THREE DIMENSIONAL TREATMENT OUTCOMES IN CLASS II PATIENTS TREATED USING HERBST: A PILOT STUDY

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ABSTRACT

MEGAN L LECORNU: Three dimensional treatment outcomes in class II patients
treated using Herbst
(Under the direction of Dr. Tung Nguyen)

Objective: Limitations of 2D imaging underlie current controversies in Herbst literature regarding skeletal effects of the appliance. 3D imaging techniques overcome these limitations. The purpose of this study was to analyze 3-D skeletal changes in class II patients treated with the Herbst appliance and compare to treated class II controls using 3D superimposition techniques. **Methods:** This pilot study enrolled 7 consecutively treated Herbst patients and 7 consecutive class II controls (treated with class II elastics). CBCTs were taken pre-treatment (T1) and post- treatment (T2), 3-D models were generated from CBCTs, registered on the anterior cranial bases and analyzed using color map and point-to-point measurements. **Results:** Herbst patients demonstrated anterior translation of the glenoid fossa and condyles compared to controls, resulting in a difference 2.52mm and 2.94 mm for the right and left anterior fossa, and 1.83 and 2.20 for the right and left posterior fossa ($p<0.01$). In addition, a maxillary restraining effect was noted in Herbst subjects with a difference of 2.42mm when compared to control subjects ($p<0.001$). **Conclusion:** The skeletal effects of the Herbst appliance leading to improvement in the class II profile include remodeling of the glenoid fossa leading to increased mandibular projection, and a maxillary headgear effect.

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CHAPTER I

LITERATURE REVIEW

Class II skeletal relationships are commonly encountered in orthodontic practices in the United States[1]. The etiology includes a prognatic maxilla, a retrognathic mandible or a combination of both. A study by 1981 revealed that a majority of class II patients have some component of mandibular deficiency underlying the skeletal class II discrepancy [2]. Ideally, the skeletal discrepancy needs to be addressed for optimal treatment results[3].

When evaluating treatment options for these patients, two things need to be considered 1) the extent of the skeletal discrepancy and 2) the skeletal maturity of the patient. In patients with a less severe skeletal discrepancy, class II camouflage may be appropriate. However if camouflage treatment is delivered to a patient with a relative sever skeletal class II discrepancy, it can result in poor esthetic outcomes[3]. Surgical treatment may be indicated for patients with extremely severe skeletal problems, or for patients with not growth potential remaining for which camouflage treatment may result in an unaesthetic outcome. Most common surgical treatment involves mandibular bilateral sagittal split osteotomy advancement, because of course, a majority of the patients have some component of mandibular deficiency [4].However, maxillary set back can also be conducted as an isolated procedure or in conjunction with a mandibular set back procedure. Surgery is expensive and is associated with potentially severe comorbidities including paraesthesia, anaesthesia, paralysis and potentially death. Because of these potential complications, patients are often reluctant to go through surgical treatment. In fact, from 1984 to 1996, only 42% of the patients seen at the Dentofacial clinic at the University of North Carolina for surgical correction of a class II skeletal problem accepted and completed surgical treatment[4]. Alternatively, if the patient is intercepted when there is inherent growth remaining, growth modification can be attempted to correct the skeletal discrepancy.

Numerous human and animal orthopedic investigations have established the optimal time for class II growth modification is during the pubertal growth spurt[5-11]. This treatment window is during the peak pubertal growth spurt, which corresponds to CVM stage of CS3-CS4[11]. We know a majority of class II patients have mandibular deficiency, thus, utilizing growth modification treatment modalities that target the jaw at fault is ideal. Functional appliances are purported to increase mandibular projection[6, 8, 12-16]. Orthodontic treatment with appliances like the Herbst, bionator, twin block, or headgear can effectively achieve ideal overjet and class I dental relationships, however a systematic review by Cozza and Baccetti published in 2006 revealed that the Herbst appliance is the most effective at increasing mandibular projection[8] . Thus it is no wonder the Herbst is the most commonly employed functional appliance for the correction of a class II malocclusion[17, 18].

Emile Herbst, the inventor of this popular appliance first presented it at the 5th International Dental Conference in Berlin in 1909[17]. Controversies regarding adverse effects to the periodontium (that were later disproved) caused the appliance to fall out of favor. The Herbst appliance was forgotten until the late 1970's when Pancherz began to revisit the treatment method[17].

Appliance Design

Herbst appliance design has evolved over the past 100 years; however, the basic mechanism has remained unchanged. The device includes bilateral telescope mechanisms that guide the mandible into an anterior position during rest, and all functional movements[17]. Original appliance design employed by Emile Herbst included crowns on the upper first molars, and crowns on the lower canines with curved telescoping mechanisms that were designed to mimic the Curve of Spee (Figure A)[17].

Current designs include crowns on the maxillary first molars and crowns on the mandibular first premolar with straight telescoping mechanisms[17]. Variants include the acrylic splint Herbst developed by Howe, Howe and McNamara, which can be either bonded or removable, and the cantilever Herbst (Figure B,C)[17]. Problems with leakage and subsequent increased risk of calcifications and difficulty with debonding decreased the popularity of the acrylic Herbst[19]. The cantilever Herbst was initially designed for the mixed dentition prior to the eruption of the mandibular canines or first pre-molars[17]. This design involves crowns or bands on the upper and lower first molars, with a tubular arm extending mesially from the lower first molar and ending in the premolar region. This design also allows the orthodontist to bond anterior teeth for increased anchorage and concurrent leveling/ aligning of the mandibular arch [20]. The Herbst continues to evolve. Newer modifications to the cantilever Herbst design have been aimed at decreasing the length of the cantilever arm so fixed appliances (orthodontic brackets) can be placed on all teeth to further improve treatment efficiency. One such design called the Advansync

Herbst (Allesee Orthodontic Appliances, Sturtevant, WI) has been produced. This appliance allows the provider to place fixed appliances on the upper and lower arches from the second premolars. However, because of the short arm, undesirable vertical side effects may occur. Further development on this design is warranted.

Adverse effects of cantilever Herbst and design modifications: The cantilever Herbst design requires extra consideration. Because of the long anterior arm extension, the distance of the force to the center of rotation is very large and can lead to significant mesial tipping of the mandibular molars. For this reason, an occlusal rest that extends from the mesial of the mandibular molar to the occlusal of the 1st premolar is recommended. In addition, a rest from the distal of the mandibular first molars to the occlusal of the mandibular second molars helps to prevent eruption of the second molar. A lower lingual holding(LLHA) arch is often included in the design of the cantilever Herbst in order to prevent mesial crown tip of the mandibular molars.

In the maxilla, occlusal rests are extended from the distal of the first molars to the occlusal of the second molars. This also helps to control distal tipping of the first molars and prevents extrusion of the second molar.

Proclination of the lower incisors can be prevented in the cantilever Herbst with labial wires that add negative root torque of 10 degrees. Adding brackets to the lower incisors can also help to control the cantilever forces exhibited on the molars by increasing anchorage. In addition, the archwire tubes on the terminal ends of the Herbst appliance can be placed gingivally in order to help correct deep bites with lower incisor intrusion. Conversely, the archwire tubes can be placed occlusally to help in the correction of open bites.

University of North Carolina (UNC) graduate orthodontic department commonly utilizes the Mini Scope cantilever design (Allesee Orthodontic Appliances, Sturtevant, WI) to improve treatment efficiency without the unwanted vertical side effects. The rest of this discussion will focus on the Miniscope cantilever Herbst design since it is the most widely used. The purpose of this paper is to review the literature on the Herbst appliance and investigate the biomechanical effects leading to dentoalveolar and skeletal changes.

Dentoalveolar effects

Dentoalveolar effects of the Herbst provide large changes leading to class II correction. In general, mandibular molars will move mesially (often tipping) between 0.5 and 5-5mm. Maxillary molars may have up to 1 mm of intrusion, and distalize between 0.6 and 3.0 mm[19]. Distal tipping of the maxillary molars between 5.6° and 6.4° are also observed[19]. The mandibular and maxillary 2nd molars often extrude because overcorrection of the OJ to an end-to end or negative overjet causes posterior disocclusion. The lower incisors will Procline between 5.4° and 10.8° and will move mesially between 0.2mm and 4.0 mm[19]. The occlusal plane rotates in a clockwise direction due to intrusion of maxillary molars between 1.1° -5.5°.

Skeletal Effects

The Herbst is a tooth supported appliance. As such, some studies suggest the effects of the Herbst are primarily dentoalveolar. [21, 22] Many studies report the Herbst, improves mandibular projection, consequently improving the underlying skeletal discrepancy. [8, 21, 23, 24] Studies also cannot agree on the effect of the Herbst on the Maxilla. A mild restraining effect in response to Herbst treatment has been noted by many studies, and the effect has been shown to be statistically similar to the effect produced by headgear[16, 25-29]. Meanwhile, some studies suggest the skeletal headgear effect displayed by the Herbst is negligible. [6, 30, 31] Ultimately, available data which examines the extent of skeletal verse dentoalveolar adaptation in that lead to the class II correction when using the Herbst is controversial. [24, 28, 30, 32] The skeletal component of class II correction has been reported to extend from 13% to 85%. [5, 7, 14, 28-30, 30, 31, 33-35]

Maxillary changes:

When considering the variance in the literature, it is important to understand the various methodologies employed to measure changes in A point. The method developed by Pancherz utilizes a reference grid constructed from the occlusal line (OL) and the occlusal line perpendicular (OLp)[14]. Maxillary measurements using this method are subject to patient positioning errors. Many studies use SNA to examine maxillary changes [5, 25, 26]. However, increases in the vertical dimension as seen with growth will mask the anterior-posterior change when using these angular measurements[8]. Skeletal changes observed at A point, undeniably depend on the methodologies used.

Studies supporting a maxillary restraining effect of the Herbst theoretically make sense. During treatment the Herbst appliance exerts an upward and posterior force that is similar to a high-pull headgear. Studies report a restraining effect on the maxilla with decrease SNA ranging from 0.4°-1.2°[19, 25, 36]. However, the SNA angle often relapses to preclinical values[19]Authors using the grid system to evaluate maxillary restraint found 0.4 mm maxillary restraint to 2.8 mm[16, 28, 29, 34]. It is important to understand that authors often found different effects on the maxilla depending on the method of analysis employed[25, 30, 34]. Mild tipping of the palatal plane (average: 0.2°-1.0°) have also been reported [19, 25, 30, 34]. It is important to understand many studies found no difference in the anterior-posterior projection of the maxilla. [6, 30, 31]

Mandibular changes:

Alteration of anterior-posterior projection of the mandible can be attributed to 1) changes in mandibular growth, 2) changes in the direction of growth and/ or 3) condylar/ fossa positional changes. Previous studies report conflicting results with some showing increased mandibular length with Herbst treatment [6, 8, 14, 14, 16, 25-27, 27-29]. While other studies show no significant increase in mandibular length [30, 35]. Deviations in patient positioning, as well as differences in magnification ratios between the left and right sides of the mandible can effect 2-D measurements of mandibular corpus length and ramus height.

