The validity and reliability of an automated method of scoring dental arch relationships in unilateral cleft lip and palate using the modified Huddart-Bodenham scoring system

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~~**Scoring of dental arch relationships in UCLP using the modified Huddart Bodenham system – can the process be automated?**~~

Objective: To evaluate an automated software tool for the assessment of dental arch relationships using the modified Huddart and Bodenham index.

Design: Cohort of 43 models of subjects aged 9-21 with UCLP and the ten GOSLON reference models sets.

Method: The 53 sets of plaster models were scored using the MHB index and scanned (R700, 3Shape, Copenhagen, Denmark). The digital models were MHB scored visually (Orthoanalyzer, 3Shape, Copenhagen, Denmark) and landmarked for automatic scoring using a Rhino software plug-in (Rhinoceros, version 5, www.rhino3d.co.uk). Scoring/landmarking was undertaken by three observers and repeated after one month. Intra- and inter-observer reproducibility were tested using Cronbach's Alpha and intraclass correlation coefficients (ICC) (threshold > 0.9). Bland-Altman plots demonstrated inter-observer agreement for each model format. Random and systematic error with digital landmark identification error were determined using the x, y and z co-ordinates for 28 models digitized twice one month apart using Cronbach's alpha and a t-test, respectively.

Results: Intra-operator landmark identification was excellent (Cronbach's alpha = 0.933) with no differences between sessions (P>0.05). Intra-observer reproducibility was excellent for all examiners (Cronbach's alpha and ICC 0.986-0.988~~Cronbach's alpha 0.972-0.975~~). Inter-observer reproducibility was highest for the ~~Rhino plug-in~~software plug-in (0.991), followed by plaster (0.989) and Orthoanalyzer (0.979) and Bland-Altman plots confirmed no systematic bias and greater consistency of scores with the automated software.

Conclusion: The automated MHB software tool is valid, reproducible and the most objective method of assessing maxillary arch constriction for patients with UCLP.

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Introduction

~~Oral clefts are a significant functional and cosmetic burden for patients and families. The prevalence of CL/P is 9.92 cases per 10,000 births (1) with a female predominance for CP (0.93) and a male predominance for CL(P) (1.81) (2). Disruption to the palatal structures results in unfavorable growth of the midface (3) and surgical repair can have deleterious effects on growth of the maxilla (4-6). The optimal surgical protocol is still under debate.~~

There are various methods for assessing surgical outcomes in cleft lip and palate from dental models. These include the GOSLON yardstick, 5 Year Old, Eurocran, BCLP Yardstick, and modified Huddart/Bodenham indices (1, 2). The GOSLON Yardstick was introduced for the assessment of dental arch relationships for subjects with UCLP in the late mixed or early permanent dentition (3~~7~~) to provide an indication of treatment complexity and expected outcome. The 5 Year Old Index was later developed to determine earlier surgical outcomes (4~~8~~). Both have been widely used in multicentre~~r~~ outcome comparisons and have good intra- and inter-observer reproducibility. However, they are only suitable for UCLP and require calibration and a set of reference models (5~~9~~). Moreover, their five category nature lacks sensitivity as borderline cases are scored using subjective professional judgment (6~~10~~), resulting in the potential for significant error (7~~11~~). The Eurocran Yardstick modified from the GOSLON Yardstick and 5 year indices (8~~12~~) but is not user friendly (9~~13~~) whilst the reliability of scoring palatal morphology is only moderate (10~~4~~).

The Huddart/Bodenham index was developed as an ordinal scoring system for the assessment of archform in the deciduous dentition stage in cases with UCLP (11~~5~~). This was modified for use with any cleft sub-phenotype at any age and stage of dental development (6~~10~~,7~~11~~,12~~6~~,13~~7~~). The relationship of each maxillary tooth with the corresponding tooth in the mandibular arch is scored (excluding the frequently absent lateral incisors). Summation of scores from the 10 pairs of teeth (two incisors, canines, premolars, two molars), provides an overall score between -30 and +10. As the first permanent molars are not scored for patients younger than 6 years, scores can range between -24 to +8. Unlike the GOSLON and 5 Year Old indices, multicentre research comparisons are simplified due to the systematic method of scoring and as calibration is not required, both clinicians and non-clinicians can undertake scoring (12~~6~~). The continuous scale is also more sensitive than the GOSLON and 5 Year Old ~~I~~indice~~x~~s (6~~10~~) and a recent systematic review using WHO criteria for an ideal index recommended the MHB system as the index of choice in cleft outcome measurement (2~~18~~).

