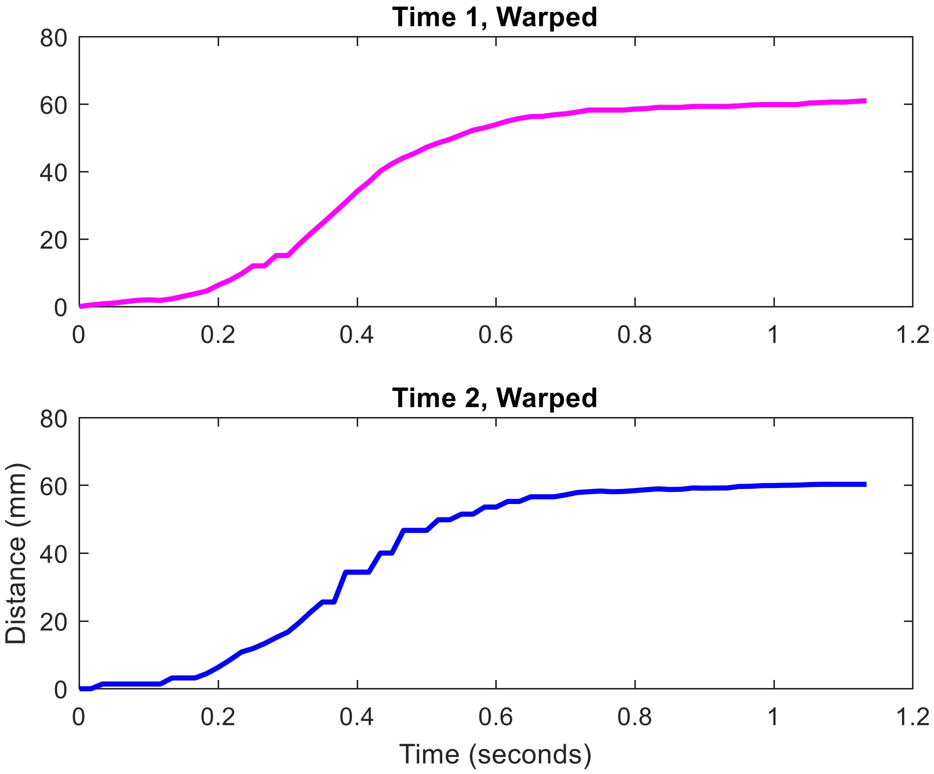


Figure 3.7b Right and left tongue tip displacement (Euclidian distance) over time at Time 1 (T_1) and Time 2 (T_2) following dynamic time warping - an example volunteer. Note the same duration of movement in the x-axis - Time

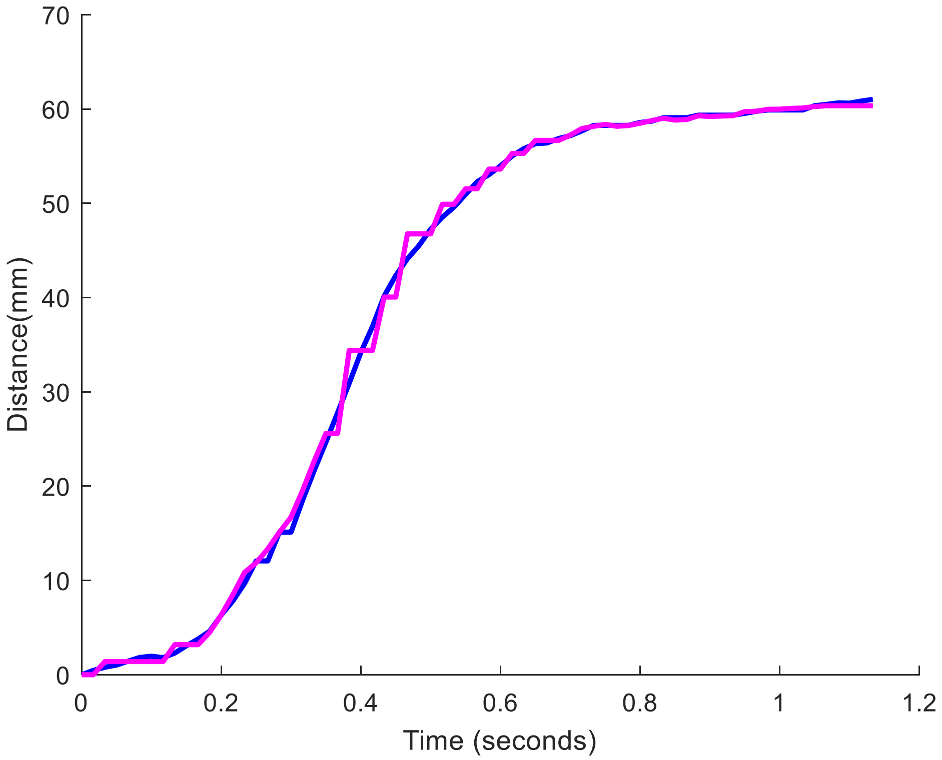


Figure 3.7c Right and left tongue tip displacement curves superimposed (Euclidian distance) over time at T_1 (pink) and T_2 (blue) - an example volunteer.

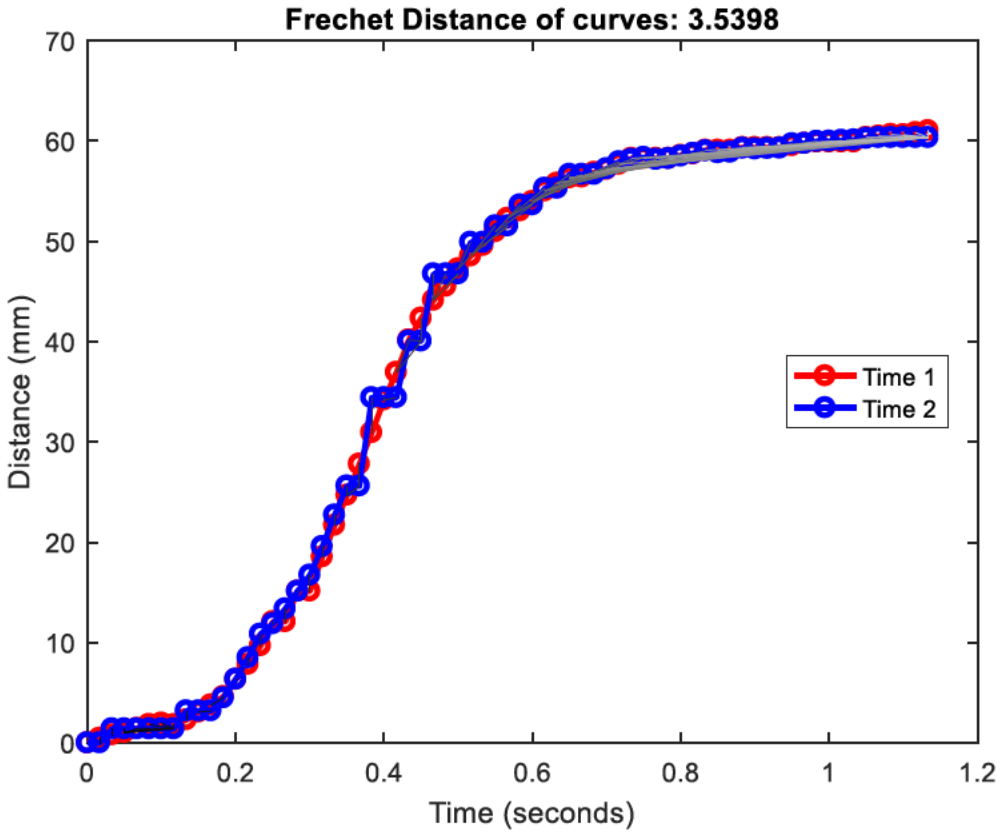


Figure 3.7d Fréchet distance for right and left tongue tip displacement (Euclidian distance) over time at Time 1 (T_1) and Time 2 (T_2) - an example volunteer.