Currently, most of the literature that evaluates mandibular growth following functional appliance therapy use condylion, an arbitrary condylar point, or a proxy- point such as articulare [6, 9, 14, 25, 27-29, 31, 33, 36-39]. Condylion landmark identification is associated with low reliability due to obstruction of the overlying temporal bone[40]. Utilizing an arbitrary condylar point, as in the method described by Creekmoor, and used by Pancherz improves landmark identification[41]. However, this method is still subject to distortion, magnification, and mandibular regional registration errors during the transfer process. A recent study showed no difference in the reliability of identifying condylion when using the arbitrary condylar point compared to simply identifying this point on a closed mouth lateral cephalogram[42]. Additionally, rotational deviations in patient positioning between T1 and T2 image capture, will have a large effect on the perceived mandibular corpus length regardless of the measurement used. Any discrepancy in “tilt” or pitch positional errors will also affect vertical measurement error. Lastly, using articulare as a proxy condylar point is going to present significant measurement error. The position of articulare is dependent on vertical and anterio-posterior changes of the glenoid fossa and condyle. Because articulare is dependent on growth, it does not suit well as a proxy point for condylion in longitudinal growth studies [38].

Despite these limitations Baccetti et. al. found that class II subjects treated with a Herbst achieved chin advancements from 2.5 mm to 5 mm greater than untreated class II patients and had 2 mm to 4 mm greater chin advancements (determined by B point and pogonion) compared to patients treated with head gear and class II elastics[25]. Increasing mandibular growth with Herbst therapy has also been reported by Pancherez et. al and many other investigators[6, 12-16, 27, 39] Meanwhile some studies show an increase in the anterior-posterior projection of the mandible without a statistically significant increase in mandibular length [30, 35]. Long-term change in SNB angles are variable, with some studies finding no difference, while other studies report increases of 0.3°-2.6°[12, 16, 19, 27-29, 33]. The ANB angle has been shown to decrease between 1.1° to 3.9°, and remains relatively stable [19, 26, 36]. The mandibular length (Co-Gn) has been shown to increase between 3.0-7.5 mm after treatment [14, 19, 23, 25, 30, 31, 43]. Pancherz reported long-term stability in mandibular length, however, many studies have not validated this finding[28, 33, 44]. A counterclockwise rotation secondary to dental effects was noted in some studies. [19] This movement helps the class II skeletal relationship. The literature is in discord regarding increases in posterior mandibular height [25, 28, 29]. Again, these differences likely arise due to different methodologies in measurement protocols.

In addition to increased length, alterations in growth pattern will also impact anterior-posterior projection of the mandibular base. Opening of the gonial angle and posterior flexure of the condyle are anatomical changes that can lead to more anterior mandibular positioning. Animal studies have shown mild opening of the gonial angle with mandibular advancement [45, 46]. And some human studies have made similar conclusions [14, 28]. Initial placement of the Herbst causes the condyle to be placed anteriorly onto the articular eminence. After 6-12 weeks, the condyles showed a more posterior position in the glenoid fossa, and the posterior superior aspect of the condyle showed increased signal intensity on MRI [39]. Condylar osteogenesis during Herbst treatment has also been shown in animal studies[45-49]. Sagittal condylar growth has been reported to occur between 1.8 and 3.8 mm[14, 15, 19, 38, 43]. The condyle moves between 1.5-3.1 mm superiorly and 2.1- 4.0 mm posteriorly[14, 15, 19]. Interestingly, the direction of condylar osteogenesis occurs in the direction of tension from the stretch of disc fibers on the condyle and glenoid fossa. [47]

It is important to realize that measurements used to evaluate changes in gonial angle and condylar flexure in human studies all rely on reliable identification of condylion, thus the findings from these studies need to be interpreted cautiously.

In addition to redirection the growth pattern of the mandible, altering the growth process of the glenoid fossa can also allow for increased mandibular projection. It is believed that there are two sites in the temporal mandibular joint (TMJ) that adapt to the forces of the Herbst: 1) condyle; and 2) glenoid fossa [39] . We have already addressed changes in condylar growth. The condylar position changes within the fossa have also been proposed however this is not significantly confirmed in ether animal or human studies [39]. Pancherz et al looked at the size of the joint space pre- and post Herbst treatment. They found that there was no statistical difference in the condylar position. However, there was great variation among patients. It was revealed that post treatment condylar positions were on average slightly more anterior than pretreatment positions.

Glenoid Fossa:

Translation of the glenoid fossa, has been shown to contribute to mandibular positional changes post Herbst treatment in animal studies [45-49]. However, 2D imaging techniques used in human studies are greatly flawed when assessing for remodeling of the glenoid fossa. Human studies often rely on an unchanged condyle-fossa relationship because they utilize the method described by Buschang and Santos-Pinto [50, 51]. Ruf and Pancherz conducted and MRI study to evaluate effective condylar growth in Herbst patients [39]. They noted increase uptake in the T2-weighted sequences in the glenoid fossa and condyle. This was interpreted to be definitive areas of condyle and fossa remodeling. However, because the incidence of capsulitis rises during Herbst treatment up to 100%, virtually all patients would be expected to have increased T2 signal due to the amplified inflammatory process [52, 53]. Differentiating inflammatory processes from the cellular cascade of skeletal remodeling is difficult. Additionally, techniques to register and superimpose MRI scans to evaluate changes critically from T1 to T2 have not been developed for the cranial base. Therefore, MRI scans cannot be used to adequately examine skeletal adaptations until a proper registration and superimposition technique is developed.

Animal studies in rats reveal that at 6-12 weeks of treatment the anterior aspect of the posterior glenoid spine began to undergo adaptive remodeling processes [47]. It was also evident that cellular responses to mandibular advancement were the most evident in the posterior glenoid fossa of rats[47]. Animal studies have clearly shown the adaptive potential of the glenoid fossa in response to functional appliance therapy [10, 45-49, 54, 55]. Studies in monkeys reveal similar adaptive potential of the glenoid fossa[45, 46, 48, 49, 54, 55]. In fact Voudouris et. al detected reversal lines in the genoid fossa in cyanomologous monkeys (*Macaca fasicularis*), that are associated with the redirection of growth[45, 46]. He extended these findings to conclude the natural downward and backward growth of the glenoid fossa from the sella-nasion plane during facial growth might have the backward component of this natural growth pattern restricted by the Herbst appliance[45, 46]. Human studies have suggested remodeling may occur. However, these studies use condylion or articulare as a proxy point to approximate the position of the fossa. Those conclusions were not absolute due to imaging limitations and measurement errors [38, 39, 50]. After examining all of the condylar and fossa changes, they concluded overall the "effective condylar growth" during Herbst treatment resulted in six-times more horizontal growth and four-times more vertical growth when compared to Bolton Standards. [39]

The literature reveals tremendous variation in the amount of skeletal adaptation leading to improvement in the class II profile. This variation stems from the limitations of 2D imaging. Further research needs to be conducted using novel three dimensional imaging techniques to clarify the skeletal response to the Herbst appliance.

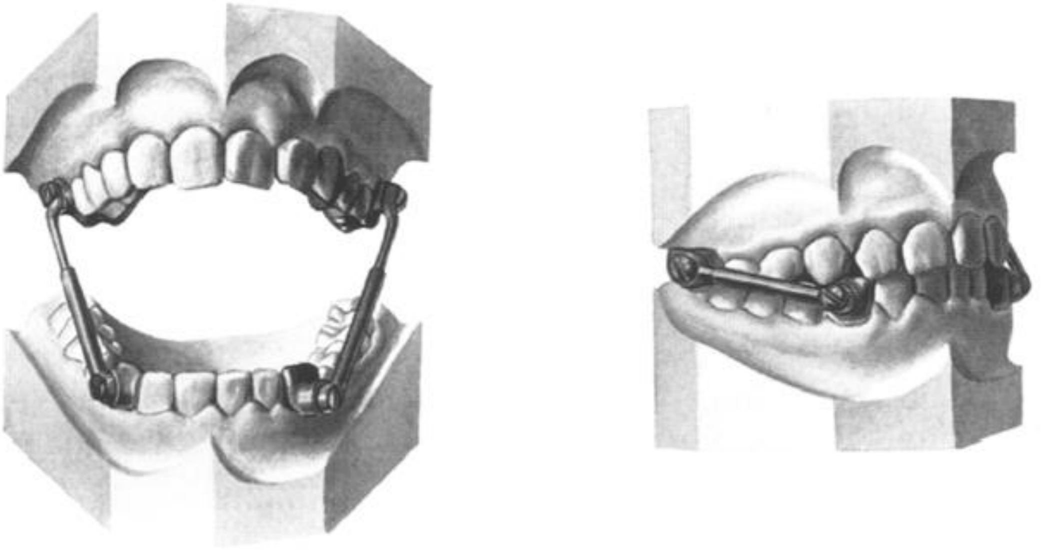

Figure A: Original Herbst Design
Pancherz et al. “History, background and development of the Herbst appliance”*Semin Orthod*. 2003; 9(1): 3-11.

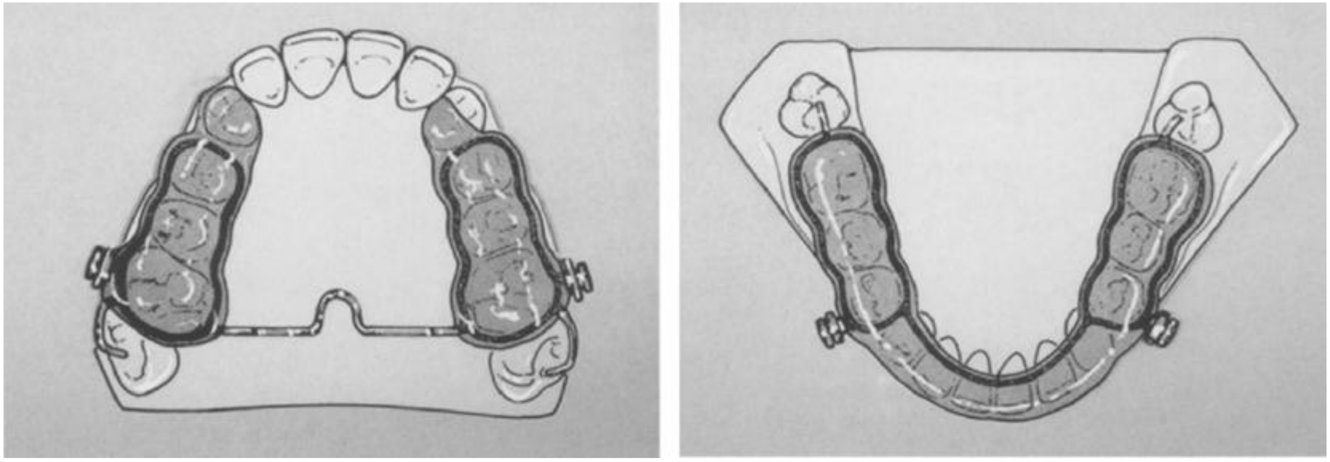

Figure B: The Acrylic Herbst Design
Pancherz et al. “History, background and development of the Herbst appliance”*Semin Orthod*. 2003; 9(1): 3-11.