Dental arch relationships can be scored directly from the patient (13~~7~~), or indirectly using photographs (14~~9,20,21~~), plaster study models (15~~22~~), digital models produced by scanning plaster models (15~~22~~), and direct intra-oral scans (16~~23~~). ~~However, photographs are not as reliable at plaster models for the assessment of surgical outcomes (9)~~ D~~whereas d~~igital study models have been shown to be reliable for the GOSLON Yardstick (15~~22~~), MHB index (17~~24~~), ~~and~~ 5 Year Old Index (18~~25~~) EUROCRAN index (19) and BCLP yardstick (20). To date all methods have involved manual methods of assessment.

There are numerous descriptions of geometric, algebraic, mathematical and statistical solutions for the assessment of dental archform in patients without clefts. ~~.~~These include the Bonwill and Hawley equilateral triangles~~ (26,27)~~, catenary curves, ~~(28)~~ ellipses and parabolas~~ (29)~~ trifocal elipse~~ (30)~~, polynomial equations from the 2^{nd} to 6^{th} order~~ (31)~~, and conic sections (21, 22)~~ (32)~~. These methods all have limitations for the assessment of asymmetric dental arches, which ~~like those~~ are frequently found ~~with~~ in patients with orofacial clefts. Geometric morphometric techniques including Euclidean Distance Matrix analysis (2~~3~~3) and cubic splines (2~~3~~4-2~~3~~6) are more useful for asymmetric dental arches. A cubic spline is the connection of a series of 'knots' or points into a smooth curve irrespective of arch size and symmetry. ~~Initially~~Previous work has used ~~,~~cubic splines ~~were used~~ with digitized x and y co-ordinates (2~~3~~5) and this has been further developed into a 2D planar computerized program for dental archform analysis (2~~3~~4). With the advent of digital models and digital landmarking, geometric shapes such as the fourth degree polynomial curve and the β function (2~~3~~6), and statistical models derived from Generalised Partial Procrustes Analysis (2~~3~~7) are now available. Several digital ~~image~~ software systems produce 2D archforms using splines and incorporate the facility to undertake symmetric archform analysis using customized user prompts.

~~Algorithms are the cornerstone of modern healthcare systems for various clinical and non-clinical applications. Computer aided diagnosis and electronic health data has expanded to equip individuals and organizations with new technologies for rapid disease identification and prevention strategies. Automated surveillance systems for healthcare associated infections (38), decision making for treatment diagnosis and planning (39,40), and the development of phenotype algorithms for clinical and translational research (41) are now available.~~

~~Since CAD/CAM became available in dentistry (41), several commercial devices and software packages have been developed. Algorithmic tools are available for orthodontic diagnosis and treatment planning, the production of orthodontic appliances and for assessing outcomes. Cephalometric planning is important for orthodontic treatment and orthognathic surgery. Assessment of dentofacial relationships, surgical outcome prediction and photo morphing are now most commonly carried out using algorithmic software. Digital software can simulate treatment outcomes, evaluate 3D measurements and 2D archform analysis. OrthAnalyzer™ (3Shape, Denmark) is one of several digital image systems that produces 2D archforms using splines and incorporating the facility to undertake orthodontic outcome analysis using customized user prompts. Algorithms have reduced the need for the manual adjustment of appliances through custom digital modification of simulated outcomes for aligners and lingual fixed appliances in CAD-CAM systems (42).~~

No study has investigated a software tool to automate scoring of cleft lip and/ or palate surgical outcomes. The objective of this study was to evaluate a plug-in developed in Rhino (www.rhino3d.co.uk), a commercial research and development software platform for use with high quality 3D images, for the assessment of dental arch relationships in cleft lip and palate using the modified Huddart and Bodenham index.

Null Hypothesis

MHB scores determined using the automatic Rhino plug-insoftware plug-in are no different to those determined using conventional visual methods with digital and plaster models of patients with UCLP.

Materials and methods

A consecutive sample of 43 UCLP subjects aged 9-21 with plaster models were identified from a concurrent study (16). In this study, 60 subjects were identified from the Cleft Care Scotland database in the Greater Glasgow and Clyde NHS Board area during 2013-2014. Of these subjects, 3 declined to participate and 14 failed their appointments. Forty-three subjects underwent alginate impressions for the construction of plaster models. A further 10 plaster models were added to the sample by anonymizing the GOSLON reference models. The 53 model sets were scanned using an R700 benchtop scanner (3Shape®, Copenhagen, Denmark) and exported as STL files (Figure 1).

Details of recruitment for this study investigating the reliability of digital models for the assessment of surgical outcomes can be found in (23) and Figure 1. Caldicott Guardian approval was obtained from the West of Scotland Ethics Service and Tayside Medical Science Centre for use of these models in the current project. A post-hoc sample size calculation using a clinically relevant difference of four MHB points at a power of 80% and p=0.05 found a sample size of 40 would be required. The range of possible scores in the MHB scoring system ranges from -30 to +10 (a 40 point scale) and the GOSLON yardstick comprises five categories, so one GOSLON category equates to 8 MHB points. It was felt reasonable to assume that clinically it would be desirable to detect half a GOSLON category, therefore a difference of 4 points was agreed by the investigators. As this study had 53 subjects, it was sufficientlyadequately powered to avoid a false positive result.

