

# Improving the concordance between various anteroposterior cephalometric measurements using Procrustes analysis

Hans Wellens

Private Practice, Brugge, Belgium

**SUMMARY** The aim of this study was to investigate a method which minimizes the effects of geometric distortion on various cephalometric measurements used to determine sagittal discrepancy, such as ANB angle, Wits appraisal, AB plane angle, projections on the palatal plane, Frankfort horizontal (FH) plane, the mandibulomaxillary bisector, and the SN line, in an attempt to optimize the correlation between them. This was accomplished by superimposing the Bolton 12-year male–female averaged template on a patient's tracing using Procrustes analysis and performing measurements while exchanging the patient's reference landmarks/planes (point N, the mandibulomaxillary bisector, FH plane, occlusal plane, palatal plane, and SN line) with those of the template. The normalized measurements were then compared with their classic counterparts using correlation coefficients.

The above cephalometric analyses, classic and normalized, were applied to 71 patients [26 males: mean age 13.1 years, standard deviation (SD) 1.1 years and 45 females: mean age of 14.6 years, SD 8.2 years]. Spearman's rank correlation coefficient was calculated between the classic measurements and their normalized counterparts, resulting in a consistent increase in the correlation between the normalized measurements in comparison with the classic ones. This increase varied in absolute value from 0.052 to 0.405. All normalized measurements were highly correlated ( $P > 0.742$ , absolute value).

Although correlation calculations do not represent a true measure of diagnostic performance, it is hoped that improving their correspondence heightens the possibility of the different tests agreeing on the patient's sagittal discrepancy, decreasing the possibility of differing, or even totally opposing diagnostic outcomes resulting from their application to (clear-cut) Class I, II, and III patients.

## Introduction

When Broadbent (1931) and Hofrath (1931) introduced standardized cephalometric radiography, it was hoped that the new diagnostic tool would provide a straightforward way of substantiating clinical dentofacial observations in orthodontic research as well as in everyday practice. In fact, today, orthodontic research without cephalometry seems almost unthinkable, providing a relatively precise and repeatable way of measuring and comparing growth, development, or treatment change (Baumrind and Frantz, 1971a,b). In daily clinical practice, however, the benefits of cephalometrics are somewhat less clear. Notwithstanding the fact that cephalometry is perceived to be an integral part of treatment planning (Atchison, 1986), several authors have demonstrated a disappointingly low 'weight' of lateral cephalometry in the therapeutic decision-making process: not only do treatment decisions seem to be made based mainly upon dental records (Atchison *et al.*, 1991; Han *et al.*, 1991) but also the addition of lateral cephalograms has been shown to cause few changes to treatment planning (Atchison *et al.*, 1991; Han *et al.*, 1991; Hansen and Bondemark, 2001). Furthermore, most of the orthodontists' certainty regarding his/her treatment plan seems to originate from dental records, the cephalometric data making only a small contribution (Atchison *et al.*, 1991).

ANB and Wits analyses are popular for assessing dentoalveolar sagittal relationships. Riedel (1952) and Steiner (1953) recommended the ANB angle, 'triangulating' the relative sagittal positions of the mandible and maxilla using SNA and SNB. Jacobson (1975) suggested the Wits analysis, constructed by dropping perpendiculars from points A and B onto the occlusal plane, the distance between the resulting points Ao and Bo representing a more or less 'direct', linear measurement. Although both analyses are intended to measure anteroposterior (AP) dental base relationships, reported correlations between them are generally fairly low, values ranging from 0.62 to 0.76 have been mentioned (Rotberg *et al.*, 1980; Järvinen, 1981; Richardson, 1982; Millett and Gravely, 1991; Del Santo, 2006). The apparent lack of 'absolute' correspondence between them suggests that both analyses do not only measure sagittal discrepancy, under the influence of various (geometric) confounding factors.

This became evident when Demisch *et al.* (1977) applied both cephalometric techniques to groups of fairly clear-cut Class I, II, and III patients: considerable areas of 'overlap' appeared where the same ANB or Wits value could belong to Class I as well as Class II patients or to Class I as well as Class III patients. For ANB analysis, overlapping was found between the values for Class II and III patients, leading Jacobson (1975) to recommend using the Wits analysis to

confirm the possibly (more) compromised results of the ANB analysis. However, after analysing 872 malocclusion patients, Kim and Vietas (1978) also found an overlapping of the Wits measurements for Class II and III patients, containing 36.4 per cent of the malocclusion group. Since the Wits appraisal evidently has its own limitations, a point could be made for applying even a third analysis (Ishikawa *et al.*, 2000) to accommodate situations where both analyses disagree, obviating the lack of sensitivity and specificity of both tests. In view of the popularity of ANB and Wits analysis, it would therefore seem fair to say that even today, the orthodontic speciality is struggling to efficiently 'distil' the required diagnostic or scientific information from cephalometric images.

The aims for the current research were therefore as follows:

1. To first provide an overview of the factors responsible for the lack of correspondence between ANB and Wits measurements of sagittal discrepancy and of previously published attempts to increase this correspondence.
2. To investigate whether the correlation between ANB and Wits measurements of sagittal discrepancy could be improved by normalizing the patient's reference landmarks (S, N, and the occlusal plane). This would be performed by applying Procrustes analysis (Halazonetis, 2004) to the 12-year male-female averaged template of the Bolton-Brush growth study (Broadbent *et al.*, 1975), calculating the normalized ANB and Wits measurements using the normalized reference landmarks and the patient's points A and B. This would allow determination of the correlation between the normalized ANB and Wits measurements and comparison of the resulting values to the correlation coefficients between the classical counterparts.
3. To evaluate whether or not the proposed technique performs similarly when applied to other methods for determining sagittal discrepancy (Figure 1): projections on the mandibulomaxillary bisector (Hall-Scott, 1994), palatal plane (Ferrazzini, 1976), Frankfort horizontal (FH) plane (Chang, 1987), the SN line (Taylor, 1969), as well as the AB plane angle (AB to N-Pog, Downs, 1948). This would again be accomplished by comparing the correlations between the classic projections with those between the normalized counterparts.

## Literature review

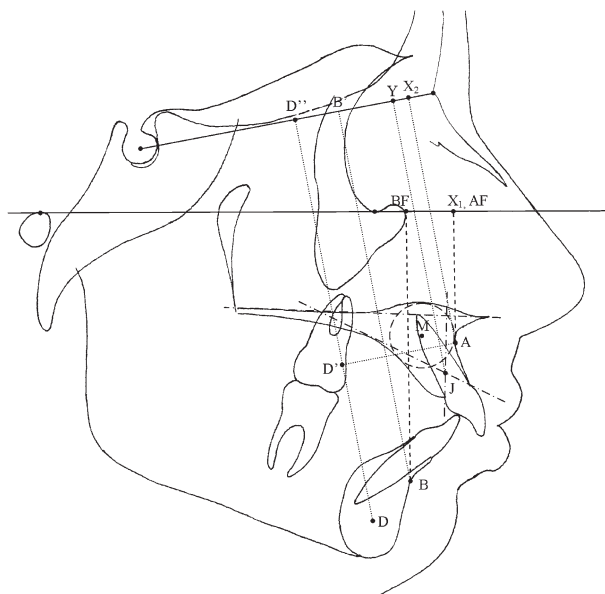
The apparent lack of correlation between ANB and Wits appraisal might, at least in part, originate from the radiographic technique itself (Broadbent *et al.*, 1975). The combination of a diverging X-ray beam with slight errors in the positioning of the patient's head results in an enlarged, distorted radiographic image. Structures located on the principal axis of the X-ray beam tend to blur, while those

located outside the patient's midsagittal plane are doubled, rendering two separate, more or less superimposed images. Furthermore, the two-dimensional (2D) superimposition of three-dimensional (3D) structures often shrouds the structures of interest, rendering reliable landmark identification difficult. While the recent introduction of 3D computed tomography (CT) suitable for use in the orthodontic office will solve some of these issues associated with 2D lateral cephalometric radiography, there are some important problems associated with conventional cephalometry for which 3D-CT does not provide a solution. One is the difficulty associated with finding appropriate ways of relating the various structures to each other. For instance, Taylor (1969) pointed out that ANB is influenced by the relative AP position of point N (cranial base length), enabling patients with the same mandibulomaxillary relationship to have different ANB angles. The same point was made by Freeman (1981), this time by varying the AP position of the jaws in relation to point N (mandibulomaxillary prognathism). Likewise, vertical changes in the position of point N influence ANB, even in the absence of changes in the sagittal jaw relationships: an upward movement of point N will decrease ANB while a downward movement will lead to an increase in this angle (Binder, 1979).

