CLINICAL REPORT

GD Singh

Morphospatial analysis of soft-tissue profile in patients with Class II division 1 malocclusion treated using twin block appliances: geometric morphometrics

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Abstract: *Author* – Singh GD
Objectives – To study soft-tissue profile changes in patients treated with twin block appliances (TBA) for the correction of Class II division 1 malocclusion. The null hypothesis is that soft-tissue profiles do not show any significant improvements associated with TBA treatment.
Design – Longitudinal, retrospective.
Setting and Sample Population – Scotland, UK, using lateral cephalographs of 46 consecutive, prepubertal children (aged 9–11 years) and 55 adolescents (aged 12–14 years) obtained from an orthodontic practice.
Experimental Variable – The prepubertal children underwent ≈13 months of TBA treatment, while the adolescents underwent ≈22 months of treatment.
Outcome Measures – Configurations of 13 digitized homologous landmarks of pre- and post-treatment soft-tissue facial profiles were compared using cephalometry, Euclidean distance matrix analysis (EDMA) and thin plate spline (TPS) analysis.
Results – Cephalometry showed that height increases associated with the TBA were in the labiomental areas, and the most significant height decreases were seen in the lip regions. The results of EDMA also indicated significant changes ($P < 0.05$). The distance between the lips decreased by >5%, with increases in length in the labiomental region. The TPS analysis showed the soft-tissues of the mandibular complex being displaced antero-inferiorly, with anterior displacement of the landmarks of the lip region. These changes showed that the lips were brought into closer proximity with each other, permitting a functional oral seal. Moreover, the labiomental groove became less pronounced, reflecting the underlying dento-alveolar correction.
Conclusion – Demonstrable improvements in soft-tissue facial profile may be associated with TBA treatment.

Key words: dentofacial orthopedics; geometric morphometrics; thin plate spline

Introduction

Historically, clinical orthodontic research has followed a reductionist approach to cope with the complex problem of assessment of form-change. Descriptive statistics often have been adopted to describe the results and although this strategy has been successful given the conditions of parsimony, some seldom consider whether this approach will lose its effectiveness. In recent years, new methodologies using computational approaches to clinical form-change have been developed to augment conventional cephalometry. As well, different views have been expressed on the aetiology of malocclusion, and this has been reflected in the methods of treatment. Generally, treatment philosophies employed in the correction of Class II division 1 malocclusions are governed by ideologies concerned with growth and development (1) and the relationship of growth to treatment (2). Thus to understand aetiology, environmental influences and genetic predisposition must be considered (3).

In early studies of malocclusion, the skeletal and dental hard tissues were measured extensively and reported upon. Later, it was found that there was an adolescent growth spurt involving the soft-tissues of the nose and also the lips and chin (4, 5). This growth was concluded to be linear, occurring between the ages of 3 and 13 years (6). Nevertheless, an important question remained unanswered: Does the soft-tissue profile simply reflect the underlying skeletal and dental hard tissues or does it have a significant role in the development of malocclusions? It was suggested (7) that the development of an occlusion is the result of interplay between the effects of skeletal pattern and the soft-tissue environment on the teeth. More recently, it has been demonstrated that the soft-tissues may contribute to the development of malocclusions (8–10), but the nature of the relationship remains incompletely understood (11). Therefore, the height of the lip-line in relation to the occlusal plane of the teeth, the behaviour of the lower lip, and the height of the lower lip during physiologic activity may be soft-tissue factors of significance in the determination of final facial profile.

In the treatment of Class II malocclusions, the twin block appliance (TBA) is a commonly used functional appliance (12–15). It is a removable, two-piece appliance, which putatively encourages mandibular growth (16) whilst stabilizing the maxilla (17). According to the lateral pterygoid hypothesis, the postural and functional activities of the superior and inferior heads of the lateral pterygoid muscle increase after the insertion of a functional appliance. This increased activity, especially in the superior head of the lateral pterygoid muscle, is thought to augment condylar growth. As biological systems are highly hierarchical and structured, however, there is some evidence for (16, 18, 19) and against (20–22) this hypothesis. As well, the effects of reductionism result in knowing more about smaller aspects of (orthodontic) change; understanding under the conditions of parsimony does not necessarily mean better understanding of the whole. This is a serious plight that orthodontists and scientists face. Thus, some means are needed to amalgamate knowledge at different levels into a structured network to understand treatment outcomes more comprehensively.

In this paper, mechanisms of quantitative computation (geometric morphometrics) are introduced and implemented; modelling and simulation of twin block treatment is taken as an example to illustrate how complex biologic behaviours can be investigated and demonstrated at different levels, developing the transformation grid concepts of D'Arcy Thompson (23). Therefore, the aim of this present study is to assess soft-tissue profile changes associated with TBA treatment in prepubertal children and adolescents exhibiting Class II division 1 malocclusion. Longitudinal comparisons will be undertaken on both groups of pre- and post-treatment patients, to show the effects of the TBA treatment. The null hypothesis to be tested is that pre- and post-treatment configurations do not show any demonstrable soft-tissue profile changes associated with the TBA treatment.

Materials and methods

Sample

After obtaining consent, pre- and post-treatment, lateral cephalographs of 46 consecutively treated children with Angle's Class II division 1 malocclusion aged between 9 and 11 years at the start of treatment were retrieved from an orthodontic practice. A further set of pre- and post-treatment cephalographs of 55 adolescents with a similar Class II relationship aged 12–14 years at the start of treatment were also obtained. The sample comprised males and females with a large overjet and a distal occlusion related to a moderate to severe Class II skeletal relationship. Exclusion criteria for sample selection were a history of previous orthodontic treatment, facial trauma requiring hospital attendance, and congenital maxillofacial deformity. The chronological age was assumed to match developmental age in this study, as carpal ages were unavailable. It was presumed that when all radiographs were taken, the central X-ray passed along the transmeatal axis while the teeth were in occlusion. The magnification of each film was standardized to 8%. For each lateral cephalograph, *x, y* co-ordinates of 13 homologous, soft-tissue landmarks (Fig. 1) were digitized using appropriate software and a digitizing tablet. These landmarks encompassed the lateral facial profile, and permitted the construction of the soft-tissue matrices to be studied.