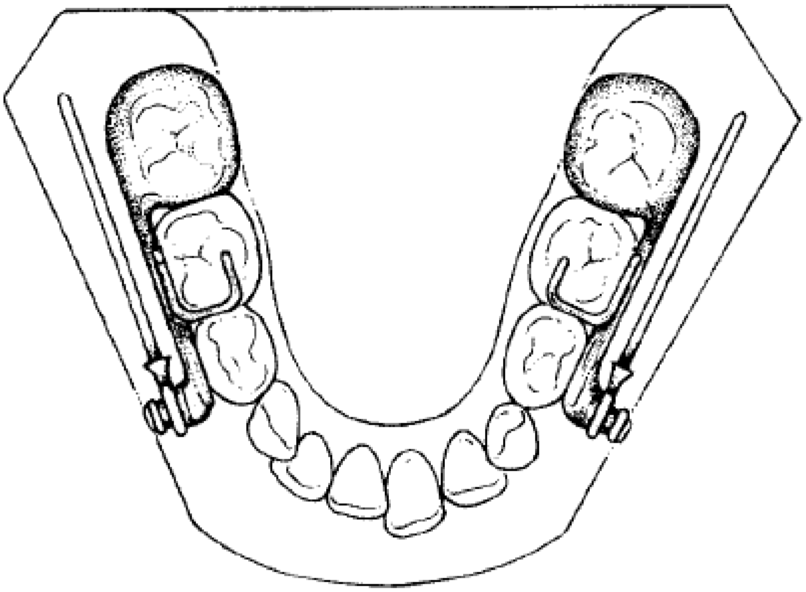

Figure C: The Cantilever Herbst Design
Pancherz et al. “History, background and development of the Herbst appliance”*Semin Orthod*. 2003; 9(1): 3-11.

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CHAPTER II

MANUSCRIPT

INTRODUCTION

Treatment of Class II malocclusions are a common challenge amongst orthodontists in the United States. Approximately one third of all patients have a Class II, Division 1 malocclusion. Mandibular retrognathism serves as the primary etiologic factor in a majority of those cases[1, 2]. Functional appliances have been shown effective in correcting class II malocclusions by decreasing overjet and achieving Angle class I canine and molar relationships [1-5]. Eliminating patient compliance factors and delivering continuous forces give fixed functional appliances a distinct treatment advantage compared to removable appliances. Specifically, many studies have reported greatest anterior-posterior improvements in mandibular projection when using the fixed Herbst functional appliance [1, 2, 5-10].

Functional appliances, such as the Herbst, have been purported to improve mandibular projection, consequently improving the underlying skeletal discrepancy [5, 6, 8, 11]. However, available data which examines the extent of skeletal verse dentoalveolar adaptation in class II correction with functional appliances is controversial [3, 4, 11, 12]. The skeletal component of class II correction has been reported to extend from 13% to 85% [3, 3, 9, 12-19]. Variations in reported skeletal changes are due to a number of factors ranging from physiologic and anatomic inconsistencies in study subjects, to limitations in study methodologies.

Skeletal adaptation depends on physiologic factors, such as skeletal maturation and growth potential. It is established most efficient treatment with the Herbst appliance is conducted during the pubertal growth spurt [6, 20, 20-22]. Yet, studies focusing on Herbst treated patients treated during the peak of pubertal growth, exhibit vast inconsistencies in the extent of skeletal verse dentoalveolar adaptation[1, 6, 11, 15, 20, 23, 24]. The differences in treatment timing alone do not account for ambiguity reported in the literature. Studies suggest that anatomical factors, such as facial type and gonial angle may have an impact on the extent of skeletal adaptation [1, 9, 15, 20]. However, literature focusing on these factors is limited and most studies include well matched control subjects thus nullifying these anatomic factors. Ultimately, it is impossible to accurately assess the extent of skeletal adaptation, let alone examine how anatomic factors affect these adaptations, with the limitations of current methodologies.

Condylion is used in several studies to evaluate mandibular length changes [1, 3, 9, 13, 20, 25, 26]. While it has been suggested translation of the glenoid fossa/ condyle complex is the source of skeletal adaptation, these studies use condylion, or a proxy point for condylion to make these assessments [4, 13, 23, 24, 27-29]. Poor reliability of identifying this landmark brings to question the accuracy of findings in these studies[30]. Excitement regarding the possibility of glenoid fossa remodeling using functional jaw orthopedic appliances arises from findings in animal studies [31-37, 37]. However, these finding have yet to be definitively extended to human subjects. Despite the fact studies report improved mandibular projection with Herbst treatment, factors leading to these changes remain elusive due to limitations in 2D cephalometric imaging.

Two-dimensional imaging is subject to magnification, distortion, patient positioning errors and obstruction of critical landmarks by overlapping anatomical structures. Additionally, there is inherent examiner bias in the registration process if examiners are not blinded. All of these factors reduce measurement accuracy, which influences our ability to accurately report skeletal changes resulting from the Herbst appliance. Shortcomings of 2D cephalometric imaging can also account for discord in the literature regarding skeletal effects of this appliance. 3D imaging techniques overcome these inadequacies. Studies by Cevidanes et. al. demonstrate accurate superimposition of CBCT scans in growing patients [38-40]. The protocol uses a voxel based registration technique which eliminates examiner bias in the registration process. Maxillary and mandibular adaptive and positional changes can be accurately examined and measured relative to the anterior cranial base using these 3D superimposition techniques [38-40]. This method gives us more accurate and detailed information when assessing for skeletal changes.

While the Herbst appliance is effective in correcting class II malocclusions by decreasing overjet and correcting to Angle molar class I, the extent of skeletal verse dentoalveolar changes producing these effects is controversial and is of great interest to the orthodontist. The aim of this study is to use 3D imaging and superimposition techniques to report skeletal changes that lead to class II correction in Herbst patients, and compare these findings to matched class II patients treated with elastics. Specifically, maxillary positional changes, differences in mandibular growth and mandibular positional changes will be evaluated.

MATERIALS AND METHODS

Adolescent patients near the pubertal growth spurt (determined by cervical vertebral maturation method stages CS3-CS4) with class II skeletal relationships (ANB≥ 4°) and Class II molar relationships seen at the University of North Carolina Department of Orthodontics were evaluated for Herbst appliance therapy[41]. Seven consecutive patients, who met the inclusion criteria, were enrolled in this prospective pilot study (Table 1). Seven control subjects (treated with Class II elastics) were obtained from the University of Minnesota database. Approval from the University of North Carolina institutional review board was obtained for this study.

Herbst appliance design included mini-scope telescoping arms with cantilever and occlusal rests second molars and first premolars (Allesee Orthodontic Appliances, Sturtevant, WI). The appliance was initially advanced to Class I molar position. Fixed appliances were placed on maxillary and mandibular incisors and canines and tied back to the molar crown after alignment was achieved. Herbst appliance was advanced at 2 mm increments to an overcorrected position (OJ= 0 to -1 mm). The duration of advancement was 6-9 months with a 3-4 month retention period thereafter. It has been suggested that an extended retention period allows for adequate bone maturation to occur, and thus may lead to a more stable result [42]. The average treatment time is 11.42 +/- 1.4 months for Herbst subjects in this study, which is longer than the traditional 6-8 month treatment duration used by other authors [1, 12, 15, 22].

CBCT scans were taken pre-treatment for both Herbst and Control patients ($T1_H$ and $T1_c$) and post Herbst removal ($T2_H$) and post- treatment for control patients ($T2_C$). Herbst patients' scans were taken using the New Tom 3G (Aperio Services LLC, Sarasota, FL) with a 12 inch field of view (FOV). Control subject CBCT scans were taken using an iCat machine (Imaging Sciences Interation, Hatfield, Pa) with a 16x22cm FOV. The dicom scans were downsized to 0.5x0.5x0.5 mm and de-identified using Imagine http://www.ia.unc.edu/dev/download/imagine/index.htm). ITK SNAP (www.itksnap.org) was used to construct virtual 3D surface models [38]. T1 and T2 scans were registered on the anterior cranial fossa using a fully automated voxel-wise ridged registration technique described by Cevidanes [38-40]. Boundaries for the anterior cranial base registration were defined anteriorly by inner cortical layer of the frontal bone, posteriorly by the anterior wall of sella, and laterally including the lesser wings of the sphenoid bone and frontal bone marking the superior boundary of the orbits. This region includes the cribiform plate and the superior aspect of the ethmoid bone. These structures are known to complete growth by the age of seven, and are thus considered stable landmarks [43-45].

Registered 3-D models were then analyzed using Vectra Analysis Model (VAM) (Canfield Imaging Systems, Fairfield, NJ) software. Quantitative evaluation of growth and treatment response were calculated using 1) an iterative closest points (ICP) using color map tools and 2) a point-to-point landmark identification. Landmarks selected for this study are shown in Figure 1. Additional landmarks included Co', and Go'. Co' is defined by the most superior-posterior point of the posterior condylar head identified from the sagittal view. Go' is defined as the most posterior aspect of the mandibular corpus at the point where it starts to curve to from the angle of the mandible, identified from a sagittal view with the functional occlusal plane parallel to the floor. For all measurements, positive values indicated an anterior displacement and negative values indicated a posterior displacement relative to time 1. Cephalometric landmark placement on 3D volumes has been shown to be accurate and reproducible [46, 47]

All measurements were repeated two times by the same examiner (ML) at one week interval to assess intraexaminer reliability for landmark identification, point to point and ICP measurements.

Statistical Analysis:

Data analysis was conducted using SPSS statistical software package. Means, standard deviations and ranges were calculated for the Herbst and Control subjects to describe the samples. Statistical differences were assessed using analysis of variance (ANOVA). Wilcoxon rank test was employed to assess differences in displacement between Herbst and Control subjects. Intraobserver reliability was evaluated for repeated measures using intraexaminer correlation coefficient (ICC) test. Statistical significance was tested at $P \leq 0.05$.

RESULTS

Descriptive statistics for Herbst and control patients are summarized in table I. Patients are well matched with regard to age, ANB and incisor angulations. Control subjects exhibit a longer observation time of 18.42+/-3.05 months compared to 13+/-0.577 months in Herbst subjects (P=0.003). Additionally, Herbst subjects had a flatter MPA angle with a mean of 25.73+/-6.13 degrees compare to 36.71+/- 2.82 degrees in controls (P=0.001).

Intraexaminer correlation coefficient revealed high correlation for all measurements. ICC was above 0.90 for all ICP, point-to-point and angular measurements indicating high reliability for landmark identification.