3.4.8 Error study

An error study was performed to assess the reproducibility of landmark placement and tracking. Each of the 30 participants had four capture sequences (right to left and up and down tongue motions at T_1 and T_2) totalling 120 sequences. A 10% sample (12 sequences) were randomly selected for the error study, comprising of both types of tongue motion. For each of the 12 sequences, the images were re-landmarked (four on the forehead and the tip of the tongue), and the sequence re-tracked. The x, y, z coordinates of tip of the tongue landmark were recorded for the last frame and compared to the coordinates from the originally analysed dataset to assess landmark placement and tracking error. Systematic error was assessed by paired *t*-tests and random error assessed by coefficients of reliability.

3.4.9 Analysis

3.4.9.1 Range of motion

The data was checked for normality using the Kolmogorov-Smirnov test and the differences were found to be normally distributed.

A paired-samples *t*-test was used to determine whether there was a statistically significant ($p<0.05$) difference in mean tongue tip displacement (x, y and z-direction and, Euclidian distance) on two separate occasions (T_1 and T_2), for each of the tongue movements.

In addition, a one-sample *t*-test was used to determine if the mean absolute difference (x, y and z-direction and, Euclidian distance) of the tongue tip was statistically significantly different to 5.0mm i.e. was the difference clinically significant.

3.4.9.2 Path of motion

The Fréchet distance was used to quantify the difference in the path of tongue tip motion between T_1 and T_2. If the tongue tip path of motion were identical on both occasions then the Fréchet distance would be zero, the more dissimilar the paths of motion the greater the Fréchet distance. The Fréchet distance, between T_1 and T_2, in the x, y and z-directions and for the Euclidian distance, were calculated.

CHAPTER 4

RESULTS

4.1 RESULTS

4.1.1 Demographics of the sample

Volunteers were recruited from October 2018 to March 2019 at the Birmingham Dental Hospital. Participants were a convenience sample recruited from Staff and Students who consented to participate in the research. Interested participants were given a "Patient Information Sheet" explaining the study aims and methods. In total fifteen female and fifteen male volunteers were recruited. The age of the participants ranged from 21 to 44, with a mean age of 27.5 years.

4.1.2 Intra-rater reliability

There was no systematic error as all the p-values were greater than 0.05. In addition there was no random error as all correlation coefficients were greater than 0.95 (Stirrups, 1993). The absolute mean difference was less than 1mm in all three directions. The error of the method was smaller than the clinical differences that were determined to be clinically significant, Table 4.1.

4.1.3 Reproducibility of up and down tongue movement

4.1.3.1 Horizontal direction (x-direction)

At T_1, whilst the tongue was in the most elevated position, the mean horizontal displacement of the tongue tip from the sagittal plane was 1.5 ± 3.1mm. At T_2, the mean displacement of the tongue tip from the sagittal plane was 1.0 ± 3.4mm. The mean difference of the tongue tip, between T_1 and T_2 was 0.6 ± 2.1mm. The absolute mean difference in the horizontal direction of the tongue tip between T_1 and T_2 was 1.7 ± 1.3mm. The upper limit of the 95% confidence interval for the mean difference

	x-direction	y-direction	z-direction
Mean difference (mm)	-0.1	0.2	-0.1
SD (mm)	0.7	0.8	0.7
Absolute Mean difference (mm)	0.4	0.7	0.6
SD (mm)	0.5	0.5	0.3
Systematic error (p-value)	0.7670	0.4450	0.5875
Random error (coefficient)	0.99	0.99	0.99

Table 4.1 Shows the random and systematic error as a result of landmark identification.

was 1.3mm, and -0.2mm for the lower limit. The mean difference in distance of the tongue tip from the sagittal plane, between T_1 and T_2 was not statistically significant ($p = 0.151$).

At its lowest, most inferior position, the tongue tip was -2.2 ± 3.0mm from the sagittal plane at T_1 and -2.7 ± 3.4mm at T_2. The mean difference of the tongue tip, between T_1 and T_2, tip was 0.5 ± 2.4mm, whilst the mean absolute distance of the tongue tip from the sagittal plane was 1.8±1.6mm. The upper limit of the 95% confidence interval for the mean difference was 1.4mm, and -0.4mm for the lower limit. The mean difference in distance of the tongue tip from the sagittal plane, between T_1 and T_2 was not statistically significant ($p = 0.264$). Participants had a similar magnitude of reproducibility of tongue movement in the horizontal direction whilst moving their tongue up (1.7 ± 1.3mm) and down (1.8 ± 1.6mm), Table 4.2 and Figure 4.1

Following a one sample *t*-test, the mean absolute difference of the tongue tip in the medio-lateral direction (x-direction), at T_1 and T_2, was statistically significantly less than 5mm ($p=0.001$, 95% CI = 1.2mm to 2.4mm). This was also the case for the tongue tip in the most depressed position ($p=0.001$, 95% CI = 1.2mm to 2.2mm).

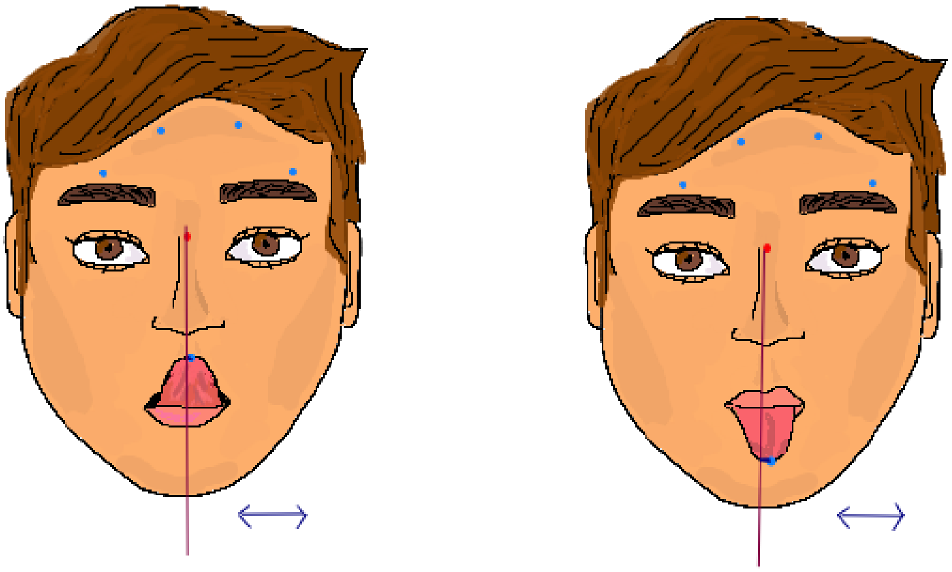
4.1.3.2 Vertical direction (y-direction)

In the vertical direction, relative to the axial plane, the mean position of the tongue tip on full upward movement was 66.2 ± 8.5mm at T_1 and 66.2 ± 7.6mm at T_2. The mean difference was 0.0 ± 2.5mm whilst the absolute mean difference in distance between T_1 and T_2 was 2.1 ± 1.2mm. The 95% confidence interval for the mean difference

Table 4.2 Showing the difference in the x-direction (mm) of the tongue tip between T_1 and T_2 whilst performing up to down tongue movement.

Tongue motion	T_1		T_2		Difference (T_1 - T_2)		Absolute difference		95% CI the for mean difference		p-value
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Upper	Lower	
Up	1.5	3.1	1.0	3.4	0.6	2.1	1.7	1.3	1.3	-0.2	0.151
Down	-2.2	3.0	-2.7	3.4	0.5	2.4	1.8	1.6	1.4	-0.4	0.264

Figure 4.1 Shows the mean and absolute difference in the x-direction (mm) of the tongue tip between T_0 and T_1 whilst performing up to down tongue movement.