Thus, in this study two cohorts were studied. The first cohort consisted of prepubertal children aged 9–11 years at the beginning of treatment. The second cohort consisted of adolescents aged 12–14 years at the beginning of treatment. The first cohort of children underwent ≈13 months of TBA treatment with extra-oral traction, while the second cohort of adolescents underwent ≈22 months of TBA treatment with extra-oral traction. The pre- and post-treatment records were inclusive of the period when only the TBA was actively used, and did not include the stabilization period. To determine how the pre-treatment and corresponding ≈13-month post-treatment soft-tissue configurations differed in prepubertal children, the pre- and post-treatment mean geometries were compared. Similarly for the adolescents, pre-treatment and corresponding ≈22-month post-treatment soft-tissue mean geometries were compared. Both cohorts were also decomposed into males and females, so that mean geometries of each sex at each developmental stage were also compared.

Cephalometry

Traditional cephalometry was carried out on inter-landmark distances of the data. Ten soft-tissue lengths were measured and the mean lengths were compared between groups using a paired *t*-test. Thus, pre-treatment lengths were compared to post-treatment lengths for the prepubertal and adolescent groups in this longitudinal study.

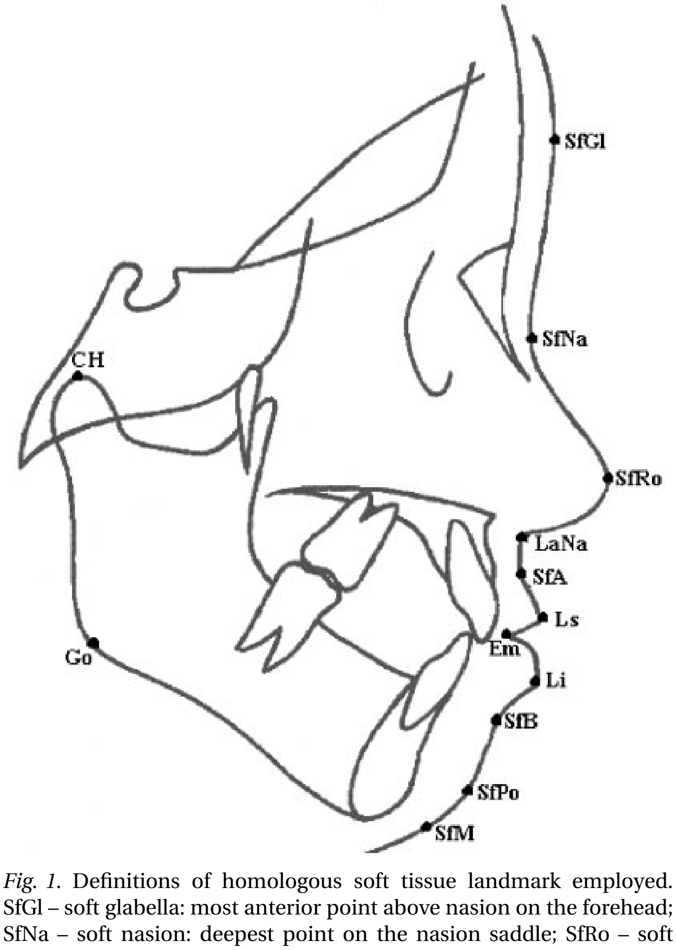


Fig. 1. Definitions of homologous soft tissue landmark employed. SfGl – soft glabella: most anterior point above nasion on the forehead; SfNa – soft nasion: deepest point on the nasion saddle; SfRo – soft rhinion: most anterior point on the nose; LaNa – labio-nasal junction: point where the nose and the upper lip meet; SfA – soft tissue A: innermost point on the curve on the upper lip; Ls – labial superioris: anterior-most point on the upper lip; Em – embrasure: most anterior point where upper and lower lips meet; Li–labial inferioris: anterior-most point on the lower lip; SfB – soft tissue B: innermost point on the curve below the lower lip; SfPo – soft pogonion: anterior-most point on the chin; SfM – soft menton: inferior-most point on the chin; Go – gonion: point at the inferior–posterior aspect of the mandible; CH – condyle head: point at the apex of the condylar head.

Procrustes superimposition

For shape-analysis, each group was subjected to Procrustes superimposition using a generalized rotational fit program (24), and represented as a mean configuration. Following this method, every object's co-ordinates were translated, rotated and scaled iteratively until the least-squares fit of all configurations was no longer improved. Therefore, all configurations were registered with respect to one another, and as a result of this procedure, geometric configurations were scaled to equivalent areas, avoiding problems introduced by differences in size.

Euclidean distance matrix analysis (EDMA)

Because of the likelihood of inequality of the variance–covariance matrices of the samples, the soft-tissue configurations were compared also using EDMA (25). This is a co-ordinate free, statistical procedure for the comparison of two forms, using all possible linear distances between homologous landmarks. Form-matrices were constructed for the numerator and denominator configurations. The EDMA compared these matrices, and the form difference matrix generated allowed determination of the way in which the two shapes differed, by identifying those linear distances that were the most and least different among the forms being compared (26). The EDMA has been successfully employed in several biological and clinical studies (27–29). Using a newer EDMA procedure (25), the assumption of equality of variance–covariance matrices is bypassed. Therefore, distances between homologous landmarks were calculated and EDMA matrices formed for the soft-tissue configurations. Corresponding linear distance matrices were compared and statistical significance of form difference was tested by the non-parametric bootstrap method (26).

