

Article

History of Mandibular Advancement Treatment Is Associated with Cranio-Cervico-Hyoid Biomechanical Alterations in Young Women with Class II Division 1 Malocclusion: An Exploratory Cross-Sectional Study

Perla Evanthia Lioudaki ¹, Sara Di Nicolantonio ^{1,2,*} , Maria Ausilia D'Angelo ¹, Marco Strada ³, Annalisa Monaco ¹, Ruggero Cattaneo ¹, Federico Basile ¹ and Eleonora Ortu ¹ 

¹ Department of Life, Health & Environmental Sciences, University of L'Aquila, 67100 L'Aquila, Italy

² Department of Medicine, School of Medicine, Case Western Reserve University, Cleveland, OH 44106, USA

³ SOMA, Istituto Osteopatico, 20126 Milano, Italy

* Correspondence: sara.dinicolantonio@graduate.univaq.it

Abstract

Background: Orthodontic treatment is widely performed in young populations, yet its post-treatment functional associations beyond dental occlusion remain poorly understood. The cranio-cervico-hyoid complex plays a central role in posture, swallowing, and airway function, and may be sensitive to developmental or treatment-related influences. This study investigated whether, among otherwise healthy young women with a diagnosis of Class II division 1 malocclusion, a history of orthodontic treatment with mandibular advancement is associated with altered passive mobility of this system. **Methods:** A cross-sectional observational study was conducted on 170 women aged 18–30 years with a diagnosis of Class II division 1 malocclusion (104 treated with mandibular advancement for 6–12 months (ortho group); 66 with the same diagnosis who had never undergone orthodontic treatment (ctrl group)). Anthropometric, epidemiological, clinical, and psychosocial variables were collected, including VAS, FIQR, CSI, and DASS-42. Passive mobility of the hyoid bone, C0–C1, and C2–C3 segments (primary outcome) was assessed by an experienced blinded examiner. Group differences were analyzed using chi-square, Fisher's exact test, Welch's *t* test, or Wilcoxon tests, with effect sizes and multiple-comparison corrections (Benjamini–Hochberg and Bonferroni). At the time of examination, all treated participants presented Class I occlusion, whereas all controls retained Class II division 1 malocclusion. **Results:** Groups were comparable in baseline anthropometric and epidemiological characteristics. The orthodontic group reported higher FIQR scores and greater pain intensity on the VAS, although these differences did not remain significant after multiple-comparison correction. Marked biomechanical differences emerged: reduced passive mobility of the hyoid bone, C0–C1, and C2–C3 was significantly more frequent in orthodontically treated subjects, with moderate to strong effect sizes. The composite variable “at least one dysfunction” was present in 74% of orthodontic subjects versus half of controls. These associations remained significant after multiple-comparison correction. Because all treated participants had been corrected to Class I while all controls remained in Class II division 1, the effect of treatment could not be separated from that of the corrected occlusion. **Conclusions:** Young women with Class II division 1 malocclusion previously treated with mandibular advancement showed a higher prevalence of altered passive mobility of the cranio-cervico-hyoid complex, and differences in cervical pain intensity and functional impact were small and did not remain significant after multiple-comparison correction. Because treatment history and current occlusion were completely confounded, the findings cannot establish



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whether these differences are attributable to mandibular advancement, occlusal correction, or pre-existing factors. Given the cross-sectional design and the lack of consistent data on retention period and exact time since treatment completion, these findings should be interpreted as post-treatment associations rather than causal or long-term effects. Further longitudinal studies are needed to clarify the temporal relationship and clinical relevance of these alterations.

Keywords: orthodontic treatment; Class II division 1 malocclusion; mandibular advancement; cranio-cervico-hyoid complex; cervical biomechanics; hyoid bone; musculoskeletal function; dental occlusion

1. Introduction

Orthodontic consensus holds that malocclusion affects dental–maxillofacial function, facial aesthetics, and long-term craniofacial development, and may also influence the psychosocial well-being of children. For these reasons, the need for early orthodontic intervention has been strongly emphasized [1].

Class II division 1 malocclusion is a frequent indication for orthodontic treatment in growing patients and is commonly managed with appliances that advance the mandible. Beyond their dentoalveolar and skeletal effects, these appliances act on a region in which mandibular, hyoid, and cervical structures are mechanically interdependent, and systematic evidence indicates that functional appliance therapy is associated with small changes in cervical spine posture [2]. By contrast, most outcome research has focused on aesthetic and occlusal results, whose magnitude remains debated [3,4].