Mean difference between
T_1 & T_2
0.6 ± 2.1 mm
95% CI (1.3 to -0.2 mm)

Mean difference between
T_1 & T_2
0.5 ± 2.4 mm
95% CI (1.4 to -0.4 mm)

was 0.9mm to -0.9mm. The mean difference in distance of the tongue tip from the axial plane, between T_1 and T_2 was not statistically significant (p = 0.989).

When the tongue was displaced to its most inferior position, the mean extent of the tongue tip, in a vertical direction relative to the axial plane, was 112.4 ± 11.9mm at T_1 and 113.3 ± 10.9mm at T_2. The mean difference was 0.9 ± 4.6mm in tongue tip distance between T_1 and T_2 and 3.8 ± 2.6mm for the absolute difference. The 95% confidence interval for the mean difference ranged from 2.6mm to -0.8mm. The mean difference in distance of the tongue tip from the axial plane, between T_1 and T_2 was not statistically significant (p = 0.302), Table 4.3 and Figure 4.2.

Following a one sample *t*-test, the mean absolute difference of the tongue tip in it most elevated position in the y-direction, at T_1 and $T_{2,}$ was statistically significantly less than 5mm (p=0.001, 95% CI = 1.7mm to 2.6mm). This was also the case for the tongue tip in the most depressed position (p=0.019, 95% CI = 2.9mm to 4.8mm).

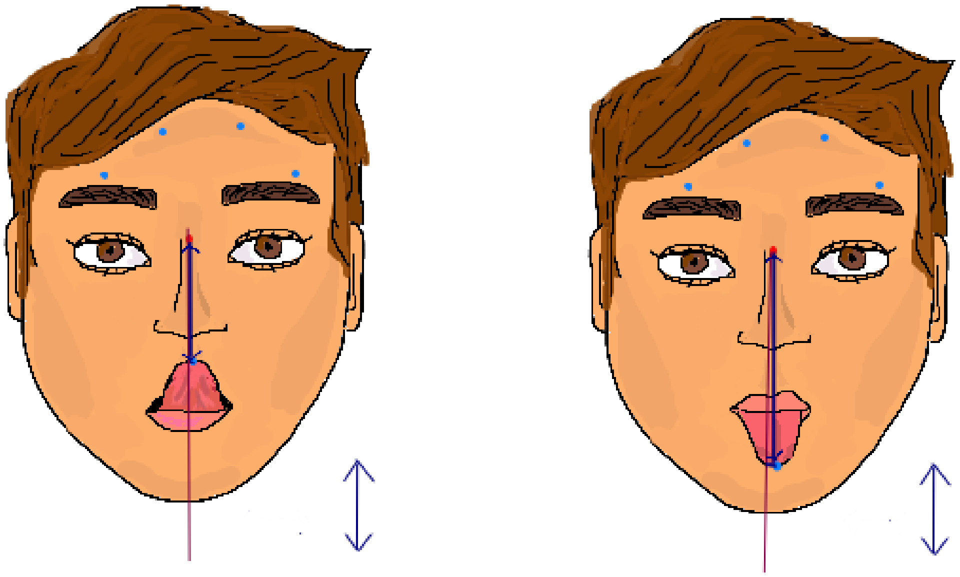
4.1.3.3 Depth (z-direction)

Tongue tip depth position was measured relative to a coronal plan passing through soft tissue nasion. At T_1, when the tongue was elevated, the mean distance between the tip of the tongue and the coronal plane was 1.1 ± 6.7mm At T_2 the mean distance was 1.1 ± 8.3mm in front of the coronal plane; giving a 0.0 ± 5.4mm difference between T_1 and T_2. The absolute difference between T_1 and T_2 was 4.2 ± 3.3mm. The 95% confidence interval for the mean difference was from 1.9mm to -2.1mm.

Table 4.3 Showing the difference in the y-direction (mm) of the tongue tip between T_1 and T_2 whilst performing up to down tongue movement.

Tongue motion	T_l		T_2		Difference (T_1 - T_2)		Absolute difference		95% CI for the mean difference		p-value
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Upper	Lower	
Up	66.2	8.5	66.2	7.6	0.0	2.5	2.1	1.2	0.9	-0.9	0.989
Down	112.4	11.9	113.3	10.9	0.9	4.6	3.8	2.6	2.6	-0.8	0.302

Figure 4.2 Shows the mean and absolute difference in the y-direction (mm) of the tongue tip between T_0 and T_1 whilst performing up to down tongue movement.



Mean difference between
T_1 & T_2
0.0 ± 2.5 mm
95% CI (0.9 to -0.9 mm)

Mean absolute difference
between T_1 & T_2
2.1 ± 1.2 mm
95% CI (1.7 to 2.6 mm)

Mean difference between
T_1 & T_2
0.9 ± 4.6 mm
95% CI (2.6 to -0.8 mm)

Mean absolute difference
between T_1 & T_2
3.8 ± 2.6 mm
95% CI (2.9 to 4.8 mm)

The mean difference in distance of the tongue tip from the coronal plane, between T_1 and T_2 was not statistically significant ($p = 0.938$).

When the tongue was extended to its most inferior position the mean distance between the tip of the tongue and the coronal plane was 17.1 ± 5.1mm at T_1 and 18.4 ±7.2mm at T_2. The differences were 1.3 ± 3.6mm and 3.1 ± 3.6mm for the mean and absolute mean differences, respectively at T_1 and T_2. The 95% confidence interval for the mean difference ranged from 2.6mm to -0.1mm. The mean difference in distance of the tongue tip, moving to the right, from the coronal plane, between T_1 and T_2 was not statistically significant ($p = 0.059$), Table 4.4 and Figure 4.3.

Following a one sample t-test, the mean absolute difference was statistically significantly more than 5mm when the tongue was in the most superior position ($p=0.172$, 95% CI = 2.9mm to 5.4mm) and in the most inferior position ($p=0.001$, 95% CI = 2.3mm to 3.9mm).

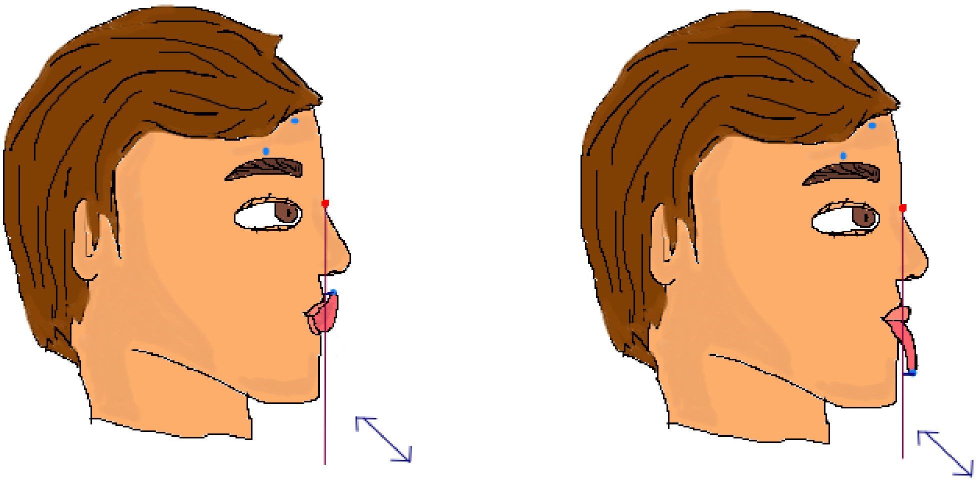
4.1.3.4 Euclidian distance

The mean Euclidian distance from the tip of the tongue at its most upward position to the tip of the tongue in the most downward position (ROM), at T_1 was 47.7 ± 10.1mm compared to 49.0 ± 10.2mm at T_2. The mean difference for the range of motion of the tongue tip between T_1 and T_2 was -1.3 ± 4.8mm; the absolute distance was 4.1 ± 2.6mm. The 95% confidence intervals for the mean difference ranged from 0.5mm to -3.1mm. The mean difference in Euclidian distance of the tongue tip between T_1 and T_2 was not statistically significant ($p = 0.160$), Table 4.5 and Figure 4.4. The

Table 4.4 Showing the difference in the z-direction (mm) of the tongue tip between T_1 and T_2 whilst performing up to down tongue movement.