Maxillary Skeletal Changes:

Qualitative assessment of skeletal changes is best conducted using a semitransparent overlay of the superimpositions (Figures 2, 3, 5, 6 and 9). For structures that are obstructed from view, alternating the transparency of the T1 and T2 images allow for better visualization. Maxillary displacement changes are shown in Figure 2 and Figure 3. All Herbst patients, except for subject A, demonstrated maxillary restraint. Herbst subjects B, C, D and G displayed largest maxillary displacements. Retroclination of upper incisors is evident in Control subjects C and E, and maxillary restraint can be noted in control subject A (Figure 3).

Quantitative assessments of maxillary changes are reported in Table II and Figure 4. More anterior projection of A point and ANS (1.2mm and 1.96mm respectively) was demonstrated by treated controls, when compared to Herbst subjects (-1.22 and 0.26mm respectively) ($P<0.01$).

Mandibular Skeletal Changes:

Skeletal changes in the mandible are reported in Tables II and Figure 7. B point had an average displacement of 2.62mm in Herbst subjects and 1.49mm in control subjects showing a statistically significant increase in anterior projection of B point in Herbst patients by 1.14mm ($P=0.05$). All other linear mandibular changes were not statistically significant when comparing Herbst and control subjects (Table II, Figure 7). In addition, angular measurements evaluating opening of the gonial angle and condylar flexure reveal no statistical difference between Herbst and control subjects (Table II, Figure 8).

Condylar/ Glenoid Fossa Changes:

Mean condylar and glenoid fossa displacement is shown in Table II and Figure 11. In general, Herbst patients showed forward displacement of the condyles while control subjects exhibited posterior displacement. The mean difference in displacement of the condyle between the two groups is approximately 2.5-2.9mm when measured from the anterior surface ($P<0.001$) and 1.74-1.35mm when measured from the posterior surface of the condyles ($P< 0.05$).

In addition, point-to-point linear changes were evaluated for condylion (Table II, Figure11). Box plots in figure 11 depict net anterior displacement of condylion in Herbst patients (right: 0.38mm, left: 0.56mm). Conversely, a net posterior displacement of condylion was observed in the control group (right: -0.88mm, left:-1.16mm). These changes in condylar position are less than those found using ICP (right: 1.26mm, left: 1.72 mm), but remain statistically significant ($P\geq0.01$).

Mean changes for fossa remodeling are shown in Table II and Figure 7. Herbst patients showed resorption at the anterior wall (right: 1.69mm and left: 1.43mm) with deposition at the posterior wall of the glenoid fossa (right: 0.59mm, left: 0.79mm) (Figure10). Conversely, the control group showed boney apposition on the anterior wall (right: -1.51mm, left: -1.31mm) with resorption at the posterior wall (right: -1.24mm, left: -1.41mm). This corresponds with the direction of condylar displacement within the respective groups. (Figure 11).

Global View of Skeletal Changes:

Figure 12 shows the composite of individual color maps which demonstrates global changes computed using iterative closest point algorithms. Although maxillary, mandibular, condylar and glenoid fossa positional changes in Herbst patients show statistical differences when compared to the control subjects, considerable variation as to the magnitude and direction of these skeletal changes are seen when examining color maps of individual cases (Figure 12).

DISCUSSION

Past literature examining functional appliances often use samples from the Bolton-Brush or Michigan Growth Studies to obtain their untreated class II controls [11, 13, 26]. Unfortunately no such 3-D sample exists today. An ethical issue regarding not treating class II malocclusion during the pubertal growth spurt, a time associated with optimal treatment response for class II correction, prevents us from obtaining 3-D scans from untreated class II patients to serve as control. Class II elastics have been shown to act primarily through dentoalveolar movements with no skeletal enhancement.[18] Nelson et al reported skeletal contribution to reduction in overjet was only 4% in control subjects treated with elastics compared to 51% in the Herbst subjects. Therefore, using class II subjects treated solely with class II elastics, as control subjects, can be substantiated.

The first aim of this study was to evaluate maxillary positional changes in Herbst subjects and compare these changes to controls. Numerous studies report a maxillary restraining effect, comparable to headgear, produced by the Herbst treatment[1, 12, 13, 26, 28, 51]. Interestingly, other studies, including a 2008 systematic review by Barnett, suggest the skeletal headgear effect displayed by the Herbst is negligible. [3, 18, 20] When considering the variance in the literature, it is important to understand the various methodologies employed to measure changes in A point. The method developed by Pancherz utilizes a reference grid constructed from the occlusal line (OL) and the occlusal line perpendicular (OLp)[15]. Maxillary measurements using this method are subject to patient positioning errors. Many studies use SNA to examine maxillary changes [1, 14, 28]. However, increases in the vertical dimension as seen with growth will mask the anterior-posterior change when using these angular measurements[6]. Skeletal changes observed at A point, undeniably depend on the methodologies used. Our 3-D study showed the anticipated forward and downward growth pattern of the maxilla in the majority of our class II control subjects. However the Herbst group showed a mild maxillary restraining effect.

Alteration of anterior-posterior projection of the mandible can be attributed to 1) changes in mandibular growth, 2) changes in the direction of growth and/ or 3) condylar/ fossa positional changes. Previous studies report conflicting results with some showing increased mandibular length with Herbst treatment [1,12, 15, 28, 51,], while other studies show no significant increase in mandibular length [3, 19]. Deviations in patient positioning, as well as differences in magnification ratios between the left and right sides of the mandible can effect 2-D measurements of mandibular corpus length and ramus height. In addition, the conflicting findings regarding mandibular length were addressed by Voudouris et. al. who noted that in pre-adolescent cyanomologous monkeys (*Macaca fasicularis*), the condylar growth response was increased with Herbst treatment however, in adolescent animals there was no increase in the thickness of the prechonroblastic or chondroblastic zones and thus no increase in condylar growth[36, 37]. They suggest the adaptive capability of adolescent monkeys and possibly that of adolescent humans might be chiefly limited to the glenoid fossa with little potential for increased condylar length.

Perhaps skeletal maturity may have a larger and more directed influence on skeletal response to the Herbst appliance than we previously understood. While our findings suggest no statistically significant difference for mandibular length between Herbst and control groups, it is important to recall the difference in observation times for these two groups. The control group had an additional 5 months of observation time which would increase the perceived mandibular growth (Co-Gn) when compared to Herbst subjects.

In additional to growth, mandibular directional growth changes, such as opening of the gonial angle and posterior condylar flexure, will impact anterior-posterior projection of the mandibular base. Animal studies have shown mild opening of the gonial angle with mandibular advancement [36, 37]. And some human studies have made similar conclusions [12, 15]. Our study, along with others [1, 9, 28], showed no difference in gonial angle or condylar flexure between Herbst and control subjects. It is worth noting that Herbst subjects in our study had lower mandibular plan angle. A previous study by Pancherz et al. examined skeletal changes in hyperdivergent and hypodivergent facial types [29]. Their results found hyperdivergent subjects demonstrated more posteriorly directed condylar growth compared to hypodivergent subjects. Posteriorly directed condylar growth would lead to an opening of the gonial angle, and increased condylar flexure. It is possible that the larger number of hypodivergent subjects in this study may effect our results on gonial angle and condylar flexure changes.

Translation of the glenoid fossa, has been shown to contribute to mandibular positional changes post Herbst treatment in animal studies [31, 32, 36, 37, 53]. However, 2D imaging techniques used in human studies have potential for errors when assessing remodeling of the glenoid fossa. Human studies often rely on an unchanged condyle-fossa relationship because they utilize the method described by Buschang and Santos-Pinto [7, 54]. Furthermore, these studies use condylion or articulare as a proxy point to approximate the position of the fossa. Ruf and Pancherz conducted an MRI study to evaluate effective condylar growth in Herbst patients [24]. They noted increase uptake in the T2-weighted sequences in the glenoid fossa and condyle. This was interpreted to be definitive areas of condyle and fossa remodeling. However, because the incidence of capsulitis rises during Herbst treatment up to 100%, virtually all patients would be expected to have increased T2 signal due to the amplified inflammatory process [55, 56]. Differentiating inflammatory processes from the cellular cascade of skeletal remodeling is difficult. In addition, MRIs lack detailed information regarding bony structure and may not be the best tool to evaluate fossa remodeling. With 3D cone beam computed tomography scans, and current registration and superimposition techniques, we were able to accurately analyze skeletal changes occurring at the glenoid fossa (figure 10). We found resorption of the anterior wall of the glenoid fossa with deposition at the posterior wall in Herbst patients. This is in direct contrast to findings in the control subjects who exhibited posteriorly directed remodeling of the fossa. Posterior repositioning of the glenoid fossa we observed in the control group has been well documented in class II subjects, and represents the expected class II growth pattern[43, 54, 57-60]. Our findings suggest the Herbst appliance is altering the growth pattern of the glenoid fossa resulting in a more anteriorly positioned fossa and therefore more anteriorly position mandible.

Concern regarding changing condylar position in the glenoid fossa with anterior repositioning appliances like the Herbst exists. However, if the condylar position and fossa position are compared in figure 11, it is evident the condyle and fossa displacements are occurring in unison. This supports conclusions made in both animal and human studies suggesting that the condyle- glenoid fossa relationship remains relatively unchanged with Herbst treatment [24, 33, 61]. This is the first 3-D study to clearly demonstrate anterior repositioning of the fossa and condyle in response to class II functional appliance therapy in humans.

This study was designed as a pilot study to determine whether skeletal differences between Herbst subjects and patients treated with class II elastics could be surmised. As a pilot study, limitations in the sample size are inherent. Additional weaknesses of this study sample arise from differences in observation time between Herbst subjects and control patients. This confounder will have an effect on the statistical comparison for treatment differences. In essence, having a control group enables us to differentiate skeletal changes due to treatment verse growth. Since the control group had an average of 5 months longer observation time, they are anticipated to exhibit larger changes due to growth. Most likely this difference might underestimate the skeletal changes resulting from Herbst treatment. A larger study, which can further evaluate changes we observed for these patients, and a long- term follow up study are recommended. Relapse potential for patients treated with the Herbst appliance is well documented; however the mechanism for relapse is not well understood[5, 16, 18, 34, 62, 65-67]. Animal studies suggest the remodeling process to allow adequate bone maturation from Type III to Type I collagen may require increased retention phase[42]. Patients in this study were treated with increased treatment duration to promote mature bone formation during the remodeling process. It will be interesting to see if the skeletal adaptations in the glenoid fossa will be retained.

Clearly, follow up studies using 3D imaging techniques to address the true nature of the relapse of Herbst subjects are indicated.

CONCLUSIONS

3D imaging and superimposition techniques revealed the following skeletal adaptations:

1. Herbst treatment produced anterior displacement of the condyles with adaptive remodeling of the glenoid fossa while Class II controls exhibited distal displacement of the TMJ complex.
2. The Herbst group showed more maxillary restraint compared to the controls.
3. No significant difference in mandibular corpus and ramal growth, condylar flexure and gonial angle change were observe between the two groups.

Considerable variation in treatment response was observed in both groups.