Far less attention has been devoted to post-treatment functional associations of orthodontic interventions, particularly regarding cranio-cervical biomechanics. The cranio-cervico-hyoid system is a highly dynamic anatomical region essential for posture, swallowing, and airway function, and alterations in its biomechanics may have clinical implications extending beyond dental occlusion [5,6].

The available evidence addresses distinct, although related, domains. First, static craniocervical posture, usually assessed cephalometrically, has been associated with sagittal skeletal malocclusion [7]. Second, hyoid bone position and upper airway dimensions have been described in patients with temporomandibular disorders and in growing patients treated with functional appliances [8,9]. Third, the biomechanical interdependence of cranial, cervical, and hyoid structures has been documented, particularly in relation to head posture [10,11]. Fourth, postural and functional musculoskeletal outcomes have been examined in orthodontically treated young adults [12], and meta-analytic evidence also indicates that orthodontic treatment can influence masticatory muscle activity, either positively or negatively [13,14].

The active range of motion of the upper cervical spine has been extensively studied in both healthy individuals and those with musculoskeletal disorders [15–17]. Physiotherapeutic techniques for assessing passive mobility of the upper cervical spine and the hyoid bone are well established and widely used in clinical practice [18–20]. These methods consistently demonstrate reduced passive range of motion with increasing age and in the presence of musculoskeletal dysfunction, pain, or cervicogenic dizziness [21,22].

Applying these techniques to young, otherwise healthy subjects may help identify early biomechanical dysfunctions affecting upper cervical and hyoid mobility. However, these domains have rarely been examined together and, to our knowledge, passive cranio-cervico-hyoid mobility, as distinct from static posture, hyoid position, or muscle activity, has not been compared between individuals sharing the same original diagnosis of Class II

division 1 malocclusion who did or did not undergo mandibular advancement treatment. The novelty of the present study therefore lies in the combination of a diagnostically homogeneous population, a defined treatment history, and a functional biomechanical outcome (passive mobility), rather than in any one of these elements alone.

It was investigated whether, in young women sharing the same diagnosis of Class II division 1 malocclusion, a history of orthodontic treatment with mandibular advancement was associated with measurable differences in crano-cervico-hyoid function and related clinical outcomes, compared with untreated subjects. Given the exploratory cross-sectional design, the study was intended to identify post-treatment associations rather than to establish causal or long-term effects. The study concerns post-treatment status: treated participants were examined in young adulthood, after completion of active orthodontic treatment, and current occlusion was recorded at that time. Women aged 18–30 years were selected to obtain a skeletally mature sample and to reduce sex- and age-related heterogeneity in pain perception and cervical mobility [20,23,24]; this restriction was intended to increase internal homogeneity and does not imply that the findings can be generalized to all patients with Class II malocclusion. We hypothesized that young women with Class II division 1 malocclusion who had undergone orthodontic treatment with mandibular advancement would show a higher prevalence of restricted passive mobility of the crano-cervico-hyoid complex (hyoid bone, C0–C1, and C2–C3; primary outcome) than untreated women with the same diagnosis (null hypothesis: no difference between groups). Secondary, exploratory aims were to compare cervical pain intensity, functional impact, central sensitization, and psychological distress between groups.

2. Materials and Methods

2.1. Study Design

This cross-sectional observational study was approved by the IRB of University of L'Aquila (protocol code 15-2019) and conducted and reported in accordance with the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines (Supplementary Table S1). Written informed consent was obtained from all participants. All procedures complied with the Declaration of Helsinki.

Women with a diagnosis of Class II division 1 malocclusion, with and without a history of orthodontic treatment with mandibular advancement, were consecutively recruited over a predefined six-month period in 2024 from the same university dental clinic during professional dental cleaning or routine follow-up visits. All women aged 18–30 years attending these appointments during the recruitment period were screened by two clinicians (PEL and SDN) through review of their clinical records and a brief structured interview, and those with a documented diagnosis of Class II division 1 malocclusion were invited to participate. Group allocation was based exclusively on documented orthodontic history (mandibular advancement treatment vs. no orthodontic treatment) and was established before the biomechanical assessment. To reduce selection bias, the same recruitment setting and procedure were used for both groups. Eligibility criteria were applied before group allocation, and participants were included only when complete clinical records and questionnaire data were available. Only women were included to reduce sex-related heterogeneity in pain perception and cervical musculoskeletal outcomes, as previous studies have reported sex differences in pain sensitivity and a higher prevalence of chronic neck pain among women [23,24]. This restriction was intended to reduce sex-related heterogeneity, not to imply that the results apply to patients with Class II malocclusion in general.