Tongue motion	T_l		T_2		Difference (T_1 - T_2)		Absolute difference		95% CI the for mean difference		p-value
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Upper	Lower	
Up	1.1	6.7	1.1	8.3	0.0	5.4	4.2	3.3	1.9	-2.1	0.938
Down	17.1	5.1	18.4	7.2	1.3	3.6	3.1	2.1	2.6	-0.1	0.059

Figure 4.3 Shows the mean and absolute difference in the z-direction (mm) of the tongue tip between T_0 and T_1 whilst performing up to down tongue movement.



Mean difference between
T_1 & T_2
0.0 ± 5.4 mm
95% CI (1.9 to -2.1mm)

Mean difference between
T_1 & T_2
1.3 ± 3.6 mm
95% CI (2.6 to -0.1 mm)

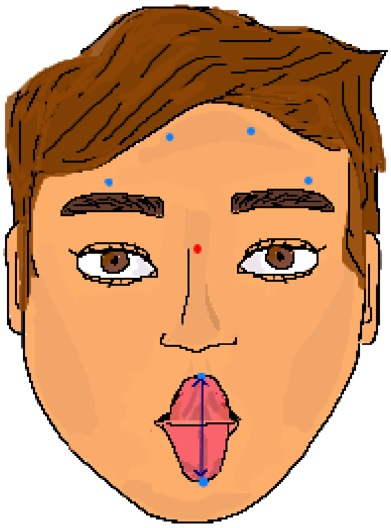
Mean absolute difference
between T_1 & T_2
4.2 ± 3.3 mm
95% CI (2.9 to 5.4 mm)

Mean absolute difference
between T_1 & T_2
3.1 ± 2.1 mm
95% CI (2.3 to 3.9 mm)

Table 4.5 Shows the difference in the range of movement (ROM) (mm) of the tongue tip between T_1 and T_2 whilst performing up to down tongue movement.

Tongue motion	T_I		T_2		Difference (T_1 - T_2)		Absolute difference		95% CI the for mean difference		p-value
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Upper	Lower	
Up to Down	47.7	10.1	49.0	10.2	-1.3	4.8	4.1	2.7	0.5	-3.1	0.160

Figure 4.4 Shows the mean and absolute difference in Euclidian distance (mm) of the tongue tip between T_0 and T_1 whilst performing up to down tongue movement.



Mean difference between
T_1 & T_2
-1.3 ± 4.8 mm
95% CI (0.5 to -3.1 mm)

Mean absolute difference
between T_1 & T_2
4.1 ± 2.6 mm
95% CI (3.1 to 5.1 mm)

difference in Euclidian distance (mm) (ROM) of the tongue tip between T_1 and T_2 whilst performing up to down tongue movement are shown in Table 4.6.

The up and down ROM of the tongue was averaged over T_1 and T_2 resulting in a mean ROM tongue motion of 48.3 ± 10.0mm with a 95% confidence interval of 45.7mm to 51.0mm.

Following a one sample *t*-test, the mean absolute difference in the ROM bases on the Euclidian distance was not statistically significantly different from 5mm when the tongue moved up and down (p=0.076, 95% CI = 3.1mm to 5.1mm).

4.1.4 Reproducibility of right to left movement of the tongue

4.1.4.1 Horizontal direction (x-direction)

Assessing the tongue in lateral motion was standardised with all measurements being taken from right lateral excursion to left lateral excursion. Measurements were taken from the mid-sagittal plane, at T_1 whilst the tongue was protruded to the right, the tip had a mean displacement of 31.9 ± 5.5mm and at T_2 the mean displacement was 31.9 ± 4.9mm; resulting in a mean difference of 0.0 ± 3.8mm between T_1 and T_2. The mean absolute difference was 3.1 ± 2.0mm. The 95% confidence interval for the mean difference ranged from 1.4mm to -1.4mm. The mean difference in distance of the tongue tip from the sagittal plane, between T_1 and T_2 was not statistically significant ($p = 0.999$).

For tongue movement to the left, the T_1 mean displacement was 33.3 ± 4.7mm compared to 34.1 ± 4.6mm at T_2 with a mean difference of 0.8 ± 2.5mm between T_1

Tongue motion	Difference (T_1 - T_2)		95% CI the for mean difference	
	Mean	SD	Upper	Lower
Up	5.6	2.8	6.7	4.5
Down	5.6	2.7	6.6	4.5

Table 4.6 Shows the difference in Euclidian distance (mm) of the tongue tip (ROM) between T_1 and T_2 whilst performing up to down tongue movement.

and T_2. The mean absolute difference was 2.1 ± 1.5mm. The 95% confidence interval for the mean absolute difference ranged from 1.7mm to -0.1mm. The mean difference in distance of the tongue tip, moving to the left, from the coronal plane, between T_1 and T_2 was not statistically significant ($p = 0.080$), Table 4.7 and Figure 4.5.

Following a one sample t-test, the mean absolute difference was statistically significantly less than 5mm when the tongue was to the right ($p=0.001$, 95% CI = 2.3mm to 3.8mm) and in the left ($p=0.001$, 95% CI = 1.5mm to 2.6mm).

4.1.4.2 Vertical direction (y-direction)

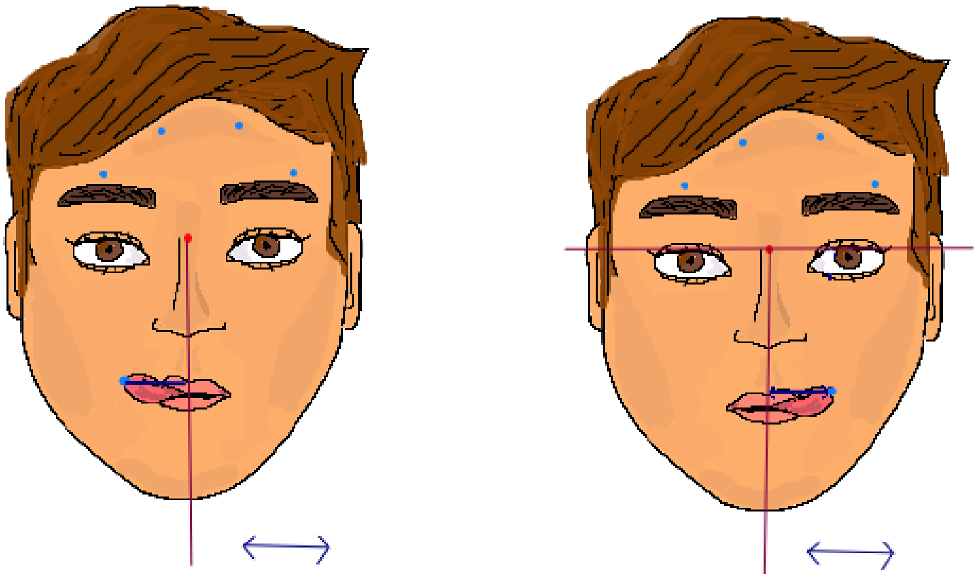
Vertically, relative to the axial plane, the mean position of the tongue tip on full movement to the right was 80.5 ± 6.2mm at T_1 and 80.2 ± 6.8mm at T_2. The mean difference was 0.3 ± 3.5mm whilst the absolute mean difference in distance between T_1 and T_2 was 2.8 ± 2.1mm. The 95% confidence interval for the mean difference was 1.0mm to -1.6mm. The mean difference in distance of the tongue tip from the axial plane, between T_1 and T_2 was not statistically significant ($p = 0.621$).