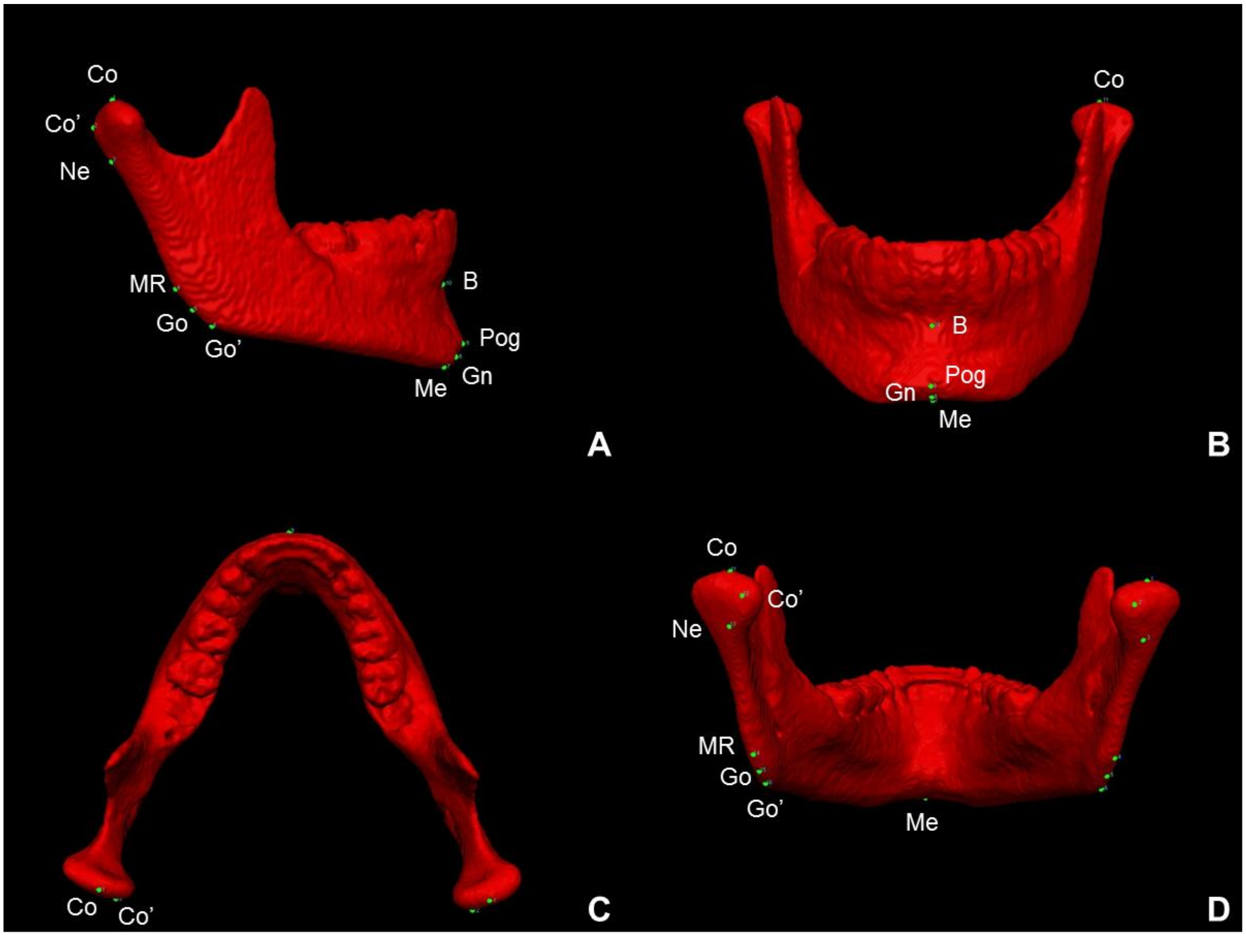

Figure 1. 3D Mandibular landmark identification from A) sagittal B) frontal C)axial and D) posterior views.

Table I. Demographics and statistical comparison for Herbst subjects and class II control subjects

Measurement	Herbst Mean	SD	Control Mean	SD	P value	Significance
Age (years)	13.00	1.00	13.40	0.98	0.43	NS
Observation time (months)	13.00	0.58	18.42	3.05	0.00	*
ANB	5.29	1.09	6.10	0.73	0.12	NS
A-N Perpendicular	0.89	3.42	5.15	3.19	0.04	*
B-N Perpendicular	-7.16	6.03	-2.62	4.07	0.14	NS
U1- SN	99.37	9.55	104.08	3.06	0.25	NS
IMPA	94.85	6.76	94.71	5.00	0.97	NS
MPA	25.73	6.13	36.71	2.82	0.00	*

*Significant at $P \leq 0.05$

Table II. Difference between T1 and T2 skeletal changes for Herbst subjects and class II controls

Measurement	Herbst Mean	SD	Control Mean	SD	Difference	P value	Significance
Maxillary Skeletal:							
A point	-1.22	0.43	1.20	0.53	2.42	0.00	*
ANS	0.26	1.09	1.96	0.87	1.70	0.01	*
Mandibular Skeletal:							
Pogonion	4.36	2.38	2.82	1.78	1.53	0.21	NS
B point	2.62	1.08	1.49	0.79	1.14	0.05	*
Co-Gn (right)	4.05	2.18	3.62	1.58	0.42	0.90	NS
Co-Gn (left)	4.05	1.80	3.05	2.06	1.00	0.38	NS
Go-Gn (right)	1.90	1.30	2.45	1.13	0.55	0.41	NS
Go-Gn (left)	2.12	1.58	1.84	1.37	0.28	0.90	NS
Go'-Co (right)	4.77	1.63	2.54	1.43	2.23	0.02	*
Go'-Co (left)	3.31	2.24	2.76	1.61	0.55	0.80	NS
Co-Go-Me (right)	0.03	2.06	-0.84	3.07	0.87	0.46	NS
Co-Go-Me (left)	-0.15	1.56	-0.37	2.03	0.21	0.71	NS
Co'-Ne-MR (right)	-3.29	3.06	0.47	3.29	3.76	0.07	NS
Co'-Ne-MR (left)	-0.22	10.29	-3.57	6.58	3.35	0.82	NS
Condyle/ Glenoid Fossa Skeletal:							
Anterior condyle (right)	1.32	0.56	-1.20	0.41	2.52	0.00	*
Anterior condyle (left)	1.65	0.93	-1.29	0.57	2.94	0.00	*
Co (right)	0.38	0.59	-0.88	0.71	1.26	0.01	*
Co(left)	0.56	0.64	-1.16	0.60	1.72	0.00	*
Posterior condyle (right)	0.44	1.19	-1.31	0.47	1.74	0.03	*
Posterior condyle (left)	0.16	1.32	-1.19	0.60	1.35	0.05	*
Anterior fossa (right)	1.69	0.62	-1.51	0.68	3.19	0.00	*
Anterior fossa (left)	1.43	0.70	-1.31	0.61	2.74	0.00	*
Posterior fossa (right)	0.59	1.49	-1.24	0.45	1.83	0.13	NS
Posterior fossa (left)	0.79	1.34	-1.41	0.55	2.20	0.01	*

*Significant at $P \leq 0.05$

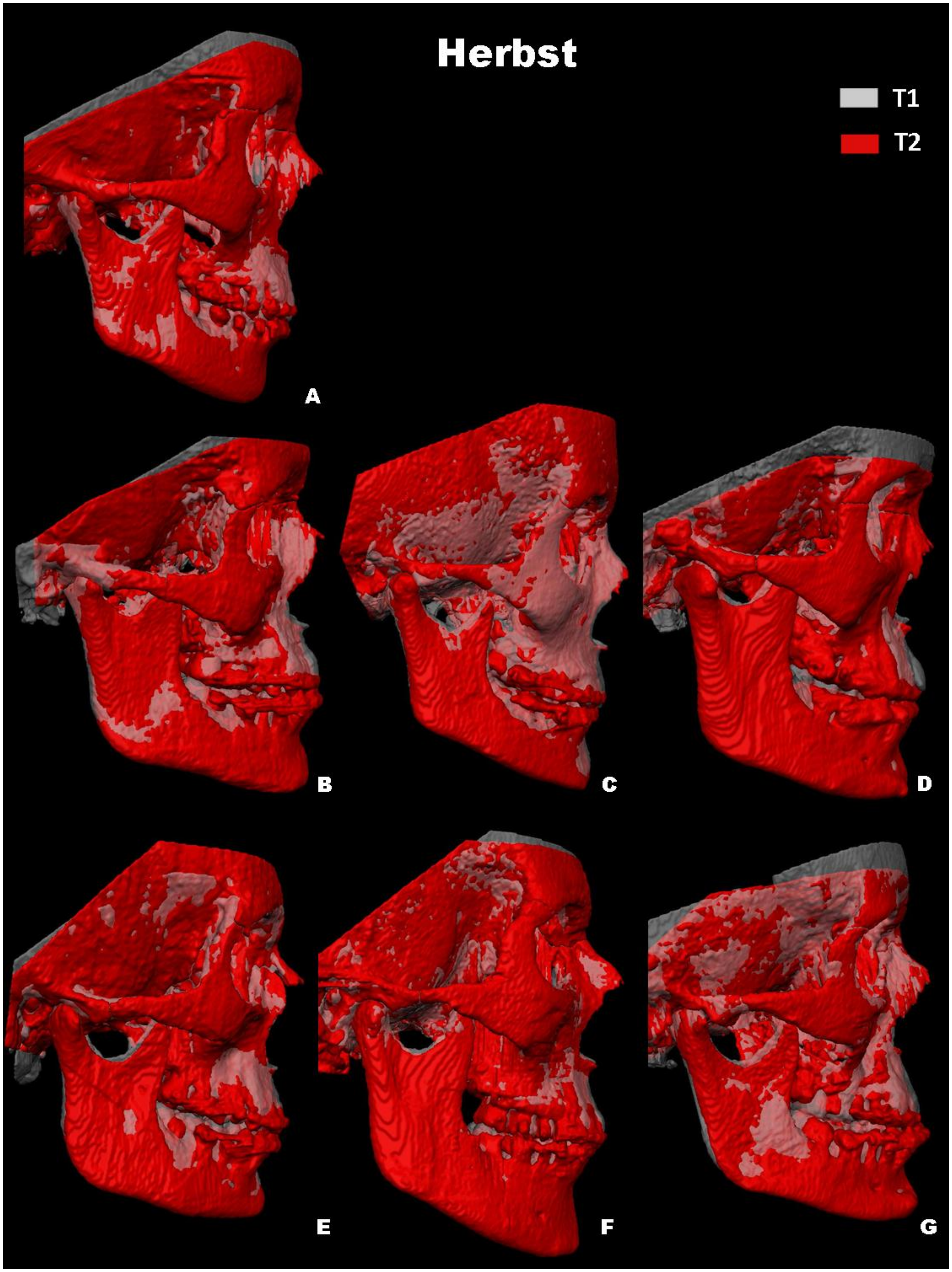

Figure 2. Herbst subject T1 semitransparency of T1 and T2 superimposed 3D renderings registered at the anterior cranial base. T1 images are shown in *white semitransparency*. T2 images are shown in *red*.