Thin plate spline (TPS)

Although EDMA is a useful technique, the tabulated output can make the findings somewhat arduous to interpret. In contrast, TPS presents results graphically as transformation grids conceptualized by Thompson (23), and somewhat analogous to those of the mesh diagram analysis (30). Thus, soft-tissue configurations of the mean forms were subjected to TPS using appropriate software (31), and transformation grids of the total deformation (TPS) were decomposed into a series of partial warps (PWs). The TPS can be thought of as a thin sheet of steel extending infinitely in all directions; deformations represented by it describe the transformation from one form to that of the other. The displacements required for the (x, y) landmark data are represented in the z plane. The minimum net bending energy required to match the homologous landmarks for the chosen comparison depicts the function describing those changes. The superimposed grid allows visualization of the transformation of the areas around the landmarks (32).

The total spline consists of affine and non-affine transformations (complementary subspaces). The affine changes are a representation of size-difference and rotational changes, requiring no bending energy, and having a uniform effect on the entire shape. The non-affine transformations are representations of non-uniform shape changes, and can be described in terms of PWs. The PWs are defined as being auxiliary representations of shape-change in sets of landmarks. They are eigenvectors of the bending energy matrix, and as such are weighted descriptions of local deformations. There are three fewer PWs than the number of homologous landmarks digitized (32). In this way, TPS transformations are geometric descriptions of shape-change, ranging from the entire form to specific localized changes. Eigenvalues, magnitudes and bending energies are reported when classifying partial warp contributions to the total non-affine changes. High eigenvalues are indicative of very localized changes of high bending energy. Magnitude indicates the importance of the PW (the higher magnitude, the more importance it has), and the bending energy is the product of its magnitude and eigenvalue. The terms used in this paper are in accord with the NATO ASI series (33).

Results

On the whole the results for cephalometry, EDMA and TPS analysis broadly complemented each other.

Cephalometry

Cephalometric results are shown in Table 1. The male prepubertal group (Table 1A) showed significant length increases in all upper facial heights measured, with significant decreases in length occurring in the midfacial region [labial superioris (Ls)–labial inferioris (Li) and Li–embrasure (Em) decreased by ≈18 and ≈20%, respectively]. Significant increases occurred also in the lower facial area [Li–soft tissue B (SfB) increased by ≈16%] but Li–soft menton (SfM) remained unchanged.

The male adolescent group (Table 1A) showed few significant length changes. In the upper facial region only soft glabella (SfGl)–soft rhinion (SfRo) increased in length by ≈5%, while height decreases occurred in the midfacial region (Ls–Em and Em–Li decreased by ≈18 and ≈20%, respectively), and the lower facial area remained unchanged.

For prepubertal females (Table 1B), significant length increases occurred in all upper facial heights measured, but only one significant decrease in length was seen in the midfacial area (Ls–Li decreased by ≈14%). In the lower facial area, Li–SfB increased in length by ≈10% and Li–SfM also increased in length.

The adolescent female group (Table 1B) showed significant length increases in all upper facial heights measured, while decreases occurred in the midfacial region (Ls–Li and Ls–Em both decreased by ≈9%). A length increase occurred also in the lower facial area (i.e. Li–SfB increased by ≈14%).

Overall, the cephalometry results indicate that length changes for the prepubertal groups were similar to those in the adolescents. The largest height increases associated with the TBA were in the labiomental areas, particularly Li–SfB, and the most significant height decreases were seen in the midfacial region, especially

Table 1. **Soft-tissue cephalometry**

		Prepubertal			Adolescent		
		Pre-treatment	Post-treatment	*P*-value	Pre-treatment	Post-treatment	*P*-value
(A) Males treated with TBA							
Upper facial heights	SfGl–SfRo	40.2 + 0.26	42.7 + 0.37	0.02017	42.0 + 0.35	44.4 + 0.32	0.00098
	SfNa–SfRo	31.8 + 0.25	33.6 + 0.28	0.01233	33.1 + 0.34	36.3 + 0.27	NS
	SfRo–Ls	18.0 + 0.28	20.9 + 0.19	0.00885	19.9 + 0.28	22.5 + 0.26	NS
Midfacial heights	LaNa–SfA	3.5 + 0.11	3.3 + 0.09	NS	3.0 + 0.10	3.2 + 0.07	NS
	Ls–Li	15.3 + 0.29	12.4 + 0.021	0.00017	16.9 + 0.34	13.1 + 0.09	NS
	Ls–Em	8.2 + 0.19	6.5 + 0.12	0.00018	8.9 + 0.17	7.6 + 0.12	0.00459
	Em–Li	8.4 + 0.19	7.6 + 0.15	0.02747	9.1 + 0.19	8.0 + 0.10	0.00463
Lower facial heights	Li–SfB	6.4 + 0.14	7.6 + 0.12	0.00595	6.7 + 0.13	8.1 + 0.16	NS
	Li–SfPo	11.5 + 0.43	18.1 + 0.27	0.00763	16.1 + 0.19	19.2 + 0.27	NS
	Li–SfM	24.5 + 0.26	27.4 + 0.20	NS	25.7 + 0.23	29.4 + 0.27	NS
(B) Females treated with TBA							
Upper facial heights	SfGl–SfRo	40.4 + 0.34	41.7 + 0.29	0.00074	42.2 + 0.38	43.7 + 0.34	0.00119
	SfNa–SfRo	32.4 + 0.30	33.6 + 0.25	0.00657	34.1 + 0.27	35.7 + 0.30	0.00167
	SfRo–Ls	19.7 + 0.26	20.6 + 0.18	0.00735	20.3 + 0.20	21.4 + 0.23	0.00090
Midfacial heights	LaNa–SfA	2.8 + 0.07	3.0 + 0.06	NS	3.0 + 0.06	2.9 + 0.07	NS
	Ls–Li	15.6 + 0.35	13.3 + 0.19	0.0014	15.7 + 0.30	14.3 + 0.23	0.00402
	Ls–Em	8.8 + 0.17	7.2 + 0.10	NS	17.9 + 0.25	8.1 + 0.13	0.00674
	Em–Li	8.6 + 0.20	8.0 + 0.13	NS	8.2 + 0.23	8.2 + 0.13	NS
Lower facial heights	Li–SfB	6.7 + 0.16	7.4 + 0.15	0.00634	6.5 + 0.11	7.5 + 0.14	0.00050
	Li–SfPo	16.8 + 0.22	17.2 + 0.29	NS	16.8 + 0.23	19.0 + 0.15	NS
	Li–SfM	25.1 + 0.25	26.7 + 0.16	0.00052	24.7 + 0.24	27.0 + 0.20	NS