Inclusion criteria were: age 18–30 years, female sex, a documented diagnosis of Class II division 1 malocclusion, and availability of complete clinical records. Exclusion criteria included: chronic or acute temporomandibular disorders (TMD) or orofacial pain, systemic

or neurological diseases, craniofacial malformations, previous maxillofacial surgery, and incomplete data.

Acute or chronic TMD and orofacial pain were screened according to the Diagnostic Criteria for Temporomandibular Disorders (DC/TMD) by an experienced operator. Screening included structured history and clinical examination. Participants were excluded if they fulfilled DC/TMD criteria for painful TMD conditions or reported acute or chronic orofacial pain at the time of evaluation.

2.2. Epidemiological and Clinical Data Collection

Epidemiological and clinical variables were collected through a structured medical history interview conducted by an assessor blinded to group allocation and study hypotheses.

Collected variables included: height (cm), weight (kg), BMI, chronic medication use, history of accidents, chronic diseases, previous surgeries, smoking status, use of vision correction (glasses or contact lenses), history of speech therapy, regular sports practice, duration of labor at birth, presence of typical or atypical swallowing, freeway space at mandibular rest position, and current Angle's classification of occlusion.

Current dental classification according to Angle's system (i.e., occlusal status at the time of the study visit) was performed by an experienced dentist/orthodontist through intraoral inspection. At the time of examination, all participants in the orthodontic group presented Class I occlusion, whereas all controls presented Class II division 1 malocclusion.

The same examiner also assessed atypical swallowing during the same session. The examiner, blinded to the study purpose, gently separated the lips to observe the position of the upper and lower incisors. Freeway space at the mandibular rest position was evaluated with the participant seated upright, with the head in a natural position, according to standard clinical practice. A spontaneous swallow was identified by hyoid movement, after which the participant was asked to close the teeth in habitual occlusion. Atypical swallowing was defined as tongue interposition between the arches or absence of occlusal closure. Binary data (1 = present, 0 = absent) were recorded in an anonymized spreadsheet.

Information on previous dental extractions, missing teeth, detailed dental arch relationships, overjet, overbite, and vertical skeletal or dentoalveolar parameters was not consistently available for all participants and therefore was not included in the analysis.

2.3. Orthodontic History

For all participants, the diagnosis of Class II division 1 malocclusion was verified from clinical records whenever available and confirmed during the structured interview. All participants assigned to the orthodontic group had undergone orthodontic treatment with mandibular advancement during growth. Treatment consisted of a mandibular advancement device (MAD), and the duration of active mandibular advancement ranged from 6 to 12 months in all treated participants. Participants assigned to the control group had the same diagnosis but had never undergone any orthodontic treatment.

Definition of the study groups and of the orthodontic intervention. The two groups shared the same original diagnosis but differed in treatment history and, consequently, in current occlusion. The orthodontic group comprised women diagnosed with Class II division 1 malocclusion during growth who had received orthodontic treatment with a mandibular advancement device (MAD) for 6–12 months and who presented Class I occlusion at the study visit. The control group comprised women with the same documented diagnosis who had never received any orthodontic treatment and who still presented Class II division 1 malocclusion at the study visit. The orthodontic intervention was therefore defined as exposure to MAD therapy for 6–12 months during growth; the specific appliance design was not consistently documented.

Accordingly, the study compares two clinical profiles, “treated and corrected” versus “untreated and uncorrected”, rather than isolating the effect of treatment: by design, treatment history and current occlusion are perfectly collinear and cannot be separated statistically. The groups were comparable with respect to recruitment setting, sex, age range, and anthropometric and epidemiological characteristics (Table 1). However, baseline malocclusion severity and the reasons why control participants had not been treated (e.g., family choice, access to care, or perceived severity) were not available, so pre-existing differences between the groups cannot be excluded.

Table 1. Anthropometric or epidemiological variables. BH = Benjamini–Hochberg false discovery rate. Bonf. = Bonferroni correction.