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The plaster models were MHB scored manually, and the digital models were scored visually on-screen using OrthoAnalyzer viewing software (3Shape®, Copenhagen, Denmark) and automatically using a plug-in written for Rhinoceros, version 5 (Rhino)(www.rhino3d.co.uk)(Robert and McNeel Associates, 2014) under similar conditions on two occasions by three observers (two faculty and one resident in orthodontics), one month apart. The Rhino platform was chosen for the development of the automatic scoring plug-in as it is a commercial research and development software platform, designed for use with high quality 3D images. Written instructions were provided in order to standardize the scoring process.
For the Rhino plug-insoftware plug-in, a series of landmarks were identified (Figure 2) using the x, y and z co-ordinates:

- Most buccal point on the groove between the mesial and mid buccal cusps of the upper and lower first andor second molar, or any deciduous molar.
- Buccal cusp tips of the first and second premolars, where erupted.
- Cusp tip of the canines.
- Mid-point of the incisal edges for all incisors.

The molar groove was used to accommodate for any rotational discrepancies. A total of 14 landmarks were identified for the lower arch, and 10 for the upper arch (as lateral incisors are commonly missing and second molars are not scored using MHB index). If

Where any teeooth wereas absent in the mandibular arch, the adjacent erupted tooth adjacent the space that was identified first in the order of landmark identification, was identified landmarked twice, to maintain continuity of keep the cubic spline continuous across the space. If a tooth was absent in the maxillary arch, the mid alveolar ridge point was where the tooth would be likely to erupt was identifiedlandmarked. The deciduous teeth were scored in exactly the same way as the permanent dentition, using the landmarks identified above. The processis waıs consistent with the scoring requirements described by Mossey et al, (2003) for scoring using the MHB index.

For the Rhino plug-insoftware plug-in, in order to compare the relative archforms of the maxillary and mandibular arches, the 3 dimensional mandibular archform was used as a reference, created with a cubic spline (Figure 2). A reference plane was also constructed from the mandibular landmarks using the least square fitting technique. (Figure 2). Two of the authors of this study had expertise in computer science and mathematics for construction of these algorithms. Details of the algorithm can be found in Ma et al. (2016) (2843). The software generated the nearest distance of the maxillary landmark to the cubic spline. Projection of the hHorizontal and vertical vectors of this distance, to the reference plane, were used to generated distances between the maxillary landmarks and the mandibular archform.
The MHB scores were recorded in a spreadsheet (Excel, Microsoft, Redmond, California). The data were examined for probability distribution using Skewness coefficients prior to statistical analysis. Intra- and inter-observer reproducibility wereas tested using Cronbach's Alpha (2944) and Intraclass Correlation coefficients (ICC) with the threshold set at 0.9 (3045). Bland-Altman plots (3146) were used for visual interpretation of inter-observer agreement for each model medium using 95% confidence intervals (the mean difference of the two readings plus or minus 1.96 times the standard deviation of the differences).

Random and systematic error with digital landmark identification for the Rhino models were determined using the x, y and z co-ordinates for 28 models digitized on two occasions one month apart (3247) using Cronbach's alpha and a t-test, respectively. Statistical analysis was carried out using SPSS version 21 (IBM Corporation, New York).

Results

Intra-operator landmark identification was excellent (Cronbach's alpha value of 0.933) with no statistically significant difference between the sessions using a paired t-test (P>0.05).

The data were found to follow a normal distribution. Intra-observer reproducibility was excellent for all observers (Cronbach's alpha and ICC 0.986-0.988972-0.975) (Table 1) demonstrating that each examiner was consistent with repeated scoring. Inter-observer reproducibility (Table 2) was highest for the softwareRhino plug-in (0.991), followed by plaster (0.989) and Orthoanalyzer™ (0.979) and Bland-Altman plots confirmed no systemic bias and greater consistency of scores with the automated software. All were in the excellent category.

The Bland-Altman plots (Figure 3) show that the majority of the data for the three examiners for the three mediums lie between the upper and lower confidence intervals with a good scatter of points around the mean difference of the two readings. ~~Moreover, t~~The confidence intervals for the ~~Rhino plug-in~~software plug-in were smaller, with a greater concentration around the mean (Figure 3) indicating that the ~~Rhino plug-in~~software plug-in was more consistent than the other two mediums. There were a lower number of outliers with the plaster and automatic scoring methods than with manual scoring of the digital models.