The aforementioned AP and vertical changes in point N are not only important for interindividual comparison of ANB values in patients with comparable maxillomandibular relationships but also for the intraindividual comparison of radiographs taken at different points in time, as growth may displace point N anteriorly and vertically, influencing ANB (Pancherz and Sack, 1990). In fact, Bishara *et al.* (1983) demonstrated significant changes in ANB between 5 and 25 years of age, without a similar change in Wits appraisal. The same conclusions were reached by Lux *et al.* (2005) between the ages of 7 (ANB) to 9 (Wits appraisal) and 15 years, at least for their Class I and 'ideal occlusion' groups.

Furthermore, Jacobson (1976, 1988) made reference to the rotational effect of the jaws, whereby a clockwise or counterclockwise rotation of the jaws in relation to cranial reference structures, such as the SN line (and without changing their mutual relationship), will tend to increase/decrease ANB. Although these effects might appear theoretical, Tanaka *et al.* (2006), in a recent clinical study, clearly demonstrated the influence of facial type on the magnitude of ANB, reporting a lower mean ANB in brachyfacial patients versus higher mean values in dolichofacial patients. Another factor that may influence ANB is the vertical dentoalveolar dimension. Hussels and Nanda (1984) explained that an increase in the vertical dimension in the form of an increase in the length of NB, or of the distance 'point A-occlusal plane', will result in a decrease in ANB. This is, of course, in analogy to the findings of Binder (1979).

Jacobson (1976, 1988) proposed the Wits analysis, in an attempt to circumvent some of the problems associated with



**Figure 1** Points, angles and planes used in the study. D: midpoint of the cross-section of the mandibular symphysis; X: constructed by dropping a perpendicular from point A on the Frankfort horizontal (FH) plane ( $X_1$ ). Alternatively, a perpendicular may be dropped from point A on the SN line ( $X_2$ ); D': constructed by dropping a perpendicular from point A on the DD" line, where DD" is constructed by dropping a perpendicular from point B on the SN line; J: tangents are drawn to the nasal floor through ANS and to the hard palate through prosthion. Point J is located where the latter tangent crosses a perpendicular to the first tangent, which is dropped from the palatal analogue of prosthion (palatal margin of the alveolar bone); Y: constructed by dropping a perpendicular from point J on the SN line; M: midpoint of a circle that best fits the anterior, superior, and palatal outlines of the premaxilla; AF, BF: constructed by dropping a perpendicular from points A and B, respectively, on FH.

the use of cranial landmarks, as in ANB. By projecting points A and B onto the occlusal plane, points S and N were no longer needed. It was further hypothesized that this would solve problems associated with rotations of the mandibulomaxillary complex relative to the cranial base, as the occlusal plane would rotate together with the jaws. Unfortunately, the Wits appraisal also proved not to be immune to geometric influences. Roth (1982) clearly demonstrated its dependence on vertical dentoalveolar dimensions and on the cant of the occlusal plane. The combination of these two factors results in a more significant influence of occlusal plane changes on the Wits value in high- compared with low-angle patients (Del Santo, 2006). Furthermore, a number of studies have reported that the occlusal plane tends to tip upward anteriorly with increasing age, influencing Wits appraisal (Sherman *et al.*, 1988; Hall-Scott, 1994). Several authors have also commented on difficulties associated with precisely locating the necessary landmarks (Demisch *et al.*, 1977; Bishara *et al.*, 1983; Sherman *et al.*, 1988; Millett and Gravely, 1991). Originally defined as situated in the 'region of maximal cuspal overlap', occlusal plane landmarks are often somewhat difficult to discern, can be influenced by the stage of dental eruption,

and are generally close together, promoting the occurrence of errors. As reproducibility is equally important for the clinical usefulness of a cephalometric technique, Rushton *et al.* (1991) advised not to ignore these imprecisions: the reproducibility of the Wits value was found to be rather poor, mainly due to difficulties in accurately locating the occlusal plane. Thoroughly defining the various landmarks (Baumrind and Frantz, 1971b) or using specific constructions to determine their position (Demisch *et al.*, 1977) can, at least in part, solve some of these problems.

Many different solutions have been formulated in order to deal with the above geometric problems.

#### *Using different reference points*

In an attempt to overcome some of the anatomic and geometric problems associated with ANB and Wits measurements, some authors have suggested using different anatomical points (Figure 1), such as point D as defined by Steiner (1953), point X (in AXB angle); Freeman (1981), points X and D' as proposed by Beatty (1975); in the AXD angle and AD' distance, points J and Y as introduced by Järvinen (1982); in the JYD angle, as well as point M (Nanda and Merrill, 1994) and points AF and BF (Chang, 1987; in the AF–BF distance). Many of these angular techniques aim at eliminating point N from the equation, as this is believed to diminish variability.

#### *Selecting different reference planes*

Other authors have tried limiting geometric or growth influences by selecting different reference planes to which points A and B are related. Hall-Scott (1994) introduced the mandibulomaxillary bisector, the maxillary plane (ANS–PNS) as proposed by Ferrazzini (1976), FH as suggested by Chang (1987; in the AF–BF distance and the A–NV and B–NV distance) and by Yang and Suhr (1995) in the F–H to AB plane angle, the nasion perpendicular recommended by McNamara (1984), the N–Po line as suggested by Holdaway (1983), and the anterior cranial base according to Taylor (1969). Since the palatal plane was found to be relatively stable in longitudinal cephalometric studies and because it is more easily located compared with the occlusal plane, Williams *et al.* (1985) proposed projecting points A and B onto a constructed occlusal plane, angled 8 degrees to the palatal plane. The reasons listed for selecting these reference planes include their superior anatomic stability over time, both in absolute terms (Williams *et al.*, 1985), as relative to the jaws (Hall-Scott, 1994; i.e. the reference plane follows the rotation of the jaws), or that the anatomic points defining the reference planes are more easily discernible (Holdaway, 1983; McNamara, 1984; Williams *et al.*, 1985; Chang, 1987; Hall-Scott, 1994; Ferrazzini, 1976; Yang and Suhr, 1995).



### Floating norms and geometric calculations

The previously mentioned points and planes were all proposed in order to minimize geometric distortions. In doing so, it was hoped that the technique-specific cut-off points used for discriminating the various Classes of skeletal discrepancy would maintain their applicability throughout the highly variable population. Another approach would be to accept geometric distortion of the measurements, but to compensate for these distortions by modifying the cut-off points accordingly: cut-off points are individualized/calculated using various statistically determined cephalometric parameters.