Variable	Mean (SD) Ctrl Group	Mean (SD) Ortho Group	% Ctrl Group	% Ortho Group	p-Value	OR [CI]
Age	22.818 (2.455)	22.577 (2.428)			0.48	
Height	167.833 (5.848)	167.750 (6.144)			0.92	
Weight	59.955 (8.113)	60.375 (9.444)			0.90	
BMI	21.264 (2.462)	21.454 (3.173)			0.86	
Drugs			33.3%	34.6%	0.99	
Smoke of Cigarette			33.3%	25%	0.46	
Accidents			7.6%	20.2%	0.04 (adj BH 0.11)	3.004 [1.140, 9.587]
Surgery			0%	3.8%	0.27	
Disease			0%	4.8%	0.17	
Sport			72.3%	91.3%	0.002 (adj BH 0.007; Bonf. 0.05)	3.976 [1.686, 10.019]
Labor			41.5%	41.3%	0.87	
Speech therapy			6,2%	16.3%	0.06 (adj BH 0.17)	
Glasses			40%	58.7%	0.02 (adj BH = 0.07; Bonf. = 0.77)	2.115 [1.127, 4.021]
Atypical swallowing			18.2%	26.9%	0.001 (adj BH = 0.004; adj Bonf = 0.02)	2.306 [1.067, 5.230]
FWS in RP			65.2%	57.5%	0.01 (adj BH = 0.03; adj Bonf = 0.28)	3.976 [1.686, 10.019]

2.4. Clinical and Psychosocial Assessment

Pain intensity was assessed using a 10-cm Visual Analog Scale (VAS), while functional impact and psychosocial variables were assessed using validated Italian versions of self-report questionnaires, including the FIQR, CSI, and DASS-42 [25–28]. The VAS referred to current cervical pain intensity at the time of examination.

2.5. Biomechanical Assessment

Biomechanical evaluation of passive mobility was performed through clinical assessment of the cranio-cervico-hyoid system (hyoid bone, C0–C1, C2–C3). All the assessments were performed by a trained examiner with clinical experience in cranio-cervico-hyoid mobility evaluation, blinded to group allocation and study purpose.

Participants were examined supine on a medical table in a controlled environment (temperature and humidity). Prior to assessment, they were asked to refrain from caffeine for at least four hours. Only gentle, non-invasive passive mobility assessments were performed, with no manipulative or therapeutic interventions.

After acclimatization, the examiner assessed passive range of motion (ROM) of C0–C1, C2–C3, and bilateral lateral translation of the hyoid bone (Figure 1). Palpatory mobility data were recorded in an anonymized spreadsheet. Restriction of passive ROM in any plane at C0–C1, C2–C3, or the hyoid bone was considered indicative of reduced mobility. Once recorded, data were incorporated into the general database without further access by the examiner.



Figure 1. Clinical assessment of passive mobility of the cranio-cervico-hyoid complex, demonstrated on volunteers. With the subject in the supine position, the examiner evaluated: (A) passive mobility of the C2–C3 segment; (B) passive mobility of the C0–C1 (occipito-atlantal) segment; (C) bilateral lateral translation of the hyoid bone. Restriction of passive range of motion in any plane was recorded as reduced mobility (binary outcome: present/absent).

Variables were treated as binary (1 = presence, 0 = absence) or continuous (e.g., age, BMI, height, weight) (Figure 1).

2.6. Primary and Secondary Outcomes

The primary outcome was restricted passive mobility of the cranio-cervico-hyoid complex, recorded as three binary segment-level outcomes (hyoid bone, C0–C1, and C2–C3) and summarized by the composite outcome “at least one dysfunction” (restriction in at least one of the three segments). Secondary outcomes were current cervical pain intensity (VAS), functional impact (FIQR), central sensitization (CSI), and psychological distress (DASS-42). Anthropometric, epidemiological, and clinical variables were analysed as descriptive characteristics and potential confounders.

2.7. Statistics

All Statistical analyses were performed using R software version 4.5.3.

For continuous variables, distributional assumptions were assessed using the Shapiro–Wilk test for normality, and homogeneity of variances was evaluated with Levene’s test.