When the tongue was displaced to the left, the mean displacement of the tongue tip, in a vertical direction relative to the axial plane, was 86.7 ± 7.3mm at T_1 and 86.4 ± 7.9mm at T_2. The mean difference was 0.3 ± 4.0mm between T_1 and T_2 and 2.8 ± 2.1mm for the mean absolute difference. The 95% confidence interval for the mean difference ranged from 1.1mm to -1.7mm. The mean difference in distance of the

Table 4.7 Showing the difference in the x-direction (mm) of the tongue tip between T_1 and T_2 whilst performing right to left tongue movement.

Tongue motion	T_l		T_2		Difference ($T_1 – T_2$)		Absolute difference		95% CI for the mean difference		p-value
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Upper	Lower	
Right	31.9	5.5	31.9	4.9	0.0	3.8	3.1	2.0	1.4	-1.4	0.999
Left	33.3	4.7	34.1	4.6	0.8	2.5	2.1	1.5	1.7	-0.1	0.080

Figure 4.5 Shows the mean and absolute difference in the x-direction (mm) of the tongue tip between T_0 and T_1 whilst performing right to left tongue movement.



Mean difference between
T_1 & T_2
0.0 ± 3.8 mm
95% CI (1.4 to -1.4 mm)

Mean difference between
T_1 & T_2
0.8 ± 2.5 mm
95% CI (1.7 to -0.1 mm)

Mean absolute difference
between T_1 & T_2
3.1 ± 2.0 mm
95% CI (2.3 to 3.8 mm)

Mean absolute difference
between T_1 & T_2
2.1 ± 1.5 mm
95% CI (1.5 to 2.6 mm)

tongue tip from the axial plane to the left, between T_1 and T_2 was not statistically significant ($p = 0.590$), Table 4.8 and Figure 4.6.

Following a one sample t-test, the mean absolute difference was statistically significantly less than 5mm when the tongue was to the right ($p=0.001$, 95% CI = 2.2mm to 4.0mm) and in the left ($p=0.001$, 95% CI = 2.0mm to 3.5mm).

4.1.4.3 Depth (z-direction)

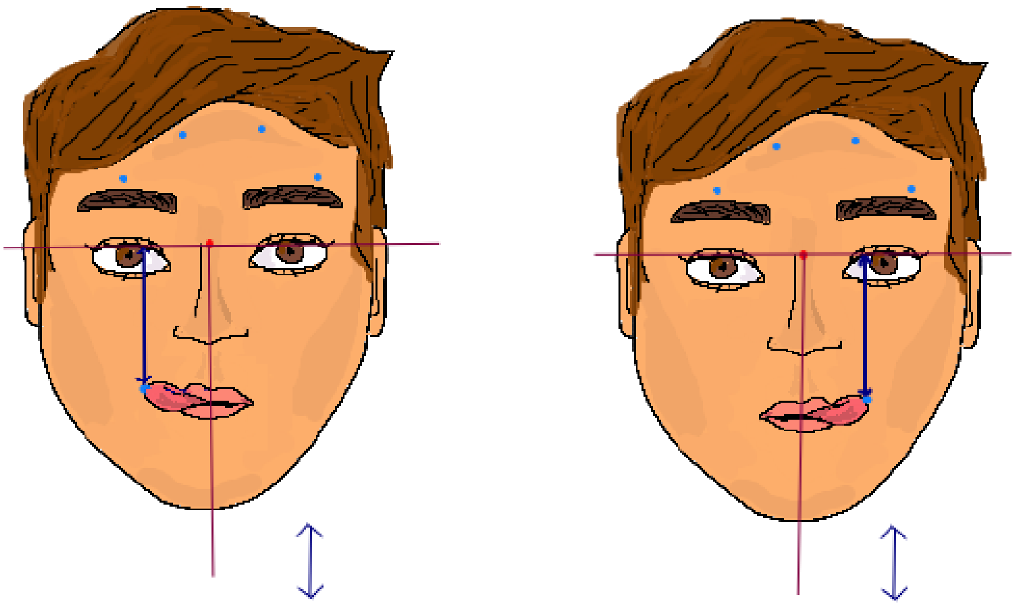
At T_1, whilst the tongue was displaced to the right, the mean distance of the tongue tip from the coronal plane was 10.5 ± 7.6mm; at T_2 the distance was 11.8 ± 6.4mm. The mean difference was -1.3 ± 4.4mm and the mean absolute distance difference was 3.9 ± 2.4mm. The 95% confidence interval for the mean difference between T_1 and T_2 was between 0.4mm and -3.0mm. The mean difference in distance of the tongue tip from the coronal plane to the right was not statistically significant ($p = 0.181$).

As the tongue moved across to the left, there was less change in depth compared to on the right. At T_1 on the left, the mean distance of the tongue tip from the coronal plane was 8.3 ± 6.5mm compared to 9.1 ± 6.0mm at T_2. The mean difference between T_1 and T_2 was 0.8 ± 3.4mm and the mean absolute difference was 2.7 ± 2.2mm. The 95% confidence interval for mean difference ranged from 0.5mm to –2.1mm. The mean difference in distance of the tongue tip from the coronal plane to the left was not statistically significant ($p = 0.232$), Table 4.9 and Figure 4.7.

Table 4.8 Showing the difference in the y-direction (mm) of the tongue tip between T_1 and T_2 whilst performing right to left tongue movement.

Tongue motion	T_l		T_2		Difference ($T_1 – T_2$)		Absolute difference		95% CI for the mean difference		p-value
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Upper	Lower	
Right	80.5	6.2	80.2	6.8	0.3	3.5	2.8	2.1	1.0	-1.6	0.621
Left	86.7	7.3	86.4	7.9	0.3	4.0	3.1	2.5	1.1	-1.7	0.590

Figure 4.6 Shows the mean and absolute difference in the y-direction (mm) of the tongue tip between T_0 and T_1 whilst performing right to left tongue movement.



Mean difference between
T_1 & T_2
0.3 ± 3.5 mm
95% CI (1.0 to -1.6 mm)

Mean difference between
T_1 & T_2
0.3 ± 4.0 mm
95% CI (1.1 to -1.7 mm)

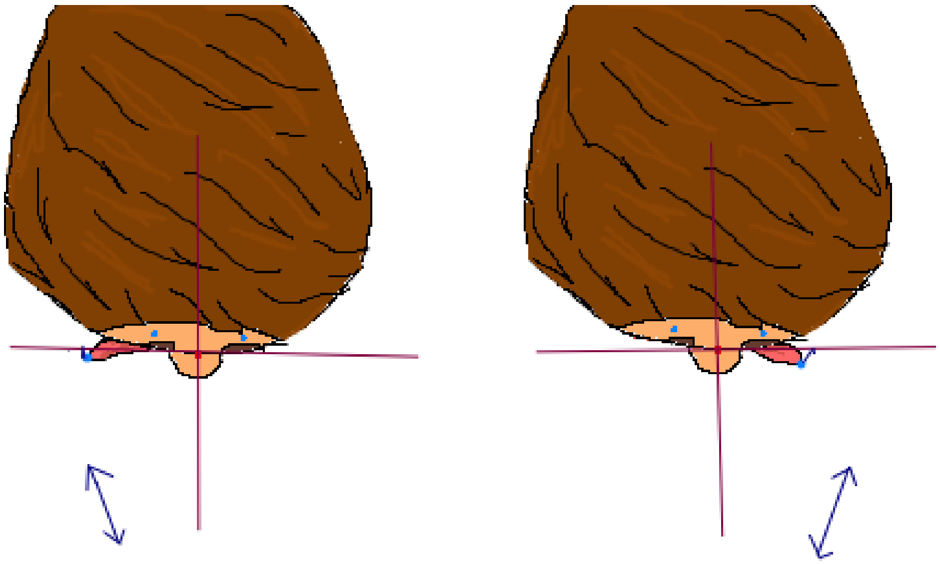
Mean absolute difference
between T_1 & T_2
2.8 ± 2.1 mm
95% CI (2.2 to 4.0 mm)

Mean absolute difference
between T_1 & T_2
3.1 ± 2.5 mm
95% CI (2.0 to 3.5 mm)

Table 4.9 Showing the difference in the z-direction (mm) of the tongue tip between T_1 and T_2 whilst performing right to left tongue movement.