From a sample of 96 (dental) Class I patients, Panagiotidis and Witt (1976) calculated the correlation between ANB, SNA, and SN-MP (mandibular plane to SN line) angles. They derived the following formula:  $ANB = -35.16 + 0.4 SNA + 0.2 SN-MP$ , reflecting the ANB angle that would be found in a Class I patient with angles SNA and SN-MP ( $r=0.808$ ). Calculating the theoretical 'individualized' ANB angle allows comparison with the actual measured value, the difference between the two representing a measure of the 'true' sagittal discrepancy. An analogous approach was adopted by Järvinen (1986), who found that 63 per cent of the variability in ANB could be explained by variations in SNA and SN-MP angles. Including the NSAr angles increased this figure to 65.9 per cent. This led to the formula  $y = 0.472x_1 + 0.204x_2 - 43.386$ , where  $y = ANB$ ,  $x_1 = SNA$ , and  $x_2 = SN-MP$  angle. As explained by Järvinen (1986), the calculated ANB value represents a floating (or individualized) norm, which can be compared with the measured value.

Yet another approach was proposed by Hussels and Nanda (1984). They calculated ANB geometrically using the formula:

$$ANB = \tan^{-1} \left( \frac{a \sin \gamma}{b - a \cos \gamma} \right),$$

where

$a$  is the distance from point A to B

$b$  is the distance from point N to B

$\gamma = SNB + NS-MP - 90$

The resulting value is compared with the measured one to assess the true sagittal discrepancy. However, as pointed out by Järvinen (1986), their geometric approach supposes the AB plane is perpendicular to the occlusal plane in 'normal' patients. This may or may not be true, depending on the degree of eruption of the teeth and on the ever-present interindividual variations. Significant individual error may therefore result.

In keeping with the studies of Panagiotidis and Witt (1976), Järvinen (1986), and Hussels and Nanda (1984), Kim and Vietas (1978) introduced the AP dysplasia indicator (APDI), calculated using the facial angle  $\pm$  the A-B plane angle  $\pm$  the palatal plane angle. The underlying philosophy was that it might be more advantageous to combine various single measurements in order to obtain a more robust

interpretation of sagittal discrepancy. In fact, when correlating various cephalometric analyses to occlusal relationships, their index showed the highest coefficient among those investigated. Furthermore, although the difference with the Wits appraisal was small, the APDI showed a superior separation of the three skeletal Classes.

### Optimizing cut-off points

It has been suggested that the disagreement between ANB and Wits measurements of skeletal discrepancy might be caused by inadequacies in the proposed cut-off points. For instance, Walker and Kowalski (1971) investigated the cephalograms of 474 males and 630 females and found an average ANB of 4.5 degrees [males: 4.65 degrees, standard deviation (SD) 2.23 degrees; females: 4.34 degrees, SD 2.66 degrees], which is considerably different from the originally proposed ideal value of 2 degrees (Steiner, 1953). Even when they included only patients classified as having a dental Class I occlusion, they found an average ANB of 4 degrees in approximately 1000 patients. Therefore, strict adherence to the ideal values of Steiner (1953), who emphasized that his proposed values should rather be used as 'rough estimates', could lead to Class I patients being misclassified as Class II.

In a more recent report, Anderson *et al.* (2006) used receiver operator characteristic curves to determine and subsequently test optimized cut-off points for various cephalometric analyses, including the ANB and Wits analyses. Their conclusion was that using the optimized cut-off points improved accuracy in diagnosis for (among others) the Wits appraisal, in comparison with the conventional cephalometric norms. For ANB analysis, the difference between the traditional and optimized cut-off points was not statistically significant.

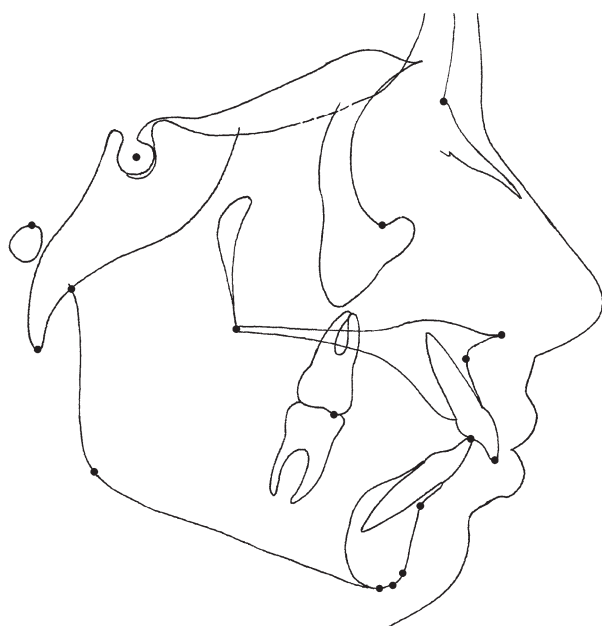
### Materials and methods

The study sample was obtained from the records of the author's private practice and consisted of 71 prospectively and consecutively collected patients, for whom good quality lateral cephalograms were available, using as the only additional inclusion criterion, the absence of craniofacial deformities. Of these 71 patients, 26 were male, mean age 13.1 years (SD 1.1 years, range 10.8–15.4) and 45 were female, mean age 14.6 years (SD 8.2 years, range 8.4–44.9). None had received previous orthodontic treatment. The lateral cephalograms were traced on a light box in a darkened room, using matte acetate tracing paper and a sharp pencil (Staedler 100-HB). The tracing paper was fixed to the cephalogram using tape, and background light due to size differences between the light box and the cephalogram was blocked out using cardboard. The landmarks used in the current research are shown in Figure 2.

The finished tracing was placed approximately in the middle of the scanning surface of a desktop scanner (Scanjet

8200, Hewlett-Packard, Palo Alto, California, USA). After scanning, the resulting image file was then imported into a digitizing software program (DigitizeIt 1.5.7, I. Bormann, Bormisoft, Braunschweig, Germany). This program was used to determine the landmark co-ordinates using three calibration points, located on a transparent calibration sheet, which was included in the scan. The co-ordinates were subsequently imported into a graphing and curve-fitting program (FindGraph for Windows, version 1.482, UNIPHIZ Lab, 2001–2004, Tver, Russia), which was used to perform Procrustes analysis, a statistical technique which allows comparison of shape, independent of size (Halazonetis, 2004).

Procrustes analysis attempts to find a 'best fit' of various clusters of analogous points. For this project, one cluster of points consisted of the template's landmarks (12-year male–female average template of the Bolton-Brush growth