Discussion

This study is the first to present an automated~~ic~~ method ~~for~~ of ~~the~~ scoring ~~of~~ dental arch relationships in cleft lip and palate. Excellent agreement was found between all examiners for MHB scores for all three mediums with excellent intra and inter examiner reproducibility for land~~-~~marking ~~on~~ the digital models. It has been suggested that a reproducibility coefficient greater than 0.9 should be regarded as a suitable threshold for clinical applications (31~~45~~), which was exceeded by all ~~of the~~ three mediums. Furthermore, there was excellent agreement between the examiners for each scoring medium. The highest level of inter-observer agreement was found for the ~~Rhino plug-in~~software plug-in ~~and~~ followed closely by plaster models. The ~~Rhino plug-in~~software plug-in also had the narrowest confidence intervals for all three methods indicating that the ~~new~~ automated system was more accurate than conventional methods of MHB scoring. The null hypothesis was therefore accepted.

The results of this study demonstrate that the inherently objective ~~Rhino plug-in~~software plug-in is a more reliable system than visual scoring of plaster and digital models. This is most likely due to the elimination of human error associated with the visual estimation of dental anatomical landmarks. Although landmark identification was still required in conjunction with the measurement algorithm, random and systematic error resulting from visual judgment of the relationship of each pair of teeth and errors resulting during data transcription are eliminated. Furthermore, when working with digital models the occlusal relationship is fixed at the time of scanning. This is particularly advantageous for cases with an anterior open bite or class III relationship where the true occlusal relationship on plaster models is more difficult to estimate in vertical and horizontal dimensions with the potential for measurement error.

~~To date, investigations of cleft surgery outcomes have focused on comparing methods of assessment involving 2D images or 3D digital models with plaster models. Our novel automatic method for the scoring of dental arch relationships compares well with these previous studies. Good to very good intra- and inter-observer agreement has been found between plaster and indirect digital models produced from scanned plaster models when using the 5 Year old, GOSLON and MHB indices (24,25). A recent study identified that plaster, OrthoAnalyzer™ and digital models produced by intraoral scans also had excellent intra- and inter-observer agreement (23).~~

The GOSLON reference models were added to the existing 43 UCLP models to ensure a full range of malocclusions were~~as~~ ~~accounted~~ included ~~for~~ to test reliability of the software. We chose similar dental anatomical landmarks for the ~~Rhino plug-in~~software plug-in to those used in other studies. Adaškevičius and Vasiliauskas (2009) used the x and y co-ordinates of 12 landmarks on digital models to generate polynomial curves for the prediction of customised archforms for a selection of pre-treated malocclusions (2~~3~~6). Landmarks using occlusal cusps have also been used in a recent study for comparing maxillary and mandibular archforms using Generalised Procrustes Analysis (33~~48~~). Intra-observer reliability for landmark identification was excellent. This is in keeping with Brief et al. 2006, who found the intra-observer error of landmark placement for four observers to range from 0.61mm to 1.99mm when assessing a sample of 40 digital models from 20 patients with UCLP aged between 3 and 8 months (34~~49~~). Interestingly they found that landmark identification error varied between the x, y and z axis for different landmarks.

Other recent studies comparing maxillary and mandibular archforms have used the Generalised Procrustes Analysis (GPA) superimposition methods which involve rotation, translation and scaling of the dental arches (34~~49~~,35~~50~~) to achieve a best-fit relationship prior to calculating differences between the maxillary and mandibular archforms. Whilst this is a useful technique, the cubic spline was more appropriate for this project as the archform it was only needed in the mandibular arch, to which the linear distance from the maxillary landmarks could be calculated. In addition, as a complete maxillary arch was not always present due to the inherent nature of the cleft and the range of ages examined where teeth were either yet to erupt or had been extracted. This would have made superimposition of the dental arches difficult using the GPA method.

We minimized error through the use of an identical scoring protocol for the three model types where the models were scored in the same order at each session. The GOSLON reference models were randomly interspersed with the models from the cohort of patients aged 9-21 years. Although it was not possible to blind the observers to model type due to the visual differences between them, they were scored under identical conditions at each scoring session. Mullen et al. (2007) found that magnification of digital models was linked with improvements in measurement accuracy therefore a large monitor screen was used for the Rhino software so each examiner could magnify the digital model for landmark identification (36~~51~~). ~~A post-hoc sample size calculation using a clinically relevant difference of four MHB points at a power of 80% and p=0.05 found a sample size of 40 would be required. As this study had 53 subjects, it was sufficiently powered to avoid a false positive result.~~