Tongue motion	T_1		T_2		Difference ($T_1 - T_2$)		Absolute difference		95% CI for the mean difference		p-value
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Upper	Lower	
Right	10.5	7.6	11.8	6.4	-1.3	4.4	3.9	2.4	0.4	-3.0	0.181
Left	8.3	6.5	9.1	6.0	-0.8	3.4	2.7	2.2	0.5	-2.1	0.232

Figure 4.7 Shows the mean and absolute difference in the y-direction (mm) of the tongue tip between T_0 and T_1 whilst performing right to left tongue movement.



Mean difference between T_1 & T_2
-1.3 ± 4.4 mm
95% CI (0.4 to -3.0 mm)

Mean difference between T_1 & T_2
0.8 ± 3.4 mm
95% CI (0.5 to -2.1 mm)

Mean absolute difference between T_1 & T_2
3.9 ± 2.4 mm
95% CI (4.7 to 2.1 mm)

Mean absolute difference between T_1 & T_2
2.7 ± 2.2 mm
95% CI (4.8 to 3.0 mm)

Following a one sample t-test, the mean absolute difference was statistically significantly less than 5mm when the tongue was to the right (p=0.019, 95% CI = 4.7mm to 2.1mm) and in the left (p=0.019, 95% CI = 4.8mm to 3.0mm).

4.1.4.4 Euclidian distance

The mean Euclidian distance from the tip of the tongue from the right to the left, ROM), at T_1 was 65.9 ± 8.6mm compared to 66.9 ± 7.7mm at T_2. The mean difference for the range of motion of the tongue tip between T_1 and T_2 was -0.9 ± 4.9mm; the absolute distance was 4.0 ± 2.9mm. The confidence intervals for the mean difference ranged from 1.0mm to -2.8mm. The mean difference in Euclidian distance of the tongue tip between T_1 and T_2 was not statistically significant (p = 0.323), Table 4.10 and Figure 4.8. The difference in Euclidian distance (mm) of the tongue tip between T_1 and T_2 (ROM) whilst performing right to left tongue movement are shown in Table 4.11.

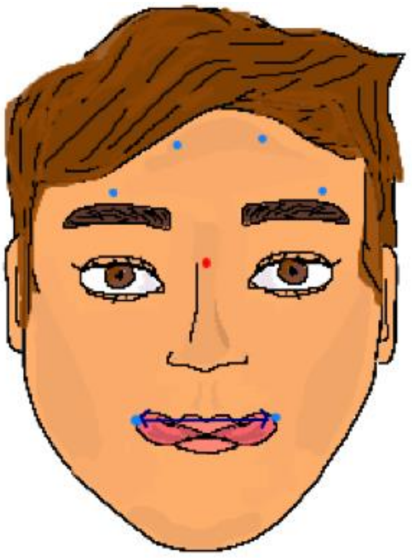
The left and right ROM of the tongue was averaged over T_1 and T_2 resulting in a mean ROM tongue motion of 66.4 ± 8.1mm with a 95% confidence interval of 64.8mm to 69.7mm.

Following a one sample *t*-test, the mean absolute difference in the ROM bases on the Euclidian distance was statistically significantly different from 5mm when the tongue moved right to left (p=0.043, 95% CI = 2.7mm to 4.9mm).

Table 4.10 Shows the difference in the range of movement (ROM) (mm) of the tongue tip between T_1 and T_2 whilst performing right to left tongue movement.

Tongue motion	T_l		T_2		Difference ($T_1 – T_2$)		Absolute difference		95% CI for the mean difference		p-value
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Upper	Lower	
Right to left	65.9	8.6	66.9	7.7	-0.9	4.9	4.0	2.9	1.0	-2.8	0.323

Figure 4.8 Shows the mean and absolute difference in Euclidian distance (mm) of the tongue tip between T_0 and T_1 whilst performing right to left movement.



Mean difference between
T_1 & T_2
0.9 ± 4.9 mm
95% CI (1.0 to -2.8 mm)

Mean absolute difference
between T_1 & T_2
4.0 ± 2.9 mm
95% CI (2.7 to 4.9 mm)

Tongue motion	Difference (T_1 - T_2)		95% CI the for mean difference	
	Mean	SD	Upper	Lower
Up	6.2	2.6	5.2	7.3
Down	5.9	3.0	4.6	6.4

Table 4.11 Shows the difference in Euclidian distance (mm) of the tongue tip between T_1 and T_2 whilst performing right to left tongue movement.

4.1.5 Fréchet distance

For up and down tongue motion the Fréchet distance was largest in the z-direction (6.1 ± 3.4) and smallest in the x-direction (3.0 ± 1.5). For right to left tongue motion the Fréchet distance was also largest in the z-direction (5.6 ± 3.0) and smallest in the x-direction (4.0 ± 1.7), Table 4.12. This suggests during up and down tongue movement the path of motion of the tongue tip was similar with little lateral variation but the path of motion posterior of the tip was more variable over the two occasions. During right to left movement, again the path of motion posterior is more variable but the horizontal path of extension of the tongue tip showed little variation.

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	Euclidian distance		x-direction		y-direction		z-direction	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Up & Down	4.6	2.4	3.0	1.5	4.6	2.0	6.1	3.4
Right to Left	4.4	2.6	4.0	1.7	5.1	2.3	5.6	3.0

Table 4.12 Shows the Fréchet distance (mm) for up to down and right to left tongue motion

CHAPTER 5

DISCUSSION

5.1 DISCUSSION

The aim of the present study was to determine whether tongue motion, measured at the tip, was reproducible using a 3D motion capture system. During development of an objective outcome measure several attributes need to be met, two of which are validity and reproducibility. Validity in this study's context is that the analysis measures the correct variable. As previously discussed, relying on Euclidian distance alone provides a measure of magnitude but does not reflect the direction of displacement of the tongue tip and is a one-dimensional measurement. In addition, the Euclidean distance is based on the individual 3D co-ordinates and will therefore overestimate the actual displacement of the tongue tip. These factors alone question the clinical validity of using the reproducibility of Euclidian distance as an outcome measure. The reproducibility of tongue motion in this respect is also important. For instance, the question is not, can the patient move the tongue to the left on two occasions; this will be clinically obvious. The real question is does the tongue tip reach the same position in 3D space i.e. in the x, y and z directions on two separate occasions and does it follow the same path of motion and ideally speed? No individual will be able to carry this out with perfect repetition i.e. in all three planes of space. This implies there will be a difference in the x, y and z co-ordinates of the tongue tip between the two occasions. The more important questions are, how large is this difference and is the difference clinically significant. For instance, if the reproducibility of tongue tip motion was found to be 10mm but the clinical difference between two interventions was found to be 5mm, any differences between the interventions is not due to the intervention per sae but would be because the patient cannot reproducibility perform the tongue tip motion. In a recent study evaluating tongue tip motion, an error study evaluating the reproducibility of tongue motion was undertaken, but the authors reported the intra class correlation coefficient (ICC). The ICC measures both correlation and agreement between measurements but does not provide information about the magnitude of the measurement error. That is, how many millimeters differences was there in tongue tip position between the two repetitions? The magnitude of this error needs to be smaller than the differences between the two clinical interventions to be “true” and not as a result of measurement error. Therefore, the present study was undertaken to determine the size and direction of this error. In addition, the “normal” range of tongue motion in an up and down direction and right to left direction was determined.