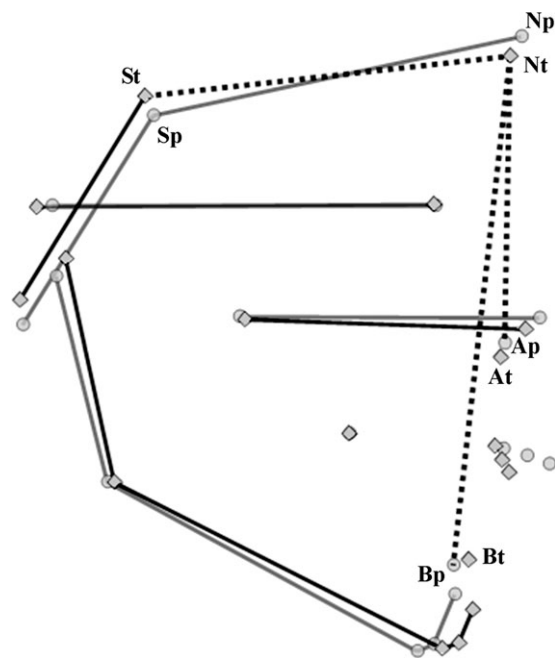


**Figure 2** Digitized landmarks—point S: midpoint of the pituitary fossa of the sphenoid bone; point N: most anterior point of the frontonasal suture; porion: highest point of the meatus acousticus externus; orbitale: lowest point on the averaged left and right inferior margin of the orbit; articular: intersection between the posterior border of the mandible, with the inferior outline of the cranial base; posterior nasal spine: the most posterior point in the median plane on the bony hard palate; anterior nasal spine, the tip of the median anterior process of the maxilla; basion: lowest point on the anterior margin of the foramen magnum, in the midsagittal plane; MBCT: the mesiobuccal cusp tip of the upper first molar; Is, tip of the crown of the most anterior maxillary central incisor; Li, tip of the crown of the most anterior mandibular central incisor; interincisal point: the midpoint between Is and Li; point A, deepest point on the anterior surface of the maxilla between ANS and prosthion; point B, deepest point on the anterior surface of the mandibular symphysis between infradentale and pogonion; pogonion: most anterior point of the mandibular symphysis; gnathion: most anterior and inferior point on the contour of the mandibular symphysis, constructed by bisecting the angle formed by the mandibular plane and N–Pog line; menton, most inferior point of the mandibular symphysis; gonion: most posterior and inferior point of the mandibular angle, determined by bisecting the angle formed by the tangent to the posterior border of the mandible and the mandibular plane.

study; Broadbent *et al.*, 1975), while the other was represented by the tracing's reference points, which were digitized earlier. The procedure consists of three discrete steps: firstly, the template is shifted to align its centroid (its centre of gravity or midpoint) with that of the tracing's landmarks. Secondly, the template is rotated, minimizing the distances between the corresponding points of the template to those of the tracing. Finally, the template is scaled (inflated or shrunk 'isomorphically', without changing proportions) in order to remove size differences between the two clusters of points. The latter is performed by calculating the centroid size: the square root of the sum of the squared distances of each point to the centroid. The centroid size of the translated and rotated template is then matched to that of the tracing.

The Bolton template co-ordinates resulting from the Procrustes analysis (the template co-ordinates after it was translated, rotated, and scaled, in order to find the best fit relative to the patient's tracing) were exported back to Excel, where all further calculations were performed: the patient's digitized landmarks were used to determine ANB and Wits values, the individualized ANB angle according to Hussels and Nanda (1984), the floating norm according to Järvinen (1986), as well as the APDI as proposed by Kim and Vietas (1978). Also calculated were the AB–BB measurement according to Hall-Scott (1994), the AP–BP measurement introduced by Ferrazzini (1976), the AF–BF value proposed by Chang (1987), the ASN–BSN measurement according to Taylor (1969), and the AB plane angle as suggested by Downs (1948).

In addition, ANB and Wits values were normalized: the post-Procrustes co-ordinates for the Bolton template's points S and N (designated St and Nt, Figure 3) and the patient's points A and B were used to calculate the normalized ANB angle (ANBn), while the Bolton template's occlusal plane (constructed from MBCTt and IIPt, Figure 4) and the patient's points A and B were used to compute the normalized Wits analysis (WITSn). Similarly, normalized versions were calculated for the AB–BB measurement (AB–BBn) by determining the Bolton template's mandibulomaxillary bisector (again after performing Procrustes analysis), on which the patient's points A and B were projected. The Bolton template's palatal plane was used to determine the normalized APP–BPP value (APP–BPPn). Projecting the patient's points A and B onto the Bolton template's FH rendered the normalized AF–BF measurement (AF–BFn). Finally, the normalized AB plane angle was determined by measuring the inner angle formed by the AB plane (constructed from the patient's points A and B) and the Bolton template's post-Procrustes N–Pog line, rendering ABPAn, whereas projecting the patient's points A and B onto the Bolton template's SN line revealed the normalized ASN–BSN measurement (ASN–BSNn). The term normalized refers to the template (or norm's) reference landmarks/planes used in the analysis.



**Figure 3** ANB analysis, as performed in the proposed technique, is calculated by connecting the Bolton template's point N, designated Nt (which is the point N resulting from the application of Procrustes analysis to the Bolton template), with the patient's points Ap and Bp, rendering the angle Ap–Nt–Bp. Also depicted are the Bolton template's points A, B, and S, designated At, Bt, and St, as well as the patient's points S and N, designated Sp and Np. The patient's landmarks are depicted as circles while the squares represent the Bolton template points.

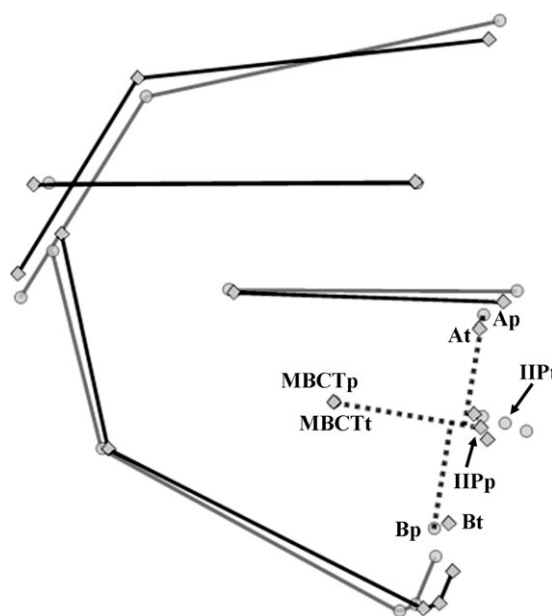
Correlation calculations were performed between classic ANB and Wits, the AB–BB, AP–BP, AF–BF, and ABPA values as well as ASN–BSN. The same procedure was repeated for their normalized counterparts (i.e. after performing Procrustes analysis).

#### Statistical procedure

All tests were performed using the Statistical Package for Social Sciences (SPSS Inc., Chicago, Illinois, USA). Significance was predetermined at the 0.05 per cent level of confidence. Intragroup comparison of males and females regarding SNA, SNB, and ANB (Riedel, 1952), Wits (Jacobson, 1975), Järvinen's floating norm (1986), individualized ANB (Hussels and Nanda, 1984), and APDI (Kim and Vietas, 1978) were performed using either *t*- or Mann–Whitney *U*-tests, depending on Levene's test to confirm homogeneity of variance and the Shapiro–Wilk test to assess normality of the distribution. The correlation between the various measurements for sagittal discrepancy was calculated using Spearman's rank correlation coefficient.

#### Error analysis

The entire procedure was repeated for 15 randomly selected cases, at least 2 weeks apart. Statistical significance was determined using paired *t*-tests. The overall method error



**Figure 4** The Wits appraisal, as performed in the proposed technique, is determined by projecting the patient's points A and B, designated Ap and Bp, onto the Bolton template's occlusal plane MBCTt–IIPt (where MBCTt and IIPt represent the mesiobuccal cusp tip and interincisal point resulting from the application of Procrustes analysis to the Bolton template). Also depicted are the patient's mesiobuccal cusp tip and interincisal point, designated MBCTp (coincides with MBCTt) and IIPp, as well as the Bolton template's points A and B, designated At and Bt. The patient's landmarks are depicted as circles while the squares represent the Bolton template points.

was determined using the standard error of the method 
$$S = \sqrt{\frac{\sum d^2}{2n}}$$
 where *d* represents the difference between the corresponding repeated measurements, and *n* the number of measurements performed.