~~The Rhino platform was chosen for the development of the automatic scoring plug-in as it is a commercial research and development software platform, designed for use with high quality 3D images. Rhino is not only versatile and robust but is used for a wide variety of disciplines including mechanical engineering, marine, architecture, reverse engineering and medical devices [http://www.rhino3d.com]. Rhino's open architecture allowed scripting using C++ SDK methods (RhinoScript). Moreover, other dental Rhino plugins such as CADental [www.cadental.eu] and Dental Shaper [www.cimsystem.com] for orthodontics and fixed dental prosthesis integrate the clinical and engineering developments.~~

A cubic spline involving third order polynomials was used to generate the mandibular archform (2~~3~~4,2~~3~~5) for several reasons. It facilitated mathematical flexibility and accuracy, whilst limiting the number of calculations required. An algebraic formula based on a cartesian co-ordinate system using the mandibular digital landmarks resulted in a mathematical expression for the cubic spline in order to generate the MHB values. Other archform methods such as the ellipse, catenary curve, parabola, hyperbola, conic sections, polynomial functions and beta functions (33~~48~~) would either impose or require arch symmetry. Cubic splines do not have this limitation and are therefore suitable for use with severe malocclusions and patients with clefts where asymmetry is a common feature (37~~52~~).

The ~~Rhino plug-in~~software plug-in could be used to assess MHB scores in other cleft sub-phenotypes for longitudinal studies and comparisons, unlike ~~which has been noted to be a limitation of some~~ other surgical outcome scoring indices which are limited to specific sub-phenotypes (38~~53~~). More importantly, developments to include automatic landmark identification in a similar manner to facial recognition from both 3D static images and 3D videos (39~~54~~,40~~55~~) would eliminate the need for landmarking.
~~This could be adapted for general orthodontic use such as in the manufacture and customisation of archwires for inherently asymmetric archforms, where maintenance of the asymmetry is desirable, such as in patients with clefts, where symmetrical movement of teeth can result in teeth being pushed out of the alveolus within or adjacent to a cleft defect. This could potentially lead to greater stability of the arches due to reduced alteration of the existing archform (56).~~

~~A global report on health strategies highlighted epidemiological data in orofacial clefting has significant international variation owing to differing methods of ascertainment, making comparability of data challenging (57). Furthermore, many areas of the globe have little or no epidemiological data on clefting defects as birth surveillance systems are limited (58). Valid, standardized outcome measures,~~ Fully ~~such a~~automated~~s automatic~~ MHB scoring has the potential to be performed remotely using uploaded digital models or intraoral scans. This would contribute much needed data on ~~has the potential for both developed and developing counties to~~ surgical outcomes ~~contribute data~~ to global registries. As a universal scoring method for all cleft types at any age, that does not require sophisticated calibration courses and anchor study models, it has advantages over existing methods for such purposes. With further development it is anticipated that this index could be developed to include a vertical component~~ to the scoring~~, and an assessment of the skeletal bases. This would distinguish between minor and major maxillary retrusion, which is one drawback to this index over the GOSLON yardstick.

Adoption of a single yet reliable method of recording surgical outcomes by international collaborative centre~~r~~s will enhance comparative research studies and enable subtle differences in global techniques to be established. Numerical MHB data can easily be fed back into the WHO database for assimilation with the Global Burden of Disease (GBD) project. With more accurate, reliable and universal measurement the effects of different methods of surgical intervention can be compared, techniques and protocols refined and ultimately there is potential for optimizing care and for reduction of the burden of care for individuals born with cleft defects.

Conclusion

The automated MHB system was found to be a valid, reproducible and a more consistent method of assessing maxillary arch constriction for patients with unilateral cleft lip and palate, than conventional MHB scoring on digital or plaster models.

Conflict of interest statement

The authors declare no conflict of interest or financial relationship with any organization or software used within the study.

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References

1. Jones, T., Al-Ghatam, R., Atack, N., Deacon, S., Power, R., Albery, L, Ireland, T., and Sandy, J. (2014) A review of outcome measures used in cleft care. *Journal of orthodontics*, 41, 128-140.

2. Altalibi, M., Saltaji, H., Edwards, R., Major, P.W., and Flores-Mir, C. (2013) Indices to assess malocclusions in patients with cleft lip and palate. *European Journal of Orthodontics*, 35(6), 772-82.

1. IPDTOC Working Group. (2011) Prevalence at birth of cleft lip with or without cleft palate: data from the International Perinatal Database of Typical Oral Clefts (IPDTOC). *Cleft Palate- Craniofacial Journal*, 48(1), 66-81.

2.Mossey, P., and Castillia, E. (2003) Global registry and database on craniofacial anomalies. *Geneva: World Health Organization*, 85-89.

3.Graber, T. (1949) Craniofacial morphology in cleft palate and cleft lip deformities. *Surgery, Gynecology & Obstetrics*, 88, 359-369.