Mean lengths (mm + SD).

in the lip regions (Ls–Li, Ls–Em and Em–Li). Significant height increases were also seen in the upper facial area, particularly SfRo–Ls in prepubertal males in which there was an increase of ≈14%.

Euclidean distance matrix analysis

The results of EDMA also indicated that significant changes ($P < 0.05$) in overall interlandmark distances occurred in the mid- and lower-facial heights for all patient groups treated with the TBA. (If no difference exists between two landmarks, the relevant form difference matrix value would be 1.00. Consequently, values of >1 or <1 indicate that distances between landmarks differ in size. For example, a value of 1.15 indicates that the numerator configuration distance is 15% longer than that of the denominator configuration.) The results are summarized in Tables 2 and 3.

For prepubertal males (Table 2), the parameters Ls–Em, Ls–Li and Em–Li decreased by ≈18, ≈17 and ≈10%, respectively. For prepubertal females (Table 3), those parameters decreased by ≈18, ≈15 and ≈7%, respectively. For adolescent males (Table 2), the parameters Ls–Em, Ls–Li and Em–Li decreased by ≈14, ≈18 and ≈13%, respectively. For adolescent females (Table 3), those parameters decreased by and ≈9, ≈9 and ≈3%, respectively. Thus, decreases in length occurred mainly in the midfacial region, i.e. in most groups the distance between the lips decreased by more than ≈5%.

In contrast, increases in lengths were seen in the labiomental region. For prepubertal males (Table 2), these increases in length were ≈18% [Li–SfB and Li–soft pogonion (SfPo)] and ≈10% for Li–SfM. For prepubertal females (Table 3), these increases in length were ≈11–8% for Li–SfB, Li–SfPo and Li–SfM, respectively. In adolescent males (Table 2), these increases in length were ≈24–21% for Li–SfB and Li–SfPo, respectively, and ≈14% for Li–SfM. For adolescent females (Table 3), these increases in length were ≈18–12% for Li–SfB and Li–SfPo, respectively, and ≈9% for Li–SfM. Thus, all treatment groups showed increased lengths between the lower lip and the inner most curve below the lower lip (Li–SfB), indicating that the lower lip had moved towards the upper lip, and the profile of the lower lip had become straighter.

Thin plate spline analysis

The soft-tissue spline transformations, corresponding to the affine and non-affine components can be seen in Figs 2 and 3, and the contributing PWs in Table 4. For the prepubertal males (Fig. 2A), the affine component showed a clockwise rotation, indicating that the soft-tissue profile had undergone an antero-inferior displacement. The non-affine component showed deformation of the labiomental complex, affecting particularly the lower lip (Li–SfB region). Partial warp 7 had the highest magnitude (Table 4) and indicated some elongation of the anterior aspect of the soft-tissue configuration.

For the adolescent males (Fig. 2B), the affine component showed a more marked clockwise rotation, indicating that the soft-tissue profile underwent an antero-inferior displacement. The non-affine component showed deformation of the labiomental complex, affecting the lower lip and chin (Li–SfM region). Partial warp 3 had the highest magnitude (Table 4) and indicated a more noticeable supero-inferior elongation of the anterior aspect of the soft-tissue configuration.

For the prepubertal females (Fig. 3A), the affine component showed a slight clockwise rotation, indicating that the soft-tissue profile had undergone a small antero-inferior displacement. The non-affine component showed deformation of the labiomental complex, affecting the upper lip [labio-nasal junction (LaNa)–SfM region]. Partial warp 9 had the highest magnitude (Table 4) and indicated some antero-inferior elongation of the soft-tissue configuration.

For the adolescent females (Fig. 3B), the affine component showed clockwise rotation, indicating that the soft-tissue profile had undergone an antero-inferior stretch. The non-affine component showed deformation of the nasolabial complex, particularly affecting the upper lip (SfRo–Li region). Partial warp 7 had the highest magnitude (Table 4), and indicated some elongation of the anterior aspect of the soft-tissue configuration.

Discussion

In the past, to assess the post-treatment changes following orthodontic treatments, many studies have