#### Results

Repeated measurements for ANB, Wits, AB–BB, AP–BP, AF–BF, ABPA, ASN–BSN, and their normalized counterparts (ANBn, WITSn, AB–BBn, AP–BPn, AF–BFn, ABPA<sub>n</sub>, and ASN–BSN<sub>n</sub>) did not reveal any statistically significant results (Table 1). Pearson's correlation coefficient varied from 0.957 (AB–BBn) to 0.984 (ASN–BSN<sub>n</sub>), all coefficients being highly significant (*P* < 0.001). Overall method error ranged from 0.34 mm (ASN–BSN<sub>n</sub>) to 0.66 mm (AF–BF), which was deemed to be acceptable when compared with the SDs. Comparing the overall method error for the classic tests with those of the normalized counterparts, it was found that the values were comparable, indicating that the normalized ANB, Wits, AB–BB, AP–BP, AF–BF, AB plane angle, and ASN–BSN measurements are as reproducible as their classic counterparts.

Table 2 summarizes the results for the intragroup comparison of males and females. Both groups were significantly different in age, the females being approximately 1.5 years older than

the males. However, since no statistically significant differences were found in any of the classic methods to describe the mandibular and maxillary sagittal position and relationship (SNA, SNB, ANB, and Wits), in the floating norm methods of assessing sagittal discrepancy as proposed by Järvinen (1986) and Hussels and Nanda (1984), in the APDI by Kim and Vietas (1978), and in the vertical dimension (GoGn–SN values), it was considered both groups were skeletally sufficiently ‘matched’ to group males and females for further analysis. Table 3 lists the descriptive statistics for the pooled sample.

Since several grouped parameters were not normally distributed, correlations were determined using Spearman’s rank correlation coefficient instead of Pearson’s correlation coefficient. The classic and normalized cross-tabulated correlation coefficients for the measurements are listed in Tables 4 and 5, respectively. Applying the currently proposed technique to ANB, Wits, AB–BB, AP–BP, AF–BF, ABPA, and ASN–BSN heightened the correlation coefficients between all tests. The smallest improvement

in concordance was found for the correlation ABPA versus ANB, from  $-0.907$  (classic tests) to  $-0.959$  (normalized tests). The greatest improvement was seen for the correlation ABPA versus AP–BP, from  $-0.545$  (classic tests) to  $-0.950$  (normalized tests). All other correlation coefficients obtained after applying Procrustes analysis were above  $0.742$  (in absolute value): from  $0.742$  for the ASN–BSN versus AB–BBn to  $-0.995$  for the ABPA versus WITSn. Normalizing ANB and Wits measurements increased the correlation to  $0.964$  in comparison with the rather modest value of  $0.624$  between their classic counterparts. The results for the application of ANB and Wits to each patient, compared with the normalized counterparts, are shown in Figure 5. From this graph, it is evident that the cluster of points representing the classic tests is scattered rather loosely around the regression line  $\text{ANB} = 3.26 + 0.38 \text{ Wits}$  (95 per cent confidence interval lower bound:  $\text{ANB} = 2.81 + 0.28 \text{ Wits}$ ; upper bound:  $\text{ANB} = 3.70 + 0.48 \text{ Wits}$ ), in comparison with the much

**Table 1** Method error analysis.

Measurement (original/repeated)	Paired differences		<i>t</i>	Significance (two-tailed)	Correlation (Pearson)	Standard error of the method
	Mean	SD				
ANB	0.25	0.76	1.27	NS	0.982	0.43
Wits	0.09	0.86	0.40	NS	0.965	0.59
AB–BB	0.31	0.74	1.65	NS	0.976	0.55
AP–BP	0.27	0.80	1.31	NS	0.977	0.58
AF–BF	0.13	0.96	0.54	NS	0.969	0.66
ABPA	–0.20	0.94	–0.81	NS	0.970	0.37
ASN–BSN	–0.05	0.70	–0.27	NS	0.982	0.48
ANBn	0.12	0.56	0.85	NS	0.961	0.39
WITSn	0.17	0.68	0.99	NS	0.965	0.48
AB–BBn	0.22	0.79	1.09	NS	0.957	0.56
AP–BPn	0.09	0.56	0.65	NS	0.977	0.39
AF–BFn	0.07	0.53	0.48	NS	0.980	0.37
ABPAn	–0.22	0.92	–0.92	NS	0.973	0.65
ASN–BSNn	–0.01	0.50	0.05	NS	0.984	0.34

NS, non-significant.

**Table 2** Intergroup comparison of males and females using Mann–Whitney *U*-test.

	Males ( <i>n</i> =26)		Females ( <i>n</i> =45)		<i>P</i>	Significance
	Mean	Standard deviation	Mean	Standard deviation		
Age	13.1	1.1	14.6	8.2	0.04	*
SNA	81.4	3.0	81.1	3.6	0.91	NS
SNB	77.1	2.9	75.5	12.0	1.00	NS
ANB	4.3	2.1	3.9	2.3	0.15	NS
Wits	2.7	3.1	1.7	4.2	0.12	NS
Hussels and Nanda (1984)	4.3	2.1	3.9	2.4	0.19	NS
Järvinen (1986)	2.7	1.7	2.4	2.0	0.39	NS
Anteroposterior dysplasia indicator (Kim and Vietas, 1978)	81.1	4.3	81.8	6.8	0.17	NS
GoGn–SN	32.3	5.1	32.1	5.6	0.75	NS

NS, non-significant. \* $P < 0.05$ .

**Table 3** Descriptive statistics for the pooled sample.

	Mean	Standard deviation	Minimum	Maximum
Age	14.1	6.6	8.5	44.9
SNA	81.2	3.4	74.5	89.0
SNB	76.1	9.7	0.0	62
ANB	4.0	2.2	-0.8	12.2
Wits	2.0	3.8	-4.5	17.8
Hussels and Nanda (1984)	4.0	2.3	-0.7	12.0
Järvinen (1986)	2.5	1.9	-1.0	8.4
Anteroposterior dysplasia indicator (Kim and Vietas, 1978)	81.6	6.0	63.4	93.2
GoGn-SN	32.2	5.4	20.4	47.3

smaller dispersion of the normalized points cluster (regression line  $ANB_n = 2.87 + 0.76 WITS_n$ , 95 per cent confidence interval lower bound:  $ANB_n = 2.73 + 0.72 WITS_n$ , upper bound:  $ANB_n = 3.00 + 0.81 WITS_n$ ).

### Discussion

The value for the correlation between ANB and Wits (0.624, Table 4) corresponds almost perfectly with those obtained by Roth (1982) in his positive Wits group and Järvinen (1981), and Richardson (1982), but is somewhat low in comparison with various other studies (Millett and Gravely, 1991; Del Santo, 2006). The latter is probably due to differences in sample size and selection criteria.