For binary categorical variables (0/1), group differences were examined using Pearson’s chi-square test; when required, Yates’ continuity correction was applied. Fisher’s exact test was used in cases of low expected frequencies. Effect sizes were expressed as odds ratios (ORs) with 95% confidence intervals. Although OR thresholds are not universally standardized, in this study they were interpreted according to conventional descriptive criteria: values close to 1 indicated no association; ORs between 1.1–1.5 were considered weak, 1.5–3.0 moderate, 3.0–10 strong, and >10 very strong. These thresholds were used heuristically to provide a consistent interpretative framework within the clinical context.

Because current occlusal class coincided with group allocation (all treated participants in Class I, all controls in Class II division 1), dental class could not be analysed as an independent variable or used for stratification.

For continuous variables, group differences were analyzed using Welch's *t*-test when normality was met but variances were unequal, or the Wilcoxon rank-sum test when distributions were non-normal. Effect sizes were quantified using Hedges' *g* for parametric tests and Cliff's delta for non-parametric tests, each accompanied by 95% confidence intervals.

To reduce the risk of Type I errors due to multiple testing, *p*-values were adjusted using both the Benjamini–Hochberg false discovery rate (FDR) method and Bonferroni correction.

No a priori sample size calculation was performed. This was an exploratory observational study based on consecutive recruitment over a predefined six-month period.

As an additional exploratory analysis, age-adjusted logistic regression models were fitted to assess whether age acted as a potential confounder of the association between orthodontic history and cranio-cervico-hyoid dysfunction. For each biomechanical outcome (hyoid, C0–C1, and C2–C3 mobility), group allocation and age (continuous, years) were entered as predictors, and odds ratios (ORs) with 95% confidence intervals (CIs) were calculated. Age was analysed as a continuous variable rather than in subgroups because of the narrow age range of the sample (18–30 years).

3. Results

A total of 170 participants were enrolled: 104 in the orthodontic group (ortho group), consisting of patients with Class II division 1 malocclusion who had undergone orthodontic treatment with mandibular advancement for at least 6 months, and 66 in the control group (ctrl group), consisting of patients with the same diagnosis who had never undergone orthodontic treatment. Each participant was assigned an anonymized alphanumeric code. Of the 200 women assessed for eligibility, 30 were excluded (painful TMD or orofacial pain, *n* = 17; declined to participate, *n* = 7; incomplete data, *n* = 6), leaving 170 participants for analysis (Figure 2).

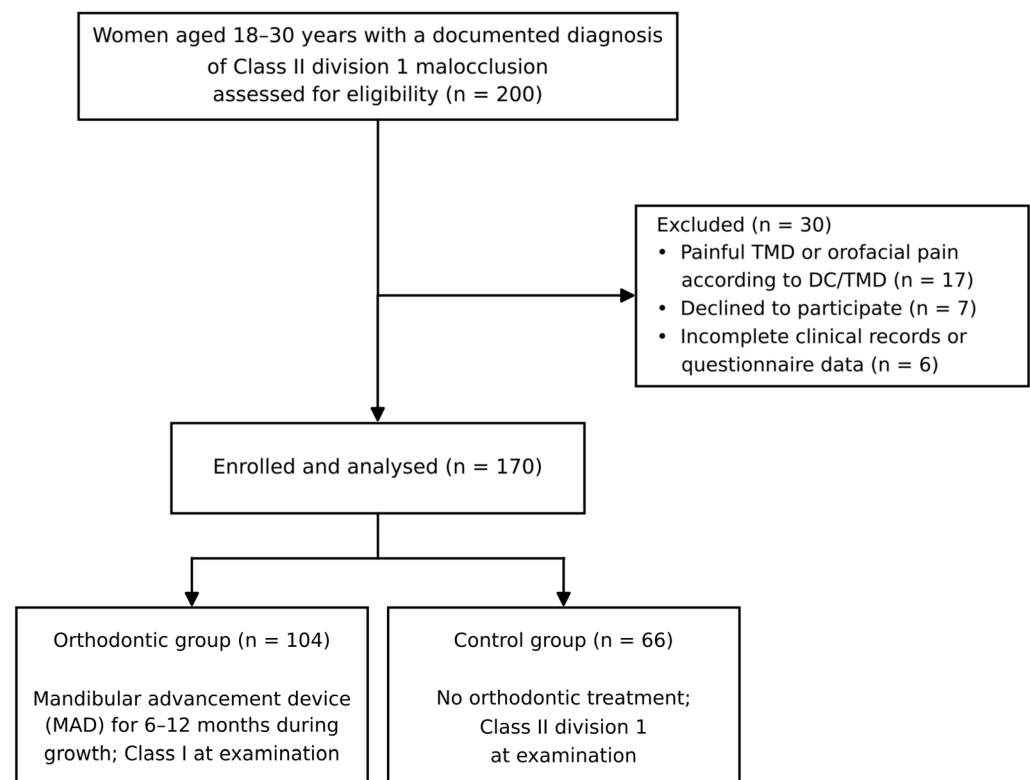


Figure 2. Flow diagram for participant selection.