***Table 2.* Male soft-tissue form matrices (sorted) (shaded areas represent changes >5%)**

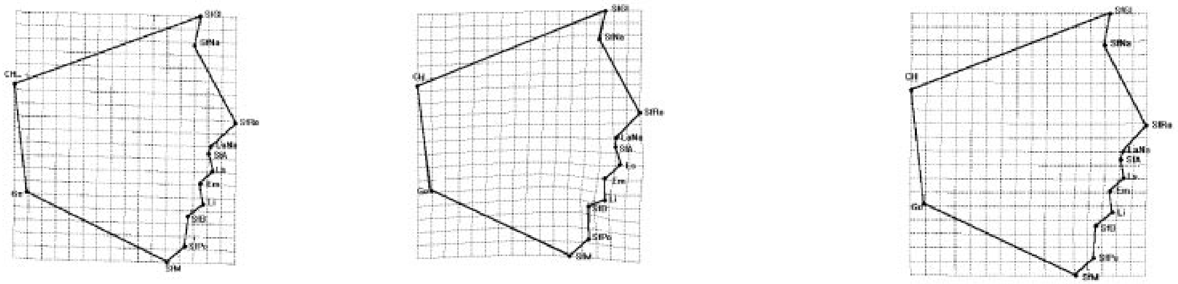
Prepubertal			Adolescent		
Ls	Em	0.825	Ls	Li	0.828
Ls	Li	0.836	Ls	Em	0.869
Em	Li	0.909	Em	Li	0.874
LaNa	SfA	0.912	SfA	Li	0.920
LaNa	Li	0.924	LaNa	Li	0.932
SfA	Li	0.926	Ls	SfB	0.974
SfRo	Li	0.941	SfA	Em	0.984
LaNa	Em	0.949	SfRo	Li	0.985
SfA	Em	0.957	LaNa	Em	0.995
Ls	SfB	0.959	Ls	Go	1.007
SfPo	SfM	0.975	Ls	SfPo	1.018
SfRo	Em	0.975	LaNa	SfA	1.018
SfRo	SfB	0.999	SfA	Go	1.018
Ls	SfM	0.999	Ls	SfM	1.019
Ls	Go	0.999	Ls	CH	1.019
SfNa	Li	1.000	Em	Go	1.020
LaNa	SfB	1.003	SfGl	Li	1.021
LaNa	Go	1.007	SfNa	Li	1.021
SfA	Go	1.007	SfNa	CH	1.023
SfRo	SfA	1.008	SfA	CH	1.023
SfRo	SfM	1.009	LaNa	Go	1.023
Ls	SfPo	1.010	Em	CH	1.026
SfGl	Li	1.012	LaNa	CH	1.027
LaNa	SfM	1.012	SfGl	CH	1.027
SfA	SfB	1.012	SfA	SfB	1.028
Ls	CH	1.013	SfGl	SfNa	1.029
LaNa	Ls	1.013	LaNa	SfB	1.032
SfRo	SfPo	1.014	Li	CH	1.033
SfRo	Go	1.015	SfA	SfM	1.040
SfA	CH	1.015	Li	Go	1.040
SfNa	Em	1.015	SfPo	SfM	1.040
LaNa	CH	1.016	LaNa	SfM	1.041
Em	Go	1.018	SfPo	Go	1.041
SfA	SfM	1.018	SfNa	Go	1.042
SfGl	CH	1.019	LaNa	SfPo	1.042
LaNa	SfPo	1.021	SfA	SfPo	1.042
SfNa	CH	1.021	SfB	Go	1.043
SfRo	Ls	1.023	SfRo	CH	1.044
SfRo	CH	1.023	SfGl	Em	1.044
Em	CH	1.023	SfGl	Go	1.044
SfNa	SfA	1.025	SfRo	Go	1.045
SfNa	Go	1.025	SfM	Go	1.045
SfB	SfM	1.026	SfNa	Em	1.047
SfGl	Em	1.027	SfB	SfPo	1.050
SfGl	Go	1.028	SfRo	SfB	1.052
SfB	SfPo	1.028	SfRo	SfM	1.052
SfPo	Go	1.029	SfB	SfM	1.053
SfNa	Ls	1.030	SfRo	SfPo	1.053
SfA	SfPo	1.031	SfB	CH	1.053
SfNa	SfM	1.031	LaNa	Ls	1.053
Li	CH	1.031	SfPo	CH	1.053
SfRo	LaNa	1.034	SfRo	Em	1.055
SfNa	LaNa	1.035	SfGl	SfA	1.055
SfNa	SfPo	1.035	SfGl	SfM	1.056
SfNa	SfB	1.036	SfGl	SfPo	1.056
SfGl	SfM	1.036	SfGl	SfB	1.057
Li	Go	1.037	SfM	CH	1.057
SfM	Go	1.038	SfGl	Ls	1.059
SfGl	SfA	1.039	SfNa	SfM	1.059
SfPo	CH	1.040	SfGl	LaNa	1.059
SfGl	SfPo	1.040	Em	SfM	1.060
SfGl	SfB	1.042	SfNa	SfPo	1.060
Em	SfM	1.042	SfNa	SfB	1.062
SfGl	Ls	1.042	SfNa	SfA	1.062
SfB	Go	1.043	SfNa	Ls	1.065
SfM	CH	1.044	SfGl	SfRo	1.067
SfNa	SfRo	1.047	Em	SfB	1.067
SfGl	LaNa	1.048	SfNa	LaNa	1.068
SfB	CH	1.050	SfA	Ls	1.071
Go	CH	1.055	Em	SfPo	1.076
SfA	Ls	1.058	Go	CH	1.079
Em	SfB	1.061	SfNa	SfRo	1.085
SfGl	SfRo	1.063	SfRo	Ls	1.121
Em	SfPo	1.070	SfRo	SfA	1.128
SfGl	SfNa	1.077	SfRo	LaNa	1.139
Li	SfM	1.104	Li	SfM	1.141
Li	SfPo	1.183	Li	SfPo	1.211
Li	SfB	1.188	Li	SfB	1.249
$P < 0.05$			$P < 0.01$		

used cephalometry. One disadvantage of cephalometry is that it does not provide rigorous analysis of shape-change (34), and measurement errors can vary greatly with any given landmark (35). Moreover, cephalometry does not take size variation into consideration and is perhaps a relatively inappropriate method