**Table 4** Correlation calculations for the classic measurements using Spearman's summed rank test.

	ANB	Wits	AB-BB	AP-BP	AF-BF	ABPA	ASN-BSN	Hussels and Nanda (1984)	Järvinen (1986)	APDI
ANB	1									
Wits	0.624	1								
AB-BB	0.732	0.807	1							
AP-BP	0.686	0.656	0.677	1						
AF-BF	0.725	0.598	0.679	0.842	1					
ABPA	-0.907	-0.685	-0.811	-0.545	-0.581	1				
ASN-BSN	0.690	0.596	0.571	0.884	0.844	-0.530	1			
Hussels and Nanda (1984)	0.967	0.580	0.664	0.643	0.701	-0.855	0.668	1		
Järvinen (1986)	0.705	0.769	0.932	0.665	0.711	-0.770	0.697	0.645	1	
Anteroposterior dysplasia indicator (Kim and Vietas, 1978)	-0.595	-0.437	-0.590	-0.477	-0.836	0.533	-0.534	-0.579	-0.631	1

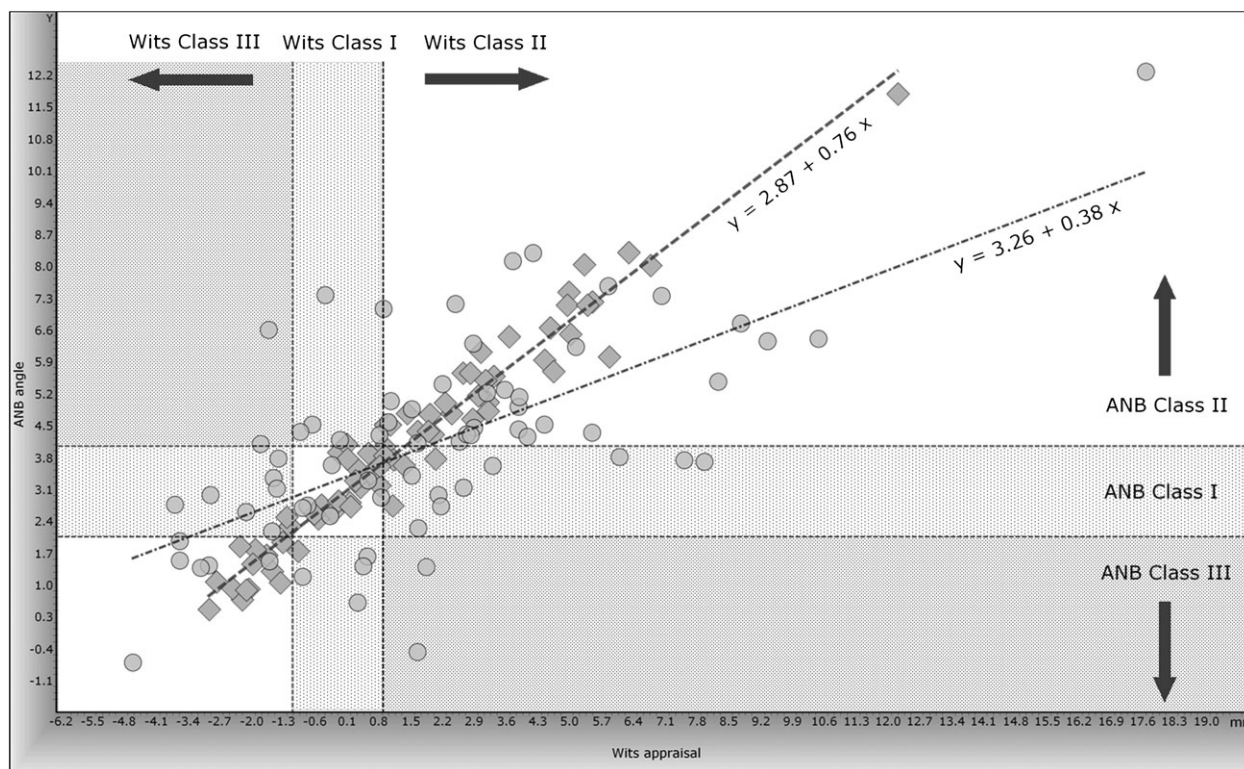
All correlation coefficients are highly significant ( $P < 0.001$ ).

**Table 5** Correlation calculations for the normalized measurements using Spearman's summed rank test.

	ANB <sub>n</sub>	Wits <sub>n</sub>	AB-BB <sub>n</sub>	AP-BP <sub>n</sub>	AF-BF <sub>n</sub>	ABPA <sub>n</sub>	ASN-BSN <sub>n</sub>	Hussels and Nanda (1984)	Järvinen (1986)	APDI
ANB <sub>n</sub>	1									
Wits <sub>n</sub>	0.964	1								
AB-BB <sub>n</sub>	0.946	0.980	1							
AP-BP <sub>n</sub>	0.944	0.966	0.908	1						
AF-BF <sub>n</sub>	0.919	0.938	0.865	0.993	1					
ABPA <sub>n</sub>	-0.959	-0.995	-0.985	-0.950	-0.916	1				
ASN-BSN <sub>n</sub>	0.835	0.846	0.742	0.948	0.972	-0.816	1			
Hussels and Nanda (1984)	0.847	0.811	0.758	0.841	0.834	-0.793	0.798	1		
Järvinen (1986)	0.854	0.909	0.893	0.871	0.834	-0.910	0.744	0.645	1	
Anteroposterior dysplasia indicator (Kim and Vietas, 1978)	-0.653	-0.688	-0.675	-0.701	-0.688	0.683	-0.625	-0.579	-0.631	1

All correlation coefficients are highly significant ( $P < 0.001$ ).





**Figure 5** Relationship of the Wits appraisal (x-axis) to ANB angle (y-axis). The classic ANB and Wits analyses are depicted as circles, while the squares represent the normalized values. The cluster of points representing the classic tests is scattered loosely around the regression line  $y = 3.26 + 0.38x$ . In contrast, the normalized values correspond much closer their regression line  $y = 2.87 + 0.76x$ . The areas shaded light grey represent areas of ambiguity, while those shaded dark grey represent areas of contradiction.

The rather modest correlation of 0.624 signifies that about 39 per cent of the variability in ANB measurements can be explained by variations in the Wits value and *vice versa*. Consequently, both analyses tend to sometimes disagree, giving rise to a great deal of uncertainty as to which one of the two (if any) measurements is correct. Figure 5 demonstrates the fairly large variation in ANB values that may be found associated with small variations in Wits appraisal. It seems most authors agree that this variation is caused by geometric distortion (Järvinen, 1981; Roth, 1982; Hussels and Nanda, 1984; Chang, 1987; Jacobson, 1988; Del Santo, 2006) which results from the application of ANB analysis and Wits appraisal to patients who, by definition, vary interindividually in the position of their reference landmarks: S, N, and the occlusal plane. Consequently, both analyses not only measure sagittal discrepancy but also equally represent variations in the AP and vertical position of N, in the vertical dentoalveolar dimension, in the rotation of both jaws in relation to the cranial base, and in molar and incisor eruptive status (which in turn determines the cant of the occlusal plane). If ANB analysis and Wits appraisal are to better correspond and hence more often agree on the admittedly ill-defined concept of sagittal discrepancy, it seems the key to improving their correlation lies in limiting geometric distortion of the measurements. If successful, this would not only improve the correlation between Wits appraisal and ANB analysis but

could also lead to an improvement in their sensitivity and specificity.

The presently proposed technique tries to limit geometric distortion by eliminating, as much as possible, individual variations in the position of the reference landmarks: S, N, and the occlusal plane. This is accomplished by 'fitting' a template on the patient's digitized landmarks using Procrustes analysis (Halazonetis, 2004). The measurements are then performed using the patient's points A and B and the template's points S and N as well as the template's occlusal plane. From Table 5, it would appear that the technique performs adequately: the correlation between ANBn and WITSn increased to 0.964, in comparison with the value of 0.624 found for the classic tests (Table 4). Therefore, 93 per cent of the variability in the ANBn measurement can be predicted by variations in the WITSn measurement, in comparison with 39 per cent for their classic counterparts. This is graphically demonstrated by the smaller dispersion of the points around the regression line in Figure 5. Although correlation itself does not represent a measure of diagnostic performance, the improved correlation between ANB and Wits considerably lowers the possibility of differing (Class I–Class II or Class I–Class III) or even totally opposing (Class II–Class III) diagnostic outcomes resulting from the application of both tests to (non-borderline) patients and could therefore possibly improve their diagnostic power.