4.Friede, H., and Enemark, H. (2001) Long-term evidence for favorable midfacial growth after delayed hard palate repair in UCLP patients. The *Cleft Palate- Craniofacial Journal*, 38, 323-329.

5.Noverraz, A.E., Kuijpers-Jagtman, A.M., Mars, M. and Van't Hof, M.A. (1993) Timing of hard palate closure and dental arch relationships in unilateral cleft lip and palate patients: a mixed-longitudinal study. *The Cleft Palate- Craniofacial Journal*, 30, 391-396.

6.Witzel, M., Salyer, K., and Ross, R. (1984) Delayed hard palate closure: the philosophy revisited. *The Cleft Palate Journal*, 21, 263-269.

1. Mars, M., Plint, D.A., Houston, W., Bergland, O. and Semb, G. (1987) The Goslon Yardstick: a new system of assessing dental arch relationships in children with unilateral clefts of the lip and palate. *The Cleft Palate Journal*, 24, 314-322.

3.

2.4. Atack, N.E., Hathorn, I.S., Semb, G.V., Dowell, T., and Sandy J.R.. (1979) A new index for assessing surgical outcome in unilateral cleft lip and palate subjects aged five: reproducibility and validity. *The Cleft Palate- Craniofacial Journal*, 34(3), 242-6.

3.5. Jones, T., Leary, S., Atack, N., Chawla, O., Ness, A., Ireland, T. and Sandy, J. (2015) Are photographs a suitable alternative to dental study casts when assessing primary surgical outcome in children born with unilateral cleft lip and palate? *The European Journal of Orthodontics* . In Press.

6. Mossey, P., Clark, J., and Gray, D. (2003) Preliminary investigation of a modified Huddart/Bodenham scoring system for assessment of maxillary arch constriction in unilateral cleft lip and palate subjects. *The European Journal of Orthodontics*, 25, 251-257.

4.7. Gray, D., and Mossey, P. (2005) Evaluation of a modified Huddart/Bodenham scoring system for assessment of maxillary arch constriction in unilateral cleft lip and palate subjects. *European Journal of Orthodontics*, 27, 507-511.

5.8. Oskouei. (2007) *Web-based Learning package on The EUROCRAN Yardstick for Rating Surgical Outcome in Unilateral cleft Lip & Palate Patients.* Master of Science, University of Manchester.

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~~6.~~9. Patel, D. (2011) *Evaluation of the use of the modified Huddart Bodenham & EUROCRAN yardstick for the assessment of surgical outcome for unilateral cleft lip and palate.* Master of Dental Science, University of Dundee.

~~7.~~10. Fudalej, P., Katsaros, C., Bongaarts, C., Dudkiewicz, Z. and Kuijpers-jagtman, A.M. (2011) Dental arch relationship in children with complete unilateral cleft lip and palate following one-stage and three-stage surgical protocols. *Clinical Oral Investigations,* 15**,** 503-510.

~~8.~~11. Huddart, A., and Bodenham, R. (1972) The evaluation of arch form and occlusion in unilateral cleft palate subjects. *The Cleft Palate Journal,* 9**,** 194-209.

~~9.~~12. Tothill, C., and Mossey, P.A. (2007) Assessment of arch constriction in patients with bilateral cleft lip and palate and isolated cleft palate: a pilot study. *The European Journal of Orthodontics,* 29**,** 193-197.

~~10.~~13. Dobbyn, L., Weir, J., Macfarlane, T. and Mossey, P. (2012) Calibration of the modified Huddart and Bodenham scoring system against the GOSLON/5-year-olds' index for unilateral cleft lip and palate. *The European Journal of Orthodontics,* 34**,** 762-767.

~~18.Altalibi, M., Saltaji, H., Edwards, R., Major, P.W., and Flores-Mir, C. (2013) Indices to assess malocclusions in patients with cleft lip and palate. *European Journal of Orthodontics,* 35(6), 772-82.~~

~~12.~~14. Nollet, P.J., Katsaros, C., Van't Hof, M.A., Bongaarts, C.A., Semb, G., Shaw, W.C. and Kuijpers-Jagtman, A.M. (2004) Photographs of study casts: an alternative medium for rating dental arch relationships in unilateral cleft lip and palate. *The Cleft Palate-Craniofacial Journal***,** 41**,** 646-650.

~~13. Liao, Y.F., Huang, C.S. and Lin, I.F. (2009) Intraoral photographs for rating dental arch relationships in unilateral cleft lip and palate. *The Cleft Palate- Craniofacial Journal,* 46, 415-419.~~

~~14. Mcauliffe, N., Jones, A., Cumberbirch, V. and Russell, J. (2011) The Use of the 5-Year-Olds' Index: Comparison Between Study Models and Intraoral Photographs. *The Cleft Palate- Craniofacial Journal,* 48, 526-531.~~

15. Nicholls, W., Singer, S.L., Southall, P.J., and Winters~~INTERS~~, J.C. (2014) The Assessment of Digital Study Models Using the GOSLON Yardstick Index. *The Cleft Palate- Craniofacial Journal,* 51**,** 264-269.