A prospective cross-sectional study was conducted based on a convenience sample of 30 healthy individuals working at the Birmingham Dental Hospital. The sample was divided equally across both genders and the exclusion criteria reduced bias by omitting any participants with underlying health conditions such as neurological disorders which may potentially impact tongue motion. The inclusion and exclusion criteria were in keeping with previous studies (van Dijk et al., 2016); whereby any neurovascular disease, tongue carcinoma or other conditions which may affect tongue motion were excluded. This produced a homogenous sample reducing any confounding factors. The sample size used for this study was larger than most studies of a similar nature where healthy participants were analysed for tongue range of motion. Sample sizes in similar studies tended to include less than 20 healthy participants (Kappert et al., 2019; van Dijk et al., 2016). These were comparative studies and as such did not specifically from the outset investigate the reproducibility of tongue motion.

At which point a reduced range of tongue motion is of clinical significance remains unknown and is unreported in the literature. In the present study a 5mm difference was taken as clinically significant, not at random, but based on the findings of van Dijk et al. (2016). The authors reported a 5mm difference in range of movement tongue between the healthy group and the glossectomy group. The assumption was there would be a clinically significant difference between the two groups i.e. normal and post-surgical. Therefore a difference of more than 5mm of tongue movement in the same healthy individual at different time points was taken as being clinically significant. This was then used with a significance level of 0.05 and power of 80% to result in a minimal sample size of 30 participants in order to detect a 5mm change.

Previous research on tongue motion has been conducted intra-orally, mainly using magnetic resonance imaging. The research focused mainly on tongue motion in relation to speech and intra oral motions. There have been more recent studies investigating extra-oral tongue motion using 3D motion capture, with only two studies reporting the range of tongue motion in healthy individuals as a comparative group (Kappert et al., 2019; van Dijk et al., 2016). However the findings should be viewed with caution as there is lack of a clear sample size calculation, which places doubt on the validity of the results. Furthermore, the dynamic motion of the tongue was not assessed and the trajectory of the tongue from one point to another was not considered. It was thus felt that a clearly directed aim of assessing tongue motion in healthy individuals using 3D motion equipment would be useful to open up options for further research.

The 3D motion capture system used for this study allows effective capture and tracking of soft tissue landmarks. An advantage of this system is the type of data that is recorded by the system i.e. x, y and z-changes over time and the ability to capture at 60 frames per second. The disadvantage of this however is that no commercially available software exists for analysis and needs to be custom written, in this case using MATLAB. The system and accompanying software allow landmarks to be placed and tracked automatically through the sequence. This process has been previously validated and the accuracy of tracking was within 0.55mm (Al-Anezi et al., 2013). The software was also able to compensate for head movement. This is an important feature as without it any changes in tongue position would be a result of combined head and tongue movement. In this case four additional landmarks were placed on the forehead, which remained motionless during tongue movement and could be used for stabilization. From an analysis perspective it was important to make sure that all four captures were analysed using the same 3D co-ordinate system and same point of origin. Again a feature of the software allows alignment of the images for that individual to re-orient to the same 3D space. This meant that all four captures were aligned to the same 3D planes and all measurements were taken from a common origin (nasion).

Disadvantages of the system were the cost and the large file sizes generated due to the amount of data being captured.

When assessing reproducibility of tongue motion or facial animation one cannot simply ask the individual to move their tongue up or down or smile. These actions are voluntary and as such participants need to be “trained” or “calibrated” to perform the motion within set boundaries. To achieve this, a standardised set of instructions was read and a video shown to each participant and they were asked to practice both tongue motions in a facial mirror multiple times prior to capture. One important feature was that the participants should not move their mandible as this could influence the data particularly as the tongue moves in the up/down direction. This was difficult given the fact that the tongue is attached to the mandible. However, with clear instructions and practice, it was possible to limit mandibular movement. There was also a challenge in ensuring the tip of the tongue was able to be landmarked accurately as it is a wet surface which reflects light and could potentially become distorted. A paper marker could have been used at the tip of the tongue such as in a study looking at impaired tongue mobility (Kappert et al., 2019). However, for this study a simple surgical marker was used to place a point at the tip of the tongue prior to capture. This was deemed to be simple, effective in data capture and did not risk any unwanted motion or slip of a physical marker. Another potential source of error was landmark identification and placement. Intra-rater reliability was assessed with a landmarking error study using 10% of the original dataset. The results of this error study showed there was no systematic error and no random error. The mean absolute magnitude of error across the 3 directions was between 0.4mm to 0.7mm. This is in the order of magnitude seen when landmarking facial images (Gwilliam et al., 2006; Hajeer et al., 2004).

For up and down tongue motion the normal range of motion was 48.3 ± 10.0mm with a 95% confidence interval of 45.7mm to 51.0mm, this is less than the 81.7mm reported by van Dijk et al. (2016). There are several possible reasons for this difference. The first is that the participants in the present study were “trained” to produce a specific tongue motion and therefore produced a consistent range of motion, as shown by the narrow 95% CI. Secondly when depressing the tongue, the mandible may also move down adding to the total tongue tip displacement. The present study trained the participants to maintain light teeth contact onto the tongue therefore stabilising the mandible but producing a true tongue tip displacement. This was different to previous studies where tongue tip displacement in addition to mandibular displacement was not accounted for. A more recent study has tried to compensate for mandibular movement but the effect on the ROM of the tongue was not reported. A similar situation was seen with left to right tongue motion, 67.2 ± 8.9mm with a 95% confidence interval of 63.9mm to 70.6mm, Again this was less than the 97.6mm van Dijk et al. (2016) possibly for the same reasons mentioned previously. In a more recent study the highest percentage of healthy individuals had a left to right ROM of 85mm. Unsurprisingly, up or elevation of the tongue tip showed the smallest variation (SD) in all three studies, this would have been due to the fact that the tongue tip in the up or elevated position is probably least affected by mandibular position.

As discussed earlier, the shortcomings of using the Euclidean distances, measuring only magnitude and not direction, can be overcome by using changes in the x, y and z directions. Using the x, y and z changes decomposes the Euclidian distance into the medio-lateral, superior-inferior and anterior-posterior directions, which improves the clinical validity of the analysis. Whilst the tongue is in its most elevated position, the mean absolute difference of the tongue tip in the medio-lateral direction (x-direction), at T_1 and T_2 was less than 2mm. The one sample *t*-test showed this difference was statistically significantly less than 5mm (p=0.001, 95% CI = 1.2mm to 2.4mm). This was also the case for the tongue tip in the most depressed position (p=0.001, 95% CI

= 1.2mm to 2.2mm). This suggests that when the participants move their tongues up and down there is little deviation from the midsagittal plane between the two time intervals and any differences would not be clinically significant i.e. less than 5mm, in the general population. The tip of the tongue also follows a similar path between T_1 and T_2 given by the lowest Fréchet distance in all three planes (3.0 ± 1.5mm). Participants can reproducibly elevate their tongues in the y-direction, with mean absolute differences less than 4mm. The results of the one sample *t*-test confirm that when participants move their tongues up (95% CI = 1.7mm to 2.6mm) and down (95% CI = 2.9mm to 4.8mm), they reach the same extremes in the y-direction and that any differences would not be clinically significant i.e. less than 5mm, in the general population. The tip of the tongue follows a similar path of motion in the y-direction between the two occasions with a Fréchet distance of 4.6 ± 2.0mm.