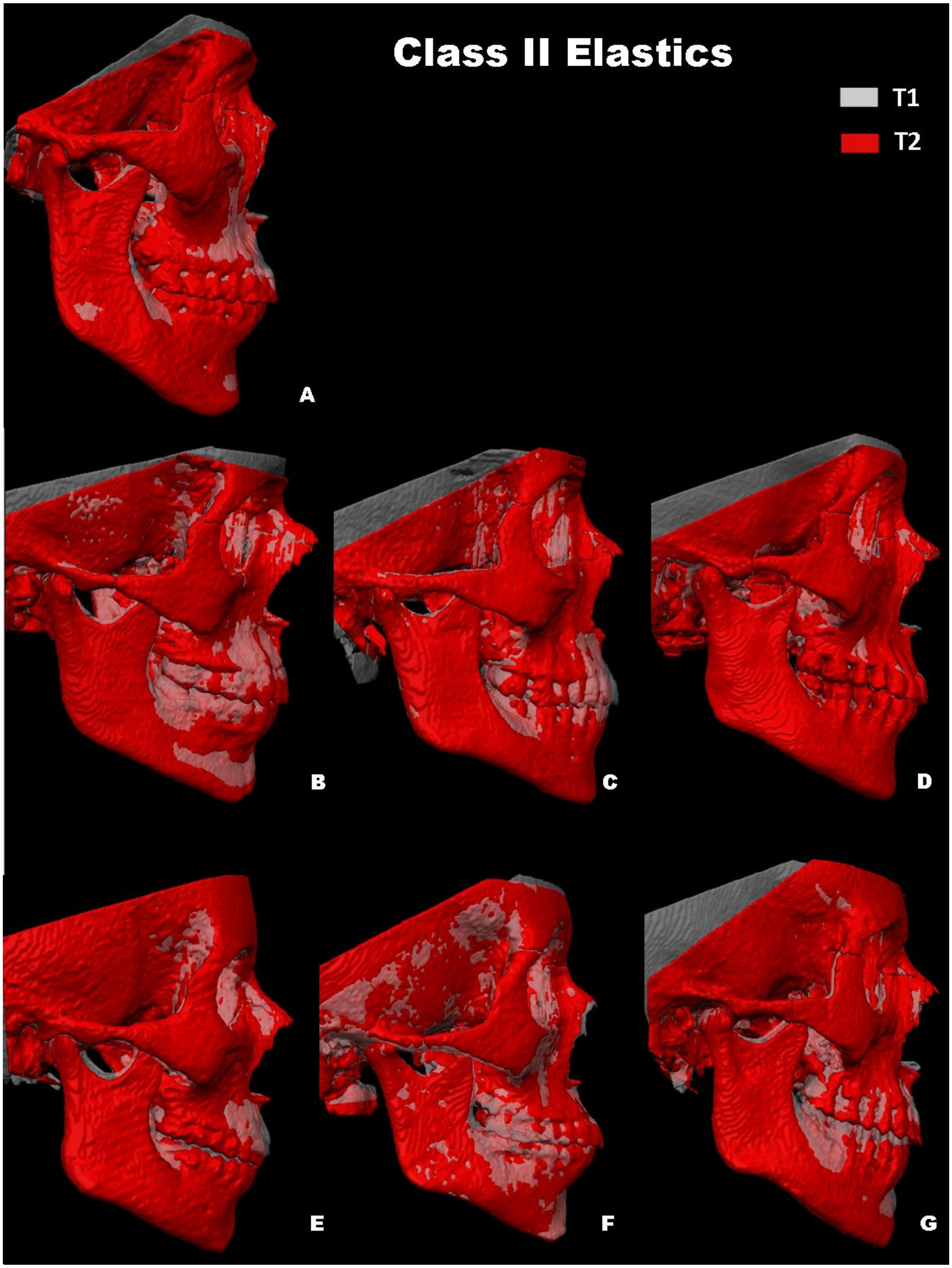

Figure 3. Class II elastic control subject T1 semitransparency of T1 and T2 superimposed 3D renderings registered at the anterior cranial base. T1 images are shown in *white semitransparency*. T2 images are shown in *red*.

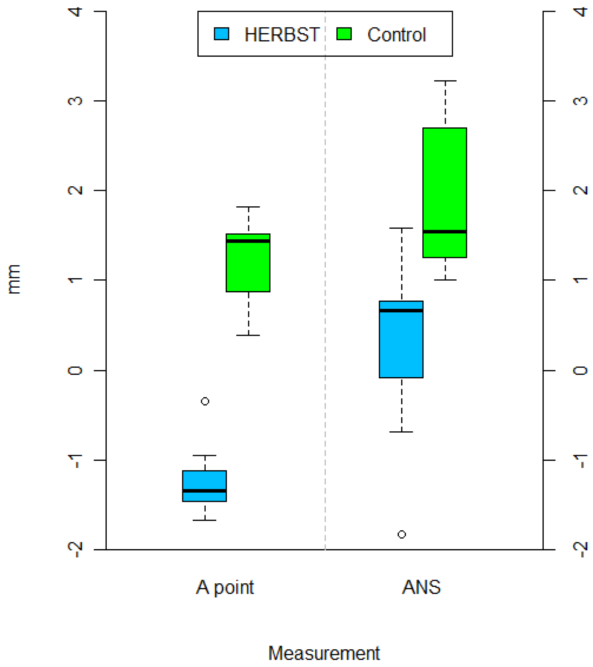

Figure 4. Box plots of maxillary skeletal changes for Herbst and control subjects.

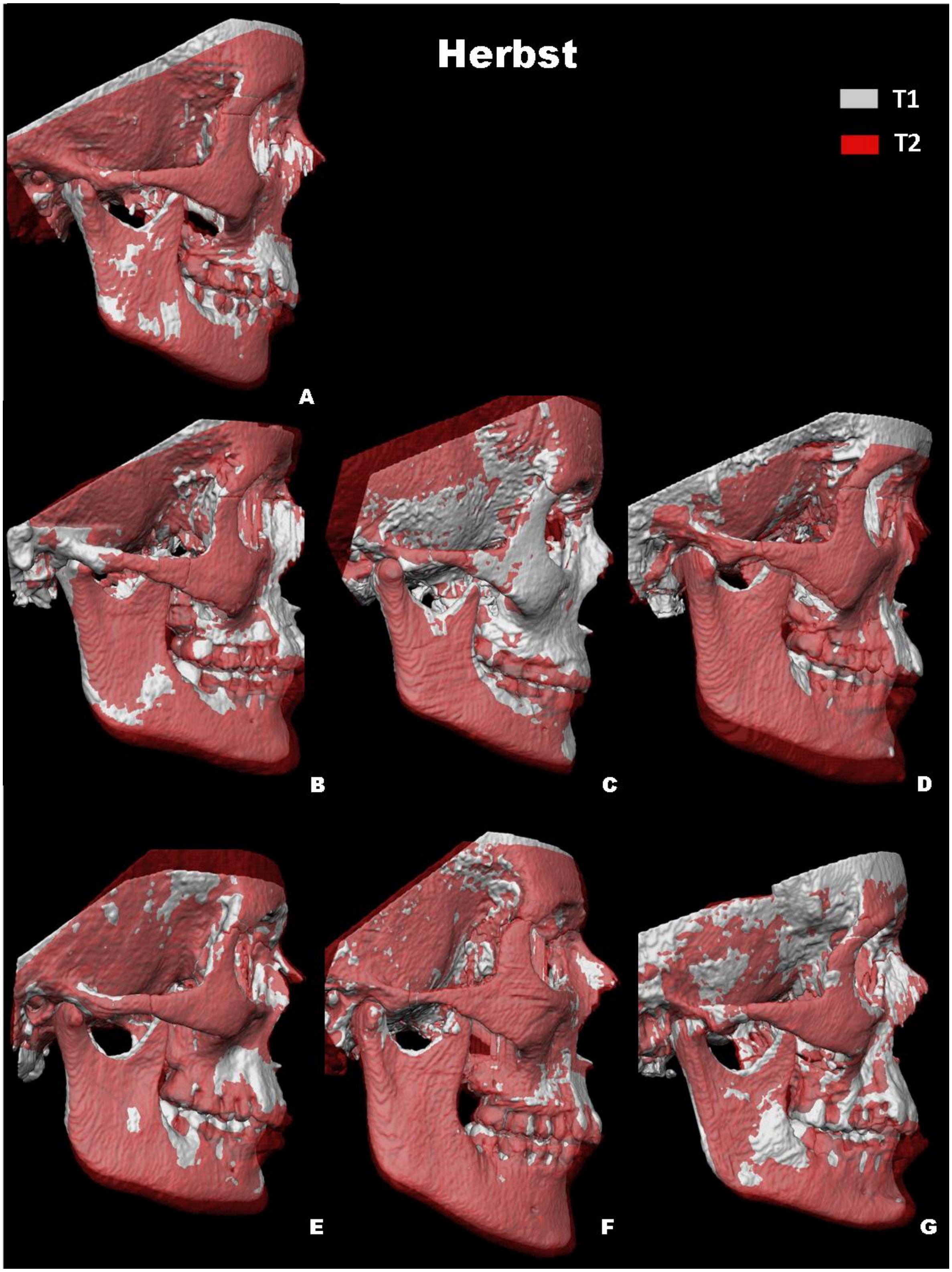

Figure 5. Herbst subject T2 semitransparency of T1 and T2 superimposed 3D renderings registered at the anterior cranial base. T1 images are shown in *white*. T2 images are shown in *red semitransparency*.