***Table 3.* Female soft-tissue form matrices (sorted) (shaded areas represent changes >5%)**

Prepubertal			Adolescent		
Ls	Em	0.820	Ls	Em	0.910
Ls	Li	0.857	Ls	Li	0.915
SfA	Li	0.915	SfA	Li	0.962
SfA	Em	0.916	LaNA	Li	0.964
Ls	SfB	0.931	LaNA	SfA	0.965
Em	Li	0.934	SfA	Em	0.975
LaNa	Li	0.935	LaNA	Em	0.978
LaNa	Em	0.946	Em	Li	0.978
SfRo	Li	0.961	SfRo	Li	0.985
SfA	SfB	0.963	LaNA	Ls	0.991
LaNa	SfB	0.976	Ls	Go	0.998
Ls	SfPo	0.976	SfGl	SfNa	0.999
SfRo	Em	0.983	Ls	CH	1.002
Ls	SfM	0.988	SfA	Go	1.004
SfA	SfPo	0.989	Ls	SfB	1.004
SfRo	SfB	0.989	SfA	CH	1.004
SfA	Ls	0.995	LaNA	CH	1.008
LaNa	SfPo	0.995	LaNA	Go	1.008
SfA	SfM	0.998	SfNa	CH	1.008
SfGl	SfNa	0.999	Em	Go	1.009
Ls	Go	0.999	SfB	SfPo	1.010
SfRo	SfPo	1.001	Em	CH	1.011
SfGl	Li	1.002	SfGl	Li	1.012
SfNa	Li	1.003	SfGl	CH	1.012
LaNa	SfM	1.003	SfA	Ls	1.013
SfA	Go	1.006	SfNa	Li	1.015
SfRo	SfM	1.007	SfRo	Em	1.015
LaNa	Go	1.009	SfPo	SfM	1.018
Em	SfB	1.010	SfGl	Em	1.018
Ls	CH	1.012	SfRo	CH	1.020
SfRo	Go	1.013	Li	CH	1.021
SfGl	Em	1.013	Ls	SfM	1.022
SfGl	SfB	1.015	SfNa	Em	1.022
SfNa	Em	1.016	SfRo	Go	1.022
SfGl	CH	1.016	SfGl	Ls	1.023
SfNa	SfB	1.017	SfPo	Go	1.023
SfGl	SfPo	1.017	SfGl	SfA	1.023
SfA	CH	1.018	SfB	SfM	1.024
LaNa	CH	1.018	Li	Go	1.025
SfGl	Go	1.019	Ls	SfPo	1.026
Em	Go	1.019	SfNa	Go	1.027
SfNa	SfPo	1.020	SfM	Go	1.027
SfRo	CH	1.020	LaNA	SfM	1.028
SfNa	CH	1.020	SfGl	Go	1.028
SfGl	SfM	1.020	SfNa	Ls	1.028
SfPo	Go	1.021	SfGl	LaNA	1.028
SfNa	Go	1.021	SfRo	SfM	1.029
Em	CH	1.022	LaNA	SfB	1.029
LaNa	Ls	1.023	SfRo	SfB	1.029
SfNa	SfM	1.023	SfRo	SfPo	1.029
Li	CH	1.023	SfNa	SfA	1.029
SfM	Go	1.025	SfA	SfM	1.030
Em	SfPo	1.026	SfB	Go	1.030
SfPo	CH	1.026	LaNA	SfPo	1.030
Li	Go	1.027	SfA	SfB	1.031
SfB	Go	1.027	SfPo	CH	1.033
SfB	CH	1.029	SfGl	SfPo	1.034
SfM	CH	1.030	SfGl	SfM	1.034
SfB	SfPo	1.030	SfA	SfPo	1.034
Em	SfM	1.031	SfGl	SfRo	1.035
SfGl	Ls	1.031	SfNa	LaNA	1.036
SfGl	LaNa	1.032	SfM	CH	1.037
SfGl	SfRo	1.033	SfGl	SfB	1.037
SfGl	SfA	1.034	SfB	CH	1.037
SfRo	LaNa	1.035	SfNa	SfM	1.037
SfNa	Ls	1.035	SfNa	SfPo	1.038
SfPo	SfM	1.036	SfNa	SfB	1.043
SfNa	SfRo	1.037	SfRo	Ls	1.048
Go	CH	1.037	SfNa	SfRo	1.049
SfNa	LaNa	1.039	Em	SfM	1.051
SfNa	SfA	1.041	Go	CH	1.059
SfB	SfM	1.044	SfRo	SfA	1.063
SfRo	SfA	1.045	Em	SfPo	1.065
SfRo	Ls	1.048	SfRo	LaNA	1.071
Li	SfM	1.072	Em	SfB	1.088
LaNa	SfA	1.079	Li	SfM	1.092
Li	SfPo	1.085	Li	SfPo	1.126
Li	SfB	1.109	Li	SfB	1.180
$P < 0.01$			$P < 0.01$		

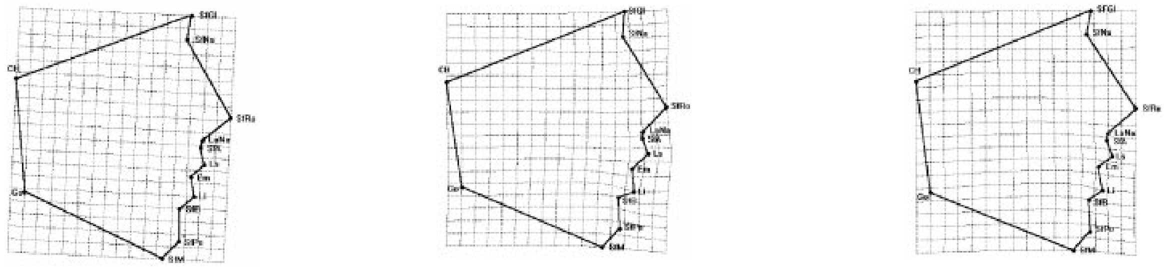
of shape-analysis; traditional cephalometric measures do not represent growth patterns well (36). In view of this deficiency, geometric morphometrics have become useful as they facilitate experimental hypothesis testing (8–11, 19). Accordingly, working in statistical shape-spaces (37), modelling and simulation based on mathematical computing is one approach to meet these



A Affine spline. Indicating antero-inferior displacement of the soft-tissue configuration

Non-affine spline. Indicating anterior displacement and vertical elongation of the soft-tissue configuration

PW7 Indicating antero-inferior displacement of soft-tissue configuration



B Affine spline. Indicating antero-inferior displacement of soft-tissue configuration

Non-affine spline. Indicating anterior displacement and elongation of soft-tissue configuration with localized changes occuring in the midfacial region

PW3 Indicating antero-inferior displacement of soft-tissue configuration

Fig. 2. (A) Soft-tissue profile changes in prepubertal males following twin block appliance treatment shown by thin plate spline analysis. The partial warp of greatest magnitude is also shown. (B) Soft-tissue profile changes in adolescent males following TBA treatment shown by thin plate spline analysis. The partial warp of greatest magnitude is also shown.

needs. Indeed, morphospatial analysis is becoming increasingly important, as experience is showing that the application of geometric morphometric techniques is robust in terms of orthodontic conclusions.