16. Chalmers, E. (2015) Intra-oral three dimensional scanning for assessment of surgical outcome in patients with unilateral cleft lip and palate. *Clinical MDSc by Research,* University of Dundee.

17. Asquith, J.A., and McIntyre, G.T. (2012) Dental arch relationships on three-dimensional digital study models and conventional plaster study models for patients with unilateral cleft lip and palate. *The Cleft Palate- Craniofacial Journal*, 49(5), 530-4.

18. Chawla, O., Atack, N., Deacon, S., Leary, S., Ireland, A. and Sandy, J. (2013) Three-dimensional digital models for rating dental arch relationships in unilateral cleft lip and palate. *The Cleft Palate-Craniofacial Journal,* 50**,** 182-186.

19. Sabelis, A.J., Kuijpers, M.A., Nada, R.M., Chiu, Y.T., Bronkhorst, E.M., Kuijpers-Jagtman, A.M., and Fudalej, P.S. (2015) Rating dental arch relationships and palatal morphology with the EUROCRAN index on three different formats of dental casts in children with unilateral cleft lip and palate. *Clinical oral investigations*, 13, 1-8.

20. Leenarts C.M., Bartzela, T.N., Bronkhorst, E.M., Semb, G., Shaw, W.C., Katsaros, C., and Kuijpers-Jagtman, A.M. (2012) Photographs of dental casts or digital models: rating

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dental arch relationships in bilateral cleft lip and palate. *International journal of oral and maxillofacial surgery*, 29,180-5.

21. Rudge, S. (1981) Dental arch analysis: arch form A review of the literature. *The European Journal of Orthodontics*, 3, 279-284.
22. Fleming, P., Dibiase, A., and Lee, R. (2007) Arch form and dimensional changes in orthodontics. *Progress in orthodontics*, 9, 58-64.
19. Angle, E.H. (1899) Classification of malocclusion. *Dental Cosmos.*. 41, 248-264.
20. Hawley, C. (1905) Determination of the normal arch, and its application to orthodontia. *Dental Cosmos*, 47, 541-552.
21. Macconaill, M. and Scher, E. (1949) The ideal form of the human dental arcade, with some prosthetic application. *The Dental Record*, 69, 285-302.
22. Currier, J.H. (1969) A computerized geometric analysis of human dental arch form. *American Journal of Orthodontics*, 56, 164-179.
23. Brader, A.C. (1972) Dental arch form related with intraoral forces: PR= C. *American Journal of Orthodontics*, 61, 541-561.
24. Pepe, S.H. (1975) Polynomial and catenary curve fits to human dental arches. *Journal of Dental Research*, 54, 1124-1132.
25. Sampson, P.D. (1981) Dental arch shape: a statistical analysis using conic sections. *American Journal of Orthodontics*, 79, 535-548.
26.23. Ferrario, V., Sforza, C., Miani, JR, A. and Serrao, G. (1993) Dental arch asymmetry in young healthy human subjects evaluated by Euclidean distance matrix analysis. *Archives of Oral Biology*, 38, 189-194.
27.24. Begole, E.A. (1979) A computer program for the analysis of dental arch form using the cubic spline function. *Computer Methods and Programs in Biomedicine.* 10(2), 136-42.
28.25. Begole, E. A. (1980). Application of the cubic spline function in the description of dental arch form. *Journal of Dental Research*, 59, 1549-1556.
29.26. Adaškevičius, R., and Vasiliauskas, A. (2015) Evaluation of dental arch form using 3D dental cast scanning technology. *Elektronika ir Elektrotechnika*, 93(5), 99-102.
30.27. Nam, S.E., Kim, Y.H., Park, Y.S., Baek, S.H., Hayashi, K., Kim, K.N., and Lee, S.P. (2012) Three-dimensional dental model constructed from an average dental form. *American Journal of Orthodontics and Dentofacial Orthopedics*, 141, 213-218.
31. Van mourik, M.S., Troelstra, A., Van solinge, W.W., Moons, K.G., and Bonten, M.J. (2013) Automated surveillance for healthcare-associated infections: opportunities for improvement. *Clinical Infectious Diseases*, 57 (1), 85-93
32. Shah, A.K., Eissler, J., and Radomisli, T. (2002) Algorithms for the treatment of femoral neck fractures. *Clinical Orthopaedics and Related Research*, 399, 28-34.
33. Mo, H., Thompson, W.K., Rasmussen, L.V., Pacheco, J.A., Jiang, G., Kiefer, R., Zhu, Q., Xu, J., Montague, E. and Carrell, D.S. (2015) Desiderata for computable representations of electronic health records-driven phenotype algorithms. *Journal of the American Medical Informatics Association*, 22 (6), 1220-1230.
34. Mörmann, W., Brandestini, M., Ferru, A., Lutz, F. and Krejci, I. (1985) Marginal adaptation of adhesive porcelain inlays in vitro. *Schweiz Monatsschr Zahnmed*, 95, 1118.
35. Martin, C., Chalmers, E., McIntyre, G., Cochrane, H. and Mossey, P. (2015) Orthodontic scanners: what's available? *Journal of Orthodontics*, 42, 136-143.
36.28. Ma, X., Martin, C., McIntyre, G., Lin, P., Mossey, P. (2016) Digital three-dimensional automation of the modified Huddart and Bodenham scoring system for patients with cleft lip and palate. *The Cleft Palate-Craniofacial Journal.* In Press