Age was comparable between groups, with a mean $\pm$ SD of 22.82 ± 2.46 years in the control group and 22.58 ± 2.43 years in the orthodontic group ($p = 0.48$) (Table 1). No statistically significant differences were observed between groups in anthropometric or epidemiological variables, including weight, height, BMI, smoking habits, medication use, and previous surgical interventions.

The practice of sports was more frequent in the orthodontic group, despite no differences in weight or BMI. Variables such as accidents, speech therapy, labor history, and glasses showed weaker or non-significant associations after correction for multiple testing. Atypical swallowing shows a significant difference: It was more frequent in the study group even after Bonferroni's correction ($p = 0.001$). Freeway space in rest position (FWS in RP) shows a significant difference (more frequent in the ctrl group) after the BH correction ($p = 0.01$).

General clinical measures such as the Central Sensitization Inventory (CSI) and the Depression Anxiety Stress Scale total score (DASS) did not differ significantly between groups (Table 2).

Table 2. Psychosocial and Pain scales.

Variable	Mean (SD) Ctrl Group	Mean (SD) Study Group	% Ctrl Group	% Ortho Group	<i>p</i> -Value	OR [CI]
CSI	28.36 (11.49)	31.25 (10.81)			0.25	
DASS	29.57 (16.32)	30.85 (16.88)			0.87	
Depression	6.91 (5.72)	6.92 (5.97)			0.97	
Anxiety	9.57 (6.01)	9.49 (5.69)			0.99	
Stress	13.08 (7.52)	14.42 (7.63)			0.41	
FIQR	11.13 (7.73)	14.51 (9.67)			0.03 (adj BH = 0.09)	0.206 [0.012, 0.388]
VAS	3.01 (2.43)	3.77 (2.46)			0.05 (adj BH = 0.12)	0.187 [−0.008, 0.368]

The Fibromyalgia Impact Questionnaire (FIQR) scores were higher in the orthodontic group compared to the control group ($p = 0.03$). This finding was paralleled by increased, but not significant, values on the Visual Analog Scale (VAS) for pain. In addition, the use of corrective lenses (glasses) was more frequent and significant among orthodontic subjects, but after statistical correction the significance was lost.

Marked differences were observed in biomechanical measures (Table 3): Hyoid mobility, C0–C1, and C2–C3 segments showed highly significant differences, with moderate to strong odds ratios (hyoid OR 2.70 [95% CI 1.43; 5.11]; C0–C1 OR 4.12 [2.12; 8.01]; C2–C3 OR 3.60 [1.89; 6.89]; all $p < 0.002$). The composite variable “At least one dysfunction” (presence of at least one dysfunction among hyoid and cranio-cervical mobility) was present in 77 of 104 orthodontic subjects (74.0%) and in 33 of 66 controls (50.0%) (OR 2.85 [95% CI 1.49–5.47]). In absolute terms, the between-group differences in prevalence were 23.8, 33.7, and 30.9 percentage points for the hyoid bone, C0–C1, and C2–C3, respectively, and 24.0 percentage points for the composite outcome. The differences observed in biomechanical variables (hyoid, C0–C1, C2–C3, “At least one dysfunction”) remained highly significant after both Benjamini–Hochberg and Bonferroni corrections ($p < 0.0001$). Qualitative interpretation of effect sizes classified these associations as moderate to high, or extremely high in cases where odds ratios tended toward infinity.

Table 3. Biomechanical variables of the cranio-cervico-hyoid complex.