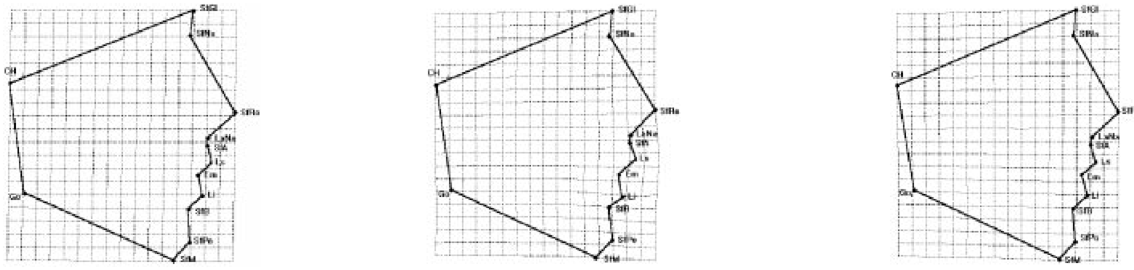
There are a number of morphometric techniques available for the study of shape-change (33), and in this study Procrustes superimposition, EDMA and TPS analysis were utilized. These techniques have their individual advantages and disadvantages. For example, superimposition-based techniques attempt to recreate vectors that depict form-change, commonly using the Procrustes distance as a measure of proximity of landmarks. Although some are of the opinion that superimposition techniques and transformation grids cannot recreate the true form change even under conditions of parsimony, others believe that Procrustes-based approaches can be justified through isotropic models. Similarly, EDMA satisfies invariance requirements, provides information about landmarks that are important in form-changes, and while it was used for drawing biological conclusions in this present study, EDMA can be sensitive to outliers (25). Thus, we also used TPS analysis to describe form differences in terms of deformation of the space in the vicinity of a reference specimen into that of a target specimen. While TPS analysis is able to provide graphical representations of the form-changes, the mathematical complexity of the technique hinders its use. Nevertheless, localization of form differences is an important concept in quantitative orthodontic morphospatial analysis. Therefore, to quantify soft-tissue profile changes in patients treated with the TBA for the correction of Class II division 1 malocclusion, a combination of geometric morphometric techniques was used in this study.

Functional appliances are frequently used in the treatment of Class II division 1 malocclusions, and there is extensive speculation on their growth-restraining effect on the maxilla, growth-enhancing effect on the mandible, as well as their dento-alveolar and soft-tissue effects (38). Animal experiments involving mandibular displacement show that skeletal form is adaptable to a functional stimulus (39) but studies in human growth are less conclusive, as they are largely based on ceph-

A Affine spline. Indicating a small antero-inferior displacement of soft-tissue configuration

Non-affine spline. Indicating anterior displacement and vertical elongation of soft-tissue configuration with localized changes in the mid- and lower facial regions

PW9 Indicating vertical elongation of soft-tissue configuration



B Affine spline. Indicating antero-inferior displacement of soft-tissue configuration

Non-affine spline. Indicating vertical elongation of soft-tissue configuration

PW7 Indicating anterior displacement of lower facial soft-tissue configuration (Ls and Em)

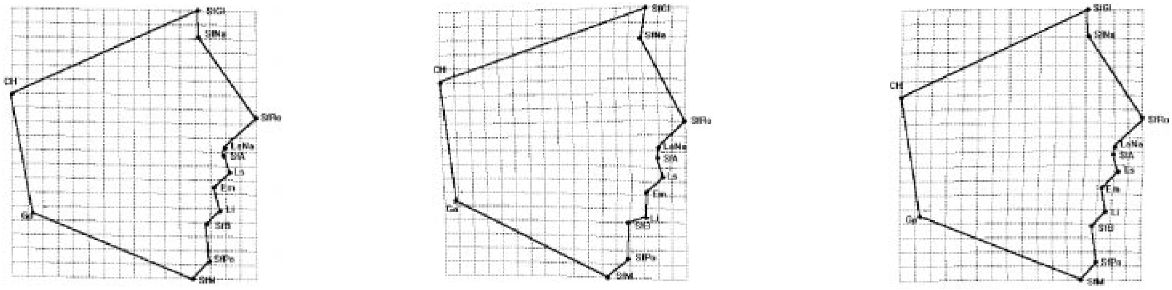


Fig. 3. (A) Soft-tissue profile changes in prepubertal females following twin block appliance shown by thin plate spline analysis. The partial warp of greatest magnitude is also shown. (B) Soft-tissue profile changes in adolescent females following TBA shown by TSP analysis. The partial warp of greatest magnitude also shown.

alometric analysis (40, 41). Currently, however, there is dearth evidence for the overall benefits of using a functional appliance. Moreover, patient co-operation is important for this study, as the true effects of TBA treatment can be observed only if the appliance is worn correctly for the specified lengths of time. From the clinical records, it was assumed that the TBA was worn as prescribed, and this included the use of extra-oral traction in all groups. Indeed, for the groups treated with TBA treatment in this current study, cephalometric evaluation of the data showed that length increases occurred in upper and lower facial regions, while height decreases occurred in the midfacial(lip) areas.