Finally in the z-direction, with the tongue elevated, the reproducibility at T_1 and T_2 was less than 5mm. However the mean absolute difference was statistically significantly more than 5mm when the tongue was in the most superior position (p=0.172, 95% CI = 2.9mm to 5.4mm). This confirms in the larger population that the difference in the amount the tongue tip is extended backwards towards subnasale varies over time and is not reproducible i.e. is more than 5mm. For tongue depression there was no clinically or statistically significant differences in the mean absolute vales 95% CI = 2.3mm to 3.9mm. This suggests that whilst performing the up and down tongue movement (elevation and depression) the 3D position of the tongue tip is clinically reproducible in the medio-lateral direction and in the inferior-superior direction. However in the anterior-direction (z-direction, depth) tongue tip reproducibility is greater than 5mm when the tongue is in the most elevated position. This was supported with the largest Fréchet distance of 6.1 ± 3.4mm in the z-direction. This may be due to the fact that the patients curl the tip of their tongue further back when elevating the tongue and this is variable between occasions. Another possible explanation is that the 3D motion capture system is unable to capture an undercut due to an occlusion i.e. loss of sight, of the tongue tip. This would make landmarking and tracking the tongue tip difficult.

For tongue motion to be reproducible whilst carrying out a right to left tongue movement the individual would need to start and finish their tongue in the same 3D position on two separate occasions. This means that relative to the three planes of space the tongue tip would need to be the same distance from the sagittal plane (x-direction) on both occasions as well as relative to the y-direction (sagittal plane) and in the z-direction (from the coronal plane). This study shows that individuals can move their tongues to the right and left (x-direction) on two separate occasions. The horizontal component of their tongue tip position is reproducible. The 95% confidence interval for the mean absolute differences confirm the differences were not clinically significant in the wider population. Tongue tip position was symmetrical between displacement to the right and left. As well as moving horizontally the tongue tip needs to maintain its vertical position at the start and finish between the two occasions. Interestingly the tongue tip did not remain horizontal but was lower by 7mm on average between right and left but was reproducible and clinically acceptable. As well as moving to the same extent and maintaining height on both occasions the tongue tip needed to move posteriorly the same amount on both occasions. The results of this study show that the tongue tip goes back more on the right than on the left and it is clinically reproducible but the upper 95% confidence interval is close to the 5mm and should therefore be viewed with caution.

The limitations of the study include the relative short time interval between the two tongue captures for each individual. In order to avoid memory bias of the tongue motion, it would have more representative of the clinical situation to increase the time between captures. In reality several months may have passed between the original capture, the surgical intervention, recovery and re-capture. In addition, the cost of the imaging equipment and expertise may prohibit its routine clinical use.

This study has highlighted the importance of determining the average range of tongue motion, as well as which motion is reproducible. This is essential before comparing the range of tongue motion of an impaired or intervention group to a healthy control. Future research would be useful at looking at how patients with conditions such as Parkinson’s, oncology patients both during and after surgery amongst many other conditions compare to a healthy baseline both in terms of measurements and trajectory. It could also be used to look at orthodontic patients with suspected endogenous tongue thrusts or macroglossia.

CHAPTER 6

CONCLUSIONS

6.1 CONCLUSIONS

In the present sample, when performing up and down tongue movement, the tip of the tongue, in both the evaluated and depressed positions, was reproducible in the x, y and z-directions as well as for the ROM. All the differences in mean absolute measurements were less than 5mm. However when the tongue was elevated this difference, based on the 95% confidence interval, could be over 5mm in the z-direction (2.9mm to 5.4mm), as could the ROM (3.1mm to 5.1mm). These differences would be clinically significant. The average ROM in the up and down direction was 48mm.

When performing right to left tongue movement, the tip of the tongue, in both the right and left positions, was reproducible in the x, y and z-direction and for ROM. All the differences mean absolute measurements were less than 5mm. The average ROM of the tongue from right to left was 66mm.

When carrying out studies based on extra-oral tongue motion, right to left tongue motion is more reproducible than up and down tongue motion. However, based on Euclidian distance differences, reproducibility of tongue tip motion in either direction were greater than 5.0mm. For tongue displacement to the right, the upper 95% confidence interval limit for the difference in mean absolute distance between T_1 and T_2 was over 7mm. For interventional studies, differences in tongue tip position in the order of 6-7mm are likely to be due to a lack of reproducibility rather than treatment effect. This should be taken into account when designing future studies. It is vital to rehearse tongue motion to reduce the magnitude of the reproducibility error.

CHAPTER 7

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7.1 REFERENCES

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CHAPTER 8

APPENDICES

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The title of the research project
How reproducible is tongue movement?

Invitation paragraph
You are being invited to take part in a research project. Before you decide it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us / me if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

What is the purpose of the project?
To image volunteers when they perform specific tongue movements using a real time 4D video imaging system so we can see if tongue movement is reproducible over time. This imaging and tongue movements will be used in the future for assessing patients that have had surgery to their tongue to see if there are any residual problems in tongue movement.

Why have I been chosen?
We are looking for 20 males and 20 female volunteers between the ages of 18 and 40 with no known history of previous neurological damage to their tongue and no tongue piercing(s). We would like to record the range of your tongue movement and see if it reproducible over a period of one week.

What do I have to do and what will happen to me if I take part?
You will be asked to attend the Birmingham Dental Hospital & School for a period of approximately 15 minutes. During this time, you will be asked to perform four tongue movements. You will be shown images of the movements first and asked to practice them for 5 minutes. When you are ready, we will place a small dot on the tip your tongue then we will take a 3-5 second 4D video clip of you preforming the tongue movements. This will repeated one week later.

It is up to you to decide whether or not to take part. If you do decide to take part you will be given this information sheet to keep (and be asked to sign a consent form). If you wish to withdraw you can do so without it affecting any benefits that you are entitled to in any way. You do not have to give a reason. You can remove your data until 12 weeks after participation.

We may use your data from this study for future research projects.

Will my taking part in this project be kept confidential and what will happen to the results of the research project?
Yes. Only the researchers involved will know you have taken part. The images generated will not be used in publications unless you have specifically consented. They may however be used in presentations to fellow researchers who are also interested in this technology. Your facial images will not be shown, only the results of the study.

What will happen to the results of the study?
The main findings will be written up and submitted to an appropriate scientific journal; again

your facial images will not appear in the journal unless formal approval has been obtained.

Contact for further information

If you have any further queries please do not hesitate to contact any of the researchers involved via the email addresses supplied above.

Professor Balvinder Khamba4
Tel
Email:

This study has been reviewed and given a favourable opinion by University of Birmingham, Research Ethics Committee on the 03 July 2017 and ethics reference ERN 17-0823.

UNIVERSITY OF BIRMINGHAM | SCHOOL OF DENTISTRY

Version 2 / 29th June 2017

Centre Number:
Study Number:
Patient Identification Number for this trial:

CONSENT FORM

Title of project: How reproducible is tongue movement?
Name of Researcher: Professor Balvinder Khambay

Please initial box

1. I confirm I have read and understand the information sheet dated 29th June 2017 (version 2) for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. ☐
2. I understand that my participation is voluntary and that I am free to Withdraw my data within 12 weeks of participation without giving any reason, without my medical care or legal rights being affected. ☐
3. I agree to take part in the above study. ☐
4. I understand that data from this study may be used in future research. ☐

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Name of Patient	Date	Signature
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Name of Person taking consent	Date	Signature

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Consent sheet	Version 2	29th June 2017