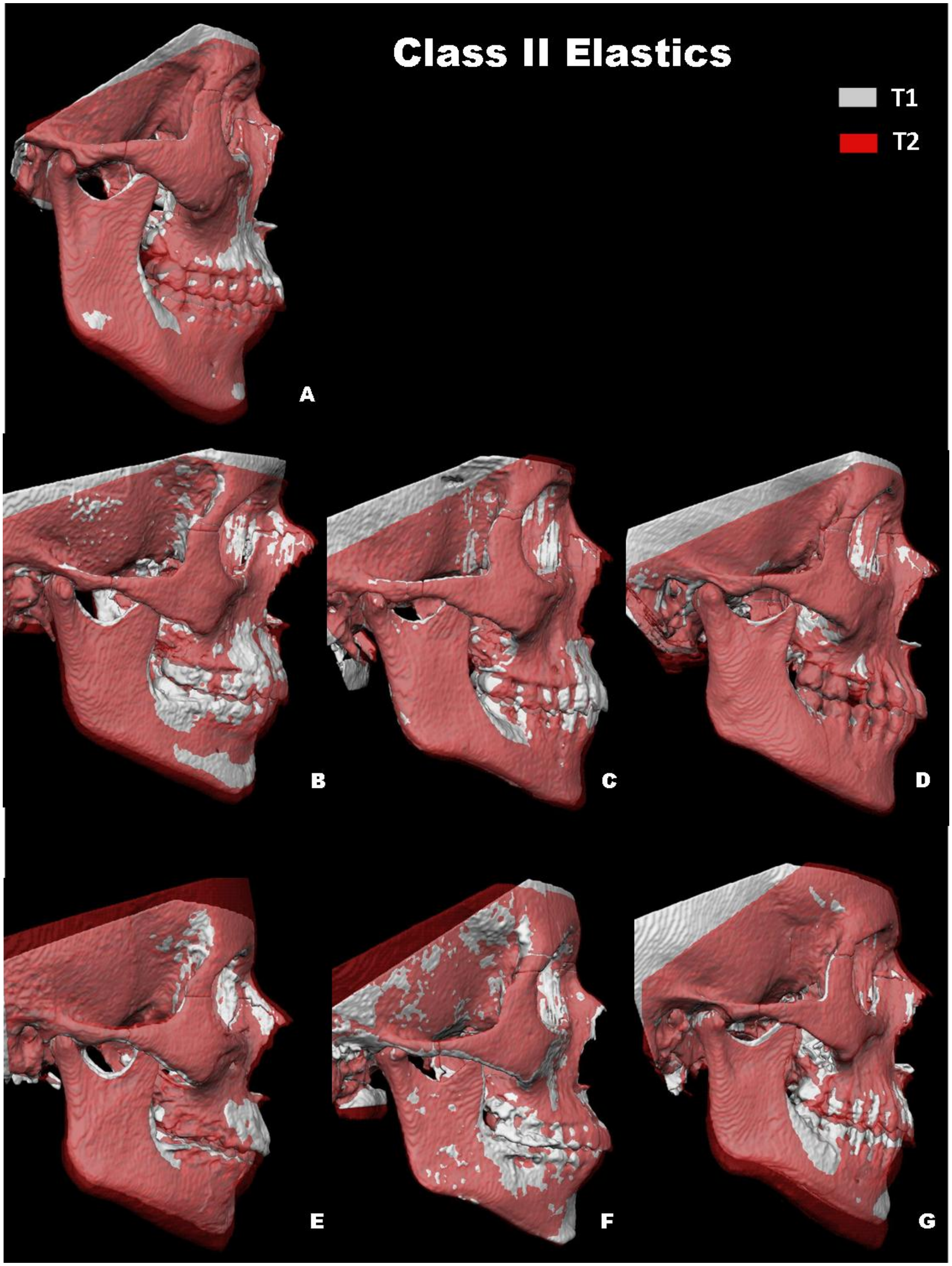

Figure 6. Herbst subject T2 semitransparency of T1 and T2 superimposed 3D renderings registered at the anterior cranial base. T1 images are shown in *white*. T2 images are shown *in red semitransparency*.

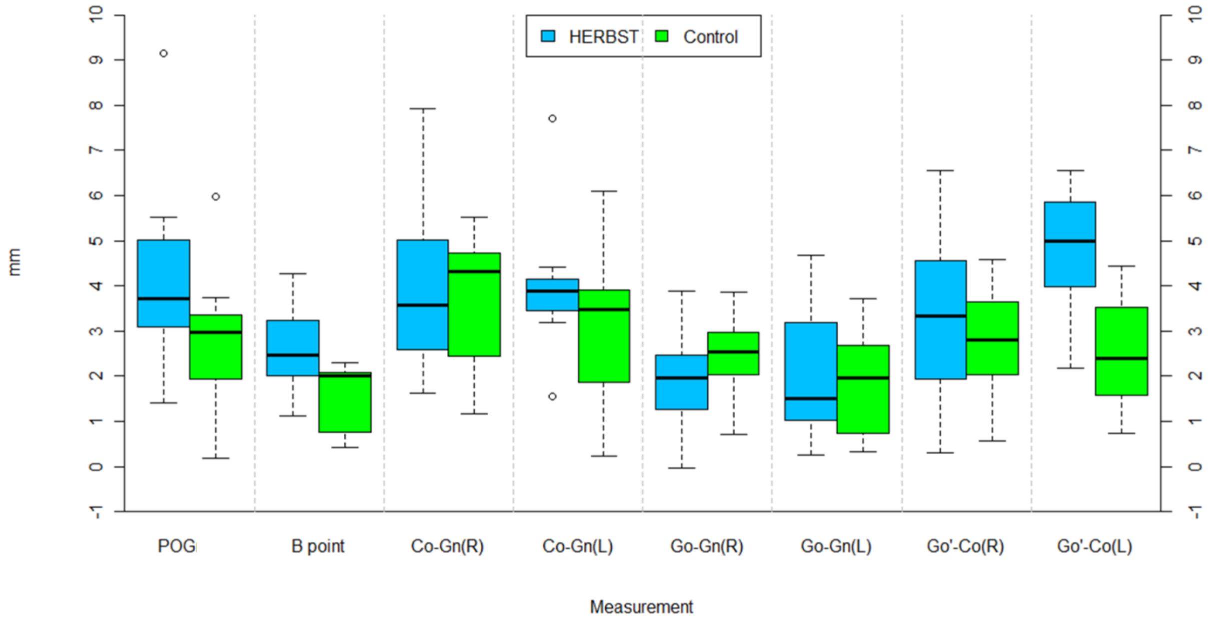

Figure 7. Box plots of mandibular skeletal changes for Herbst and control subjects.

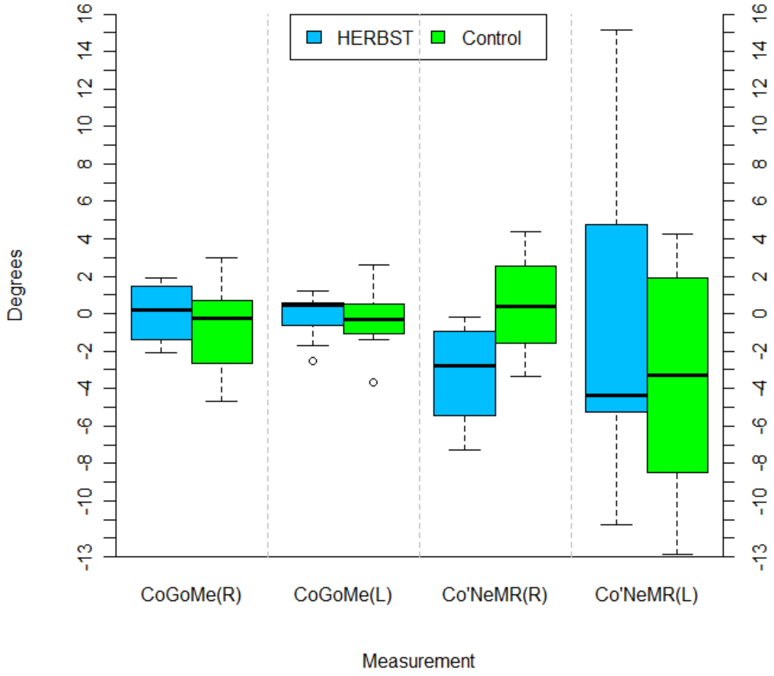

Figure 8. Box plots showing changes in gonial angle and condylar flexure for Herbst and control subjects.

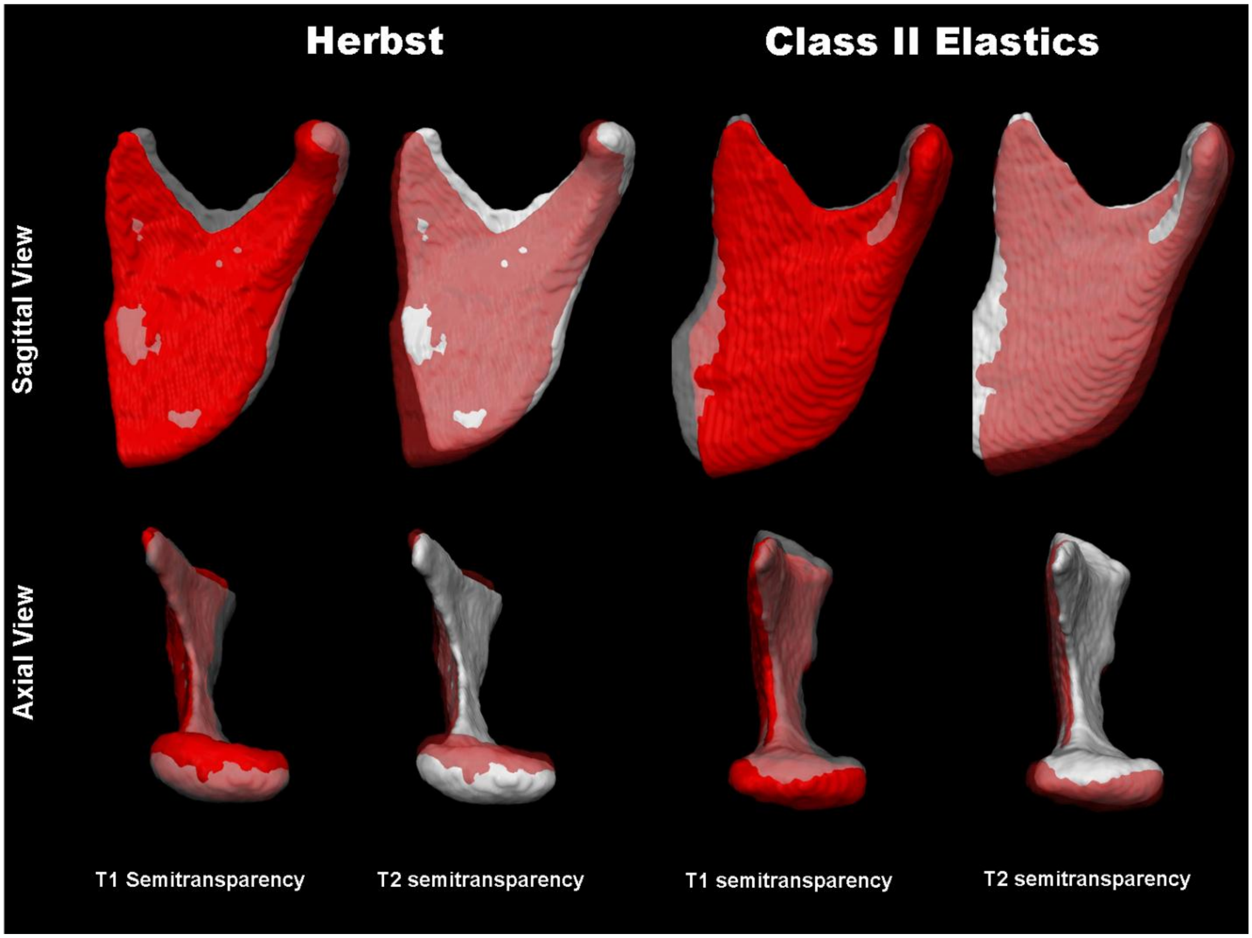

Figure 9. Semitransparencies of left condyle for one Herbst and control subject from both sagittal and axial views. T1 and T2 3D volumes were registered at the anterior cranial base. Left condyles were isolated from adjacent structures for improved viewing. Semitransparency views are displayed with T1 image shown as *white*, and T2 shown in *red*.