For the upper facial heights measured, significant increases occurred in nearly all groups measured (Table 1). These findings reflect those of an earlier study (42) that showed increased projection of the nose in untreated cases, even though the relationship of the nose, lips and chin remained relatively independent of the underlying skeletal growth. In contrast, for late adolescent males, a later study (43) reported that continued change of the soft tissue profile was the result of underlying skeletal growth, while a more recent study noted that chin form was influenced by skeletal morphology rather than by incisor position (44). Therefore, it seems likely that the nasolabial profile may be related to several interacting factors, which may be amenable to functional appliance treatments, such as TBA, that aim to produce a more balanced soft-tissue profile.

In this study, EDMA and TPS indicated that significant changes occurred in the mid- and lower-facial areas in patients treated with the TBA. The most significant height decreases as shown by EDMA were seen in the midfacial region, with the largest decreases occurring around the lower lip area. This finding was similar in all groups treated with the TBA, and indicates that TBA treatment is allowing the lips to be brought closer together, presumably resulting from the

***Table 4.* Partial warps (PWs) contributing to soft-tissue transformations following treatment with twin block appliances (TBA). PWs making the greatest contribution to the non-affine spline are shown in bold type. The total bending energies for male prepubertal, male adolescent, female prepubertal, and female adolescent are 0.019, 0.022, 0.007 and 0.011, respectively**

	Partial warp	Eigenvalue	Energy (× 10^{-3})	Magnitude (× 10^{-4})
Male prepubertal	2	12.69	2.31	0.18
	3	9.79	5.55	5.66
	4	5.99	2.79	4.66
	5	3.73	1.92	5.16
	6	2.09	0.47	2.26
	7	**1.46**	**1.00**	**6.80**
	8	0.62	0.16	2.52
	9	0.27	0.14	5.34
	10	0.14	0.06	4.12
Male adolescent	1	54.50	0.31	0.06
	2	11.88	7.08	5.95
	3	**10.02**	**8.78**	**8.76**
	4	5.58	2.00	3.58
	5	3.99	2.13	5.34
	6	2.87	2.56	0.89
	7	1.43	1.16	8.15
	8	0.59	0.46	7.79
	9	0.26	0.19	7.17
	10	0.15	0.09	6.15
Female prepubertal	1	50.39	0.18	0.04
	2	11.59	3.94	3.40
	3	9.82	0.65	0.67
	4	5.42	0.87	1.61
	5	3.98	0.09	0.22
	6	2.65	0.43	1.61
	7	1.43	0.52	3.63
	8	0.58	0.16	2.68
	9	**0.26**	**0.19**	**7.24**
	10	0.14	0.07	4.76
Female adolescent	1	61.69	3.07	0.50
	2	12.27	3.63	2.96
	3	10.24	0.28	0.27
	4	5.96	0.70	1.18
	5	4.50	1.01	2.24
	6	3.12	0.32	1.03
	7	**1.42**	**1.51**	**10.70**
	8	0.59	0.34	5.83
	9	0.29	0.15	5.29
	10	0.15	0.14	9.45

repositioning of the incisors and permitting the formation of a functional oral seal. This is an important finding because in Class II division 1 malocclusion the lips are often not in contact as the maxilla protrudes over the mandible, sometimes trapping the upper incisors. Indeed, it has been suggested that treatments that exert a growth-inhibiting effect on the maxilla should be used in such Class II cases (45). Thus, these comparisons indicate that functional appliances, such as TBA treatments, may be associated with a more favourable soft-tissue pattern, and that the magnitude of decrease in lip separation is similar in younger and older groups.

In contrast to the midfacial findings, the lower facial regions showed an increase in height. The EDMA indicated that the most significant increases occurred between the lower lip (Li) and SfB, which is located in the labiomental fold (Fig. 1). In untreated Class II division 1 malocclusions the labiomental fold can be rather pronounced, especially when compared to a normal Class I occlusion. This feature may be because of the position of the mandibular symphysis in relation to the lips (44) or it may reflect the inclination of the lower incisors. The parameter Li–SfB increased in length, presumably because the TBA treatment was associated with an antero-inferior displacement of the soft-tissues, and thereby stretched the distance between Li and SfB. This change might also be expected to occur if the mandibular symphysis was increasing in height, especially with repositioning of the lower incisors such that the labiomental groove would become less pronounced.

The pattern of deformation for each of the transformation grids was relatively similar for each treatment group (Figs 2A,B and 3A,B). Each grid showed evidence of the soft-tissues of the mandibular symphysis complex (SfB–SfM) being displaced antero-inferiorly. Anterior displacement of the landmarks of the lip region (Ls, Em and Li) was evident also. The upper facial region appeared to remain relatively similar in all groups.

Moreover, the TPS analysis indicated a localized stretch in the SfB area (Figs 2A,B and 3A,B), reflecting the dento-alveolar effects on the labiomental fold. These findings support an earlier study (46), which claimed that the use of the TBA resulted in growth changes, including improvements in mandibular length, facial height and facial convexity. It is also recognized that TBA treatment achieves correction of Class II malocclusion through some dento-alveolar effects. For example, it has been reported that dento-alveolar effects contribute to overjet correction (47). Similarly, others noted overjet reduction through improvement in dental base relationship (48), while some reported that overjet reduction was achieved by maxillary incisor retroclination (49). Similarly, a reduction in upper incisor angle has been reported following TBA treatment (50) while others reported retroclination of the maxillary incisors (51). Therefore, the flattening of labiomental fold demonstrated here using a combination of morphospatial analyses is likely to be associated, at least in part, with incisor correction as well as changes in the mandibular symphysis region. This current study provides the premise for future research; highlighting the need for three-dimensional soft-tissue morphometry (52) using advanced imaging techniques, such as digital stereophotogrammetry.

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