Similar results were found when the present methodology was applied to other methods for determining sagittal discrepancy (Tables 4 and 5): projections on the mandibulomaxillary bisector (Hall-Scott, 1994), palatal plane (Ferrazzini, 1976), FH plane (Chang, 1987), the SN line (Taylor, 1969), as well as the AB plane angle (AB to N-Pog, Downs, 1948). Not surprisingly, the lowest improvements in correlation occurred for measurements that were already well correlated initially: the correlation between ABPA and ANBn ( $\rho = -0.959$ , Table 5) improved only  $-0.052$ , but was  $-0.907$  initially. The second lowest improvement,  $0.064$ , was found for ASN-BSN versus AP-BPn ( $\rho = 0.948$ , Table 5), which started from an acceptable correlation of  $0.884$  (Table 4). Conversely, the highest improvements in correlation seem to have occurred for measurements that were poorly correlated initially; the lowest correlation coefficient of  $-0.530$  was found for ASN-BSN versus ABPA (Table 5). It improved from  $-0.286$  after applying the currently proposed technique to  $-0.816$  (Table 4). The correlation coefficient for AF-BF versus ABPA (Table 5) measured  $-0.581$  before applying Procrustes analysis, while a value of  $-0.916$  was found after normalization (Table 4). Since no deterioration was found for high initial correlations and low correlations were considerably improved, it seems the technique also performs adequately when applied to the aforementioned other methods for determining sagittal discrepancy. The basic question of course is whether the proposed methodology is valid.

The template fitted on the patient's tracing was the Bolton 12-year male-female averaged template, which by definition is indifferent to gender. However, as mentioned by Broadbent *et al.* (1975) and confirmed by Halazonetis (2007), males and females tend on average to differ mainly in size, more so than in shape. In fact, after removing gender-related size differences using Procrustes analysis, Halazonetis (2007) stated that the differences between the male and female average tracings were so small that they were hardly visible to the naked eye. Since Procrustes analysis was equally used in the current project to adjust the size of the template to the patient's tracing, the use of an averaged template in the current project would seem justified. The choice of the 12-year template was rather arbitrary. Since the patient sample was gathered prospectively, it was not known at the start what the average patient age would be. Secondly, the classic templates as developed by Broadbent *et al.* (1975) and Popovich and Thompson (1977) are generally used for direct comparison, after being superimposed on the patient's tracing. The relevance of the measurements therefore depends on selecting the right age and consequently the right size of template. Since in the current project the template size (and position) was adjusted using Procrustes analysis, the choice of template was far less critical.

The landmarks digitized in the present study were selected mainly because it was felt that they optimally characterized the anatomical structure of interest (mandible, maxilla, skull

base, and FH). Points A and B were digitized, but they were omitted during the Procrustes analysis.

The correlation coefficient found in the current investigation was quite high. Tu *et al.* (2006) recently published a report regarding the problem of mathematical coupling, which concerns correlation and regression analyses. This is said to occur in situations where both aforementioned analyses are applied when 'the relationship between two variables is due to a common component, when one variable is part of the other, or when a third variable is common to both', mathematical coupling could cause misleading results. It is, however, very unlikely that mathematical coupling applies to the current investigation for two reasons.

1. Direct mathematical coupling requires a relatively simple mathematical relationship between the variables under investigation (such as  $ANB = SNA - SNB$ ; Tu *et al.*, 2006), and therefore does not seem to apply. Although Järvinen (1985) demonstrated that the Wits analysis can be calculated from ANB, the required formula is quite complex (Figure 6):

$$\text{Wits} = \cos(\beta) \times \sqrt{NA^2 + NB^2 - 2 \times NA \times NB \cos(\alpha)},$$

where

$\beta$  = angle formed between the occlusal plane and a line joining points A and B

NA = distance between points N and A

NB = distance between points N and B

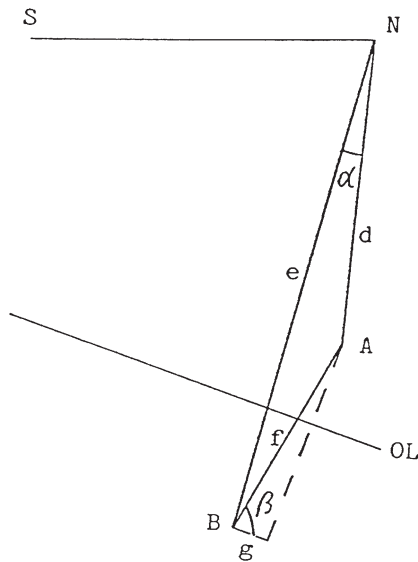
$\alpha$  = ANB angle

It is interesting to note that Järvinen's formula uses a third factor, AB plane angle, to calculate the Wits from the ANB, which by virtue of its presence allows variability. Therefore, both analyses are no longer directly coupled. Another approach to calculate Wits from ANB uses the intersection between the SN line and the occlusal plane (Figure 7):

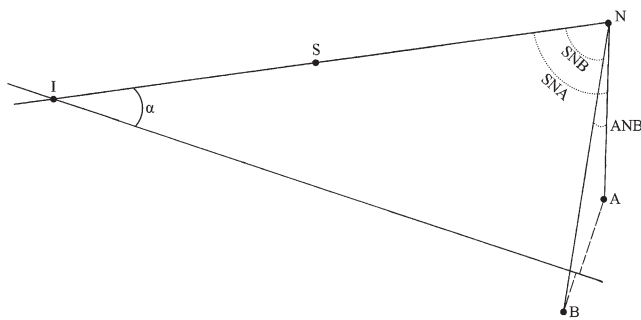
$$A_oB_o = \frac{\sin(ANB)\sin(\alpha)IN}{\sin(180 - \alpha - SNA)\sin(180 - \alpha - SNB)} - \left( \frac{\sin(\alpha)IN}{\sin(180 - \alpha - SNA)} - NA \right) \cos(180 - \alpha - SNA) - \cos(180 - \alpha - SNB) \left( NB - \frac{\sin(\alpha)IN}{\sin(180 - \alpha - SNB)} \right).$$

As before, this formula needs additional factors to differentiate one analysis from the other: adding the SN line to the equation introduces angle  $\alpha$  and length IN, which again introduce variability. Since it seems impossible to calculate the Wits from ANB without additional factors, the presence of direct mathematical coupling in the present study seems highly unlikely.

2. Indirect mathematical coupling, which assumes changes in one variable, via a third variable or via an underlying



**Figure 6** Relationship between Wits appraisal and ANB angle, according to Järvinen (1985).



**Figure 7** Calculating the Wits appraisal from ANB angle, using the SN line. 'I' represents the intercept between the SN line and the occlusal plane, while  $\alpha$  depicts the angle between these two lines. The definitions of the other landmarks can be found in Figure 2. The labels for the intersection between the perpendiculars dropped from A and B onto the occlusal plane, Ao and Bo, have been omitted for clarity.

physiological association to inevitably lead to related changes in the other variable (Tu *et al.*, 2006) also does not seem to apply. Although ANB and Wits analysis are linked via the dentoalveolar relationship, simple geometric distortions can cause ANB to change without a concomitant change in the Wits appraisal or *vice versa*. This applies even in the current methodology, where individual variation is limited using reference landmarks from the superimposed template (hence fixing the mutual relationship of N to the occlusal plane). As an example, changing the vertical position of A and B perpendicular to the template's occlusal plane (without changing their mutual AP relationship) will change the value of ANBn, without changing WITSn. Therefore, changes in one variable (ANBn), via a third variable or underlying physiological association (position of A and B), do not inevitably lead to changes in the other variable (WITSn). Similar examples, in slight variations, could be presented