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37.29. Cronbach L,J. (1951) Coefficient alpha and the internal structure of tests. *Psychometrika*; 16**,** 297-334.
38.30. Bland, J.M., and Altman, D.G., (1997) Statistics notes: Cronbach's alpha. *British Medical Journal,* 314**,** 572.
39.31. Bland, J.M., and Altman, D.G. (1986) Statistical methods for assessing agreement between two methods of clinical measurement. *The Lancet,* 327**,** 307-310.
40.32. Houston, W. (1983) The analysis of errors in orthodontic measurements. *American Journal of Orthodontics,* 83**,** 382-390.
41.33. Papagiannis, A., and Halazonetis, D.J. (2015) Shape variation and covariation of upper and lower dental arches of an orthodontic population. *The European Journal of Orthodontics* , 1, 10
42.34. Brief, J., Behle, J.H., Stellzig-eisenhauer, A., and Hassfeld, S. (2006) Precision of landmark positioning on digitized models from patients with cleft lip and palate. The *Cleft Palate- Craniofacial Journal,* 43**,** 168-173.
43.35. Nam, S.E., Kim, Y.H., Park, Y.S., Baek, S.H., Hayashi, K., Kim, K.N., and Lee, S.P. (2012) Three-dimensional dental model constructed from an average dental form. *American Journal of Orthodontics and Dentofacial Orthopedics,* 141**,** 213-218.
44.36. Mullen, S. R., Martin, C. A., Ngan, P. & Gladwin, M. (2007) Accuracy of space analysis with emodels and plaster models. *American Journal of Orthodontics and Dentofacial Orthopedics,* 132**,** 346-352.
45.37. Hechter, F. (1978) Symmetry and dental arch form of orthodontically treated patients. *Dental Journal,* 44**,** 173-184.
46.38. Mars, M., Batra, P., and Worrell, E. (2006) Complete unilateral cleft lip and palate: validity of the five-year index and the Goslon yardstick in predicting long-term dental arch relationships. *The Cleft Palate- Craniofacial Journal,* 43**,** 557-562.
47.39. Hayat, M., Bennamoun, M., and El-sallam, A.A. (2012) Fully automatic face recognition from 3D videos. Pattern Recognition (ICPR), 21st International Conference on, IEEE, 1415-1418.
48.40. Best-Rowden, L., and Jain, A.K. (2015) A longitudinal study of automatic face recognition. *International Conference on Biometrics*.
49. ~~Little, R. (1990) Stability and relapse of dental arch alignment. *Journal of Orthodontics,* 17, 235-241.~~
50. ~~Shaw, D.W. (2004) a. Global strategies to reduce the health care burden of craniofacial anomalies: report of WHO meetings on international collaborative research on craniofacial anomalies. *The Cleft Palate- Craniofacial Journal,* 41, 238-243.~~
51. ~~Mossey, P., and Modell, B. (2012) Epidemiology of Oral Clefts 2012: An International Perspective. *Frontiers of Oral Biology,* 16, 1-18.~~

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Figure captions

Figure 1: Recruitment for the study population
Figure 2: Landmark identification. Note: Landmarks have been enlarged for the purposes of illustration~~Recruitment for the study population~~
Figure ~~3~~2: Distance calculation using cubic spline interpolation
Figure ~~4~~3:. Bland-Altman plots for Total MHB scores for all examiners with different mediums. (a: plaster, b: Orthoanalyzer, c: ~~Rhino plug-in~~Software plug-in).

Table captions

Table 1: Intraclass correlation coefficients and confidence intervals for each examiner for all variables and methods of scoring combined.
Table 2: Intraclass correlation coefficients and confidence intervals for each medium using combined repeat scores, for all examiners for all variables.

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