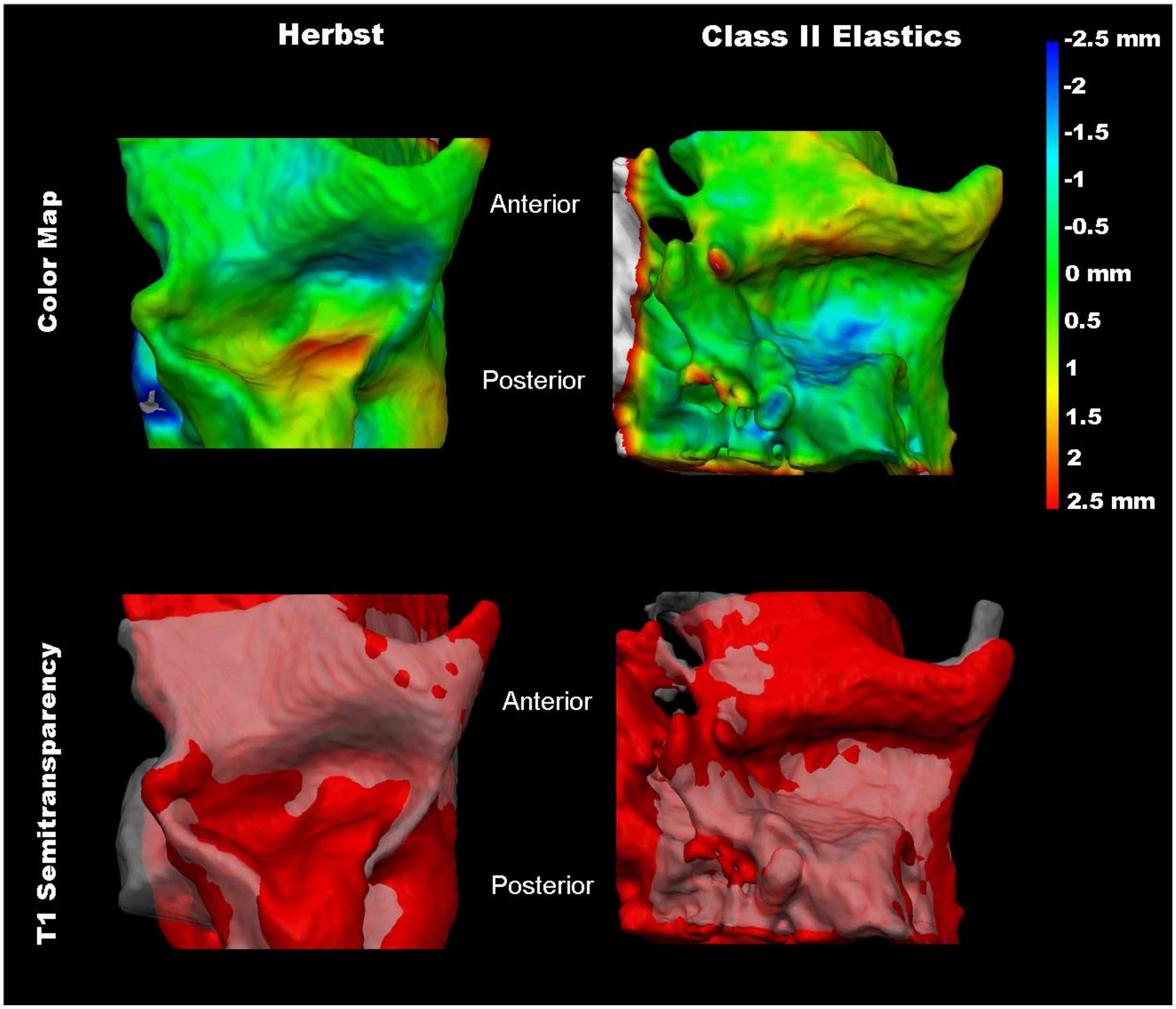

Figure 10. Color Map and semitransparency showing glenoid fossa skeletal changes. T1 and T2 superimposed 3D renderings are registered at the anterior cranial base. Fossae are orientated with the anterior aspect of the fossa near the top of the page, and posterior fossa near the bottom of the page. Color maps are shown with a scale -2.5 to +2.5mm. *Blue* represents regions of bone resorption of T2 in relation to T1, whereas *red* represents regions of bone deposition. Semitransparency views are displayed with T1 image shown as *white semitransparency*, and T2 shown in *red*.

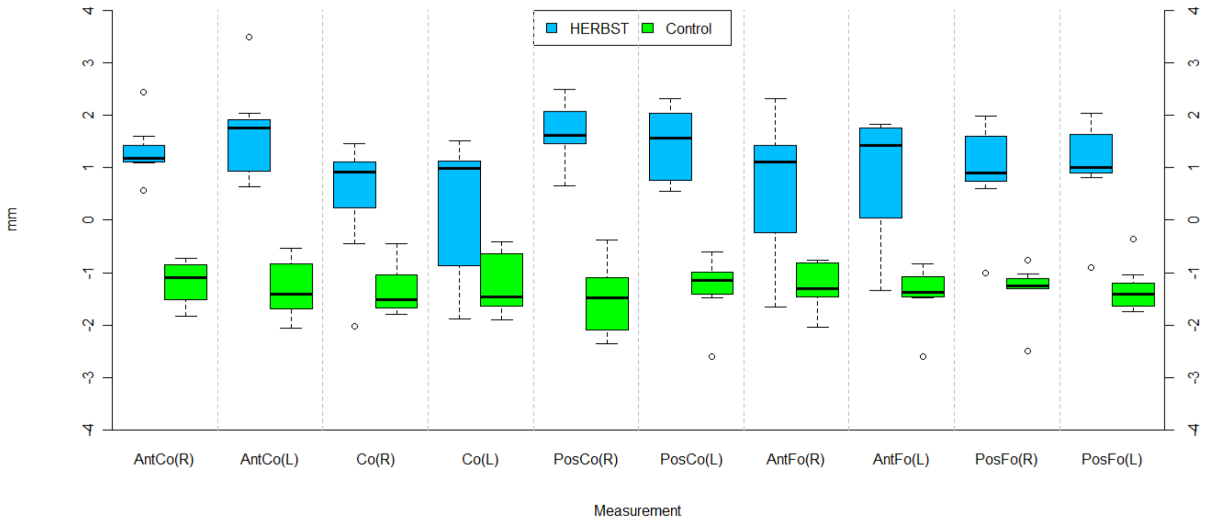

Figure 11. Box plots showing skeletal changes at the condyle and glenoid fossa for Herbst and control subjects.

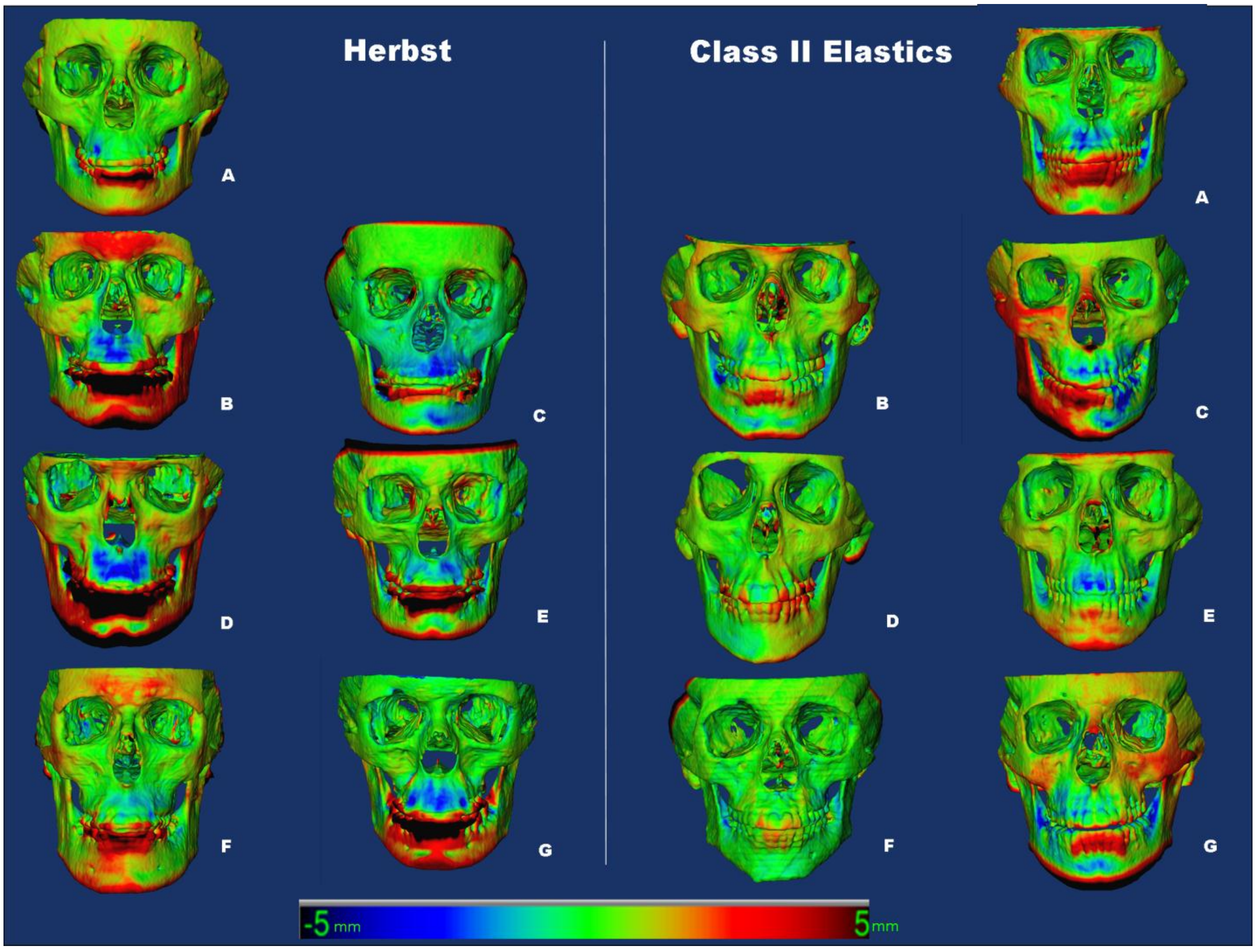

Figure 12: Color map images showing skeletal displacements calculated from T2 3D volume renderings in relation to T1 when registered and superimposed at the anterior cranial base. Color map scale is set from -5 to +5. *Red* represents regions of anterior displacement of T2 in relation to T1, whereas *blue* represents regions of posterior displacement.

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