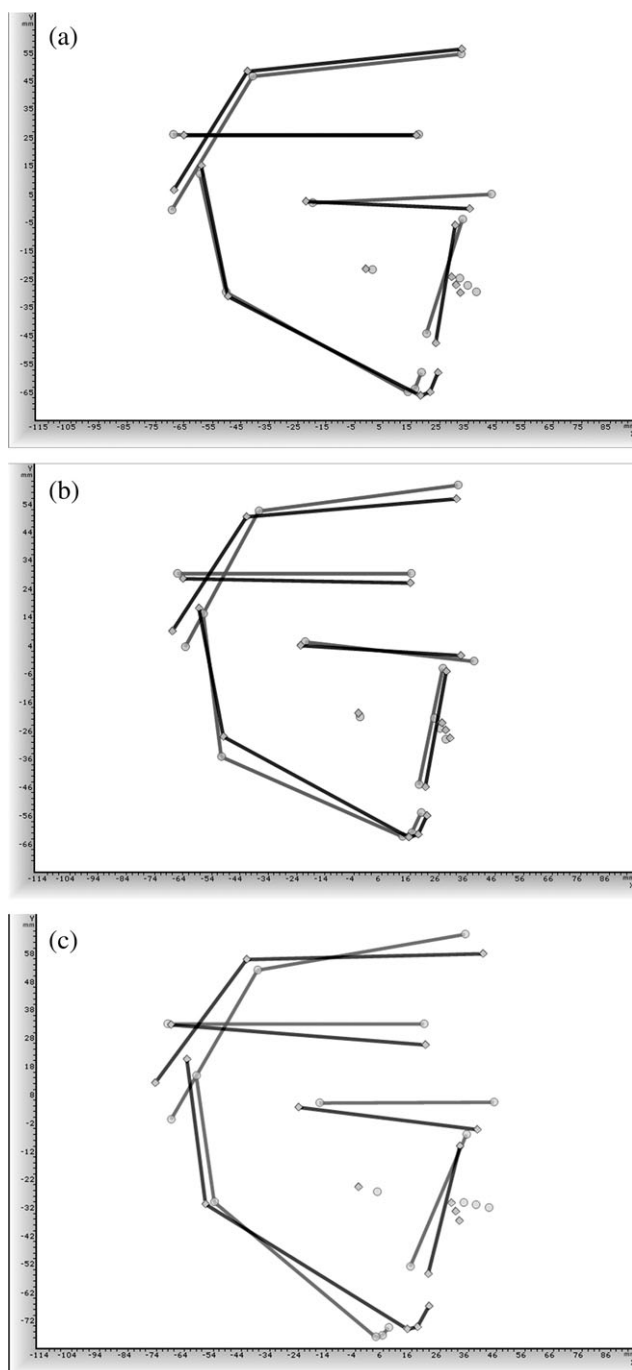
for every pair of correlated measurements in Tables 4 and 5. As an example, when studying the correlation between AP–BP and AF–BF, changing the vertical position of points A and B perpendicular to the palatal plane will change the reading of the projection on FH, without a concomitant change in AP–BP.

Since the prerequisites for the presence of indirect mathematical coupling are also not fulfilled, it seems the use of correlation analysis to describe the interrelationship between ANB and Wits measurements in the present investigation is warranted.

The correlation coefficients could probably have been improved further by limiting variability in the vertical dentoalveolar dimension. Roth (1982) proposed drawing a line through points A and B and constructing two alternative points for A' and B' on this line, at a fixed distance from one another (for instance, distance A' to B' is always 50 mm, the midpoint between them being located on the occlusal plane). The Wits appraisal would then be obtained using the two alternative points A' and B'. In doing so, Roth (1982) observed that the separation between the various Classes of sagittal discrepancy improved (less overlapping of these Classes was observed, where a Wits value could belong to Class I, Class II, as well as Class III patients). Why standardizing the vertical dentoalveolar dimension might have improved the correlation between for instance ASN–BSN and other measurements, such as ANBn, WITSn, and ABPAN, can be explained by the oblique orientation of the SN line relative to the occlusal plane. Therefore, the ASN–BSNn measurement would be very sensitive to remaining variations in the vertical dentoalveolar dimension, in comparison with the less oblique planes such as the palatal plane or the mandibulomaxillary bisector. Standardizing the vertical dentoalveolar dimension would remove this variation and hence improve correlations. However, a conscious decision was taken not to apply this approach in the current project. Firstly, there is no real consensus on how the vertical dentoalveolar dimension should be standardized: as an alternative to the technique proposed by Roth (1982), one could construct perpendiculars on the occlusal plane through points A and B, to then locate points A' and B' on these lines, at a fixed distance from the occlusal plane. Furthermore, it might be contended that standardizing the vertical dentoalveolar dimension in addition to the proposed methodology makes it very hard to assess what is finally being measured: the measurement of sagittal discrepancy may be diluted by all these manipulations to the point of having little left to do with this measurement. Finally, it would have been considerably more difficult to disprove the presence of mathematical coupling, should the vertical dentoalveolar dimension have been standardized.

The currently proposed methodology can also be used morphometrically, directly comparing the patient's tracing to the size- and position-corrected template. Figure 8a–c illustrates three patients, the first two of whom will be treated orthodontically, while the third represents the application of





**Figure 8** Examples of the morphometric application of the currently proposed technique to various patients. The template is depicted in black (squares) and the patient in grey (circles). In (a), the superimposition seems to suggest a short, retrognathic mandible, combined with slight maxillary prognathism, and a favourable mandibular plane angle. For the patient in (b), the maxillomandibular relationship seems to be normal, albeit with slight bimaxillary retrusion, a minor retrusion of the chin due to a somewhat shorter mandibular corpus, and an increased lower posterior face height. In (c), the proposed technique is applied to a surgery patient. A marked mandibular retrusion is combined with a minor maxillary protrusion and a considerably increased lower anterior face height. The dentition is clearly protrusive. Interestingly, the superimposition indicates posterior maxillary intrusion and mandibular autorotation/slight protrusion using a bimaxillary surgical approach as the treatment regimen for this patient.

the current technique to a prospective surgery patient (the tracings were not corrected for cephalometric enlargement). As evident from these examples, information may be obtained in addition to the patient's sagittal discrepancy, such as growth pattern, mandibular length and position, palatal plane inclination, dental protrusion, or retrusion, by direct comparison. Although the analysis itself might seem complicated to perform technically, Procrustes analysis can be included in any of the modern computer programs for cephalometric analysis with little programming effort. For everyday use in a clinical setting, this would clearly be preferable. However, as illustrated by this research, the procedure may also be performed using affordable, publicly available software programs, albeit requiring more work exchanging information back and forth between the various software packages.

As the currently proposed technique seems to considerably improve the correspondence between ANB and Wits appraisal, it could be used morphometrically and can easily be expanded to include the third dimension; it seems to at least warrant further investigation.

## Conclusions

Applying Procrustes analysis to fit the 12-year male–female averaged Bolton template on the patient's digitized landmarks, and combining the template's reference landmarks/planes with the patient's points A and B to determine the normalized measurements for determining sagittal discrepancy, increases the correlation between the various analyses in comparison with their classic counterparts. The significantly improved correspondence between the normalized analyses heightens the possibility of these tests agreeing on the patient's sagittal discrepancy and decreases the possibility of differing or even totally opposing diagnostic outcomes resulting from their application to (clear-cut) Class I, II, and III patients.

## Address for correspondence

Dr Hans Wellens  
Groene Poortdreef 16  
8200 Sint-Michiels  
Brugge  
Belgium  
E-mail: wellens.hans@telenet.be

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