Variable	% Ctrl Group	% Ortho Group	Pearson's Chi-Squared Test	<i>p</i> _adj_BH	<i>p</i> _adj_Bonferroni	OR [CI]
Hyoid	30 (45.5%)	72 (69.2%)	0.0020	0.002	<0.0081	2.7 [1.425, 5.11]
C0–C1	19 (28.8%)	65 (62.5%)	<0.0001	<0.0001	<0.0001	4.123 [2.121, 8.013]
C2–C3	24 (36.4%)	70 (67.3%)	<0.0001	0.002	0.0003	3.6 [1.885, 6.885]
At least one dysfunction	33 (50%)	77 (74%)	0.0014	0.0019	0.0056	2.852 [1.488, 5.468]

At the time of examination, all participants in the orthodontic group presented Class I occlusion, whereas all participants in the control group retained Class II division 1 malocclusion. Therefore, current occlusal class coincided with group allocation, and no further analysis stratified by dental class was possible.

In age-adjusted logistic regression models (Table 4), orthodontic history remained significantly associated with hyoid dysfunction (OR 39.6, 95% CI 8.3–351.9, $p = 0.0001$), C0–C1 dysfunction (OR 11.8, 95% CI 4.1–39.4, $p < 0.001$), and C2–C3 dysfunction (OR 10.8, 95% CI 3.7–38.1, $p = 0.0001$). Age showed an independent inverse association with hyoid dysfunction (OR 0.71 per year, 95% CI 0.54–0.89, $p = 0.007$) and C2–C3 dysfunction (OR 0.79, 95% CI 0.64–0.97, $p = 0.026$), whereas no significant association was observed for C0–C1 dysfunction ($p = 0.139$). Thus, age did not account for the association between orthodontic history and cranio-cervico-hyoid dysfunction; within the restricted age range investigated, increasing age was associated with lower odds of hyoid and C2–C3 dysfunction, a finding that should be interpreted cautiously.

Table 4. Age-adjusted logistic regression analysis of cranio-cervico-hyoid dysfunctions.

Outcome	Predictor	OR	95% CI	<i>p</i> -Value
Hyoid dysfunction	Orthodontic group	39.63	8.32–351.89	0.0001
Hyoid dysfunction	Age (years)	0.71	0.54–0.89	0.0066
C0–C1 dysfunction	Orthodontic group	11.79	4.13–39.35	<0.0001
C0–C1 dysfunction	Age (years)	0.86	0.70–1.05	0.1390
C2–C3 dysfunction	Orthodontic group	10.84	3.68–38.14	0.0001
C2–C3 dysfunction	Age (years)	0.79	0.64–0.97	0.0256

4. Discussion

The present exploratory cross-sectional study suggests that young women with Class II division 1 malocclusion who underwent orthodontic treatment with mandibular advancement may present distinct biomechanical alterations at the cranio-cervical and hyoid levels. While baseline anthropometric and epidemiological characteristics were comparable between groups, orthodontically treated subjects showed a markedly higher prevalence of reduced passive mobility at the hyoid bone and upper cervical segments, with moderate to strong effect sizes. Notably, these biomechanical differences remained robust after correction for multiple comparisons. However, because all treated participants had been corrected to Class I while all controls remained in Class II division 1, it cannot be established whether these differences reflect the treatment itself or the resulting change in occlusion. Importantly, no pre-treatment biomechanical measurements were available; it is therefore unknown whether the restrictions observed in the treated group were already present

before treatment, developed during or after it, or reflect characteristics of the individuals who were selected for treatment.

In our sample, CSI and DASS-42 scores did not differ significantly between groups, suggesting comparable levels of central sensitization and psychological distress. From a clinical perspective, the CSI and DASS-42 are validated instruments for screening central sensitization and psychological distress [29–32]. Although these tools demonstrate good reliability, group differences often depend on the clinical context [33,34]. The orthodontic group reported higher FIQR scores and greater pain intensity on the VAS. However, these differences were small and did not remain significant after correction for multiple comparisons; they should therefore be regarded as tentative and hypothesis-generating.

Orthodontic treatment has been investigated in relation to temporomandibular disorders and local musculoskeletal dysfunctions [35]. Notably, TMD-focused orthodontic trials have shown lower methodological transparency and a greater tendency toward interpretive bias compared with general orthodontic research [36]. While no evidence suggests that orthodontic treatment predisposes individuals to fibromyalgia or chronic widespread pain, previous studies have reported associations between fibromyalgia and TMD, craniomandibular dysfunction (CMD), or craniocervical dysfunction (CCD), all considered musculoskeletal pain syndromes [37,38]. In this study, participants were healthy and free of acute or chronic TMD or orofacial pain; therefore, an association between orthodontic treatment and TMD or fibromyalgia can be neither inferred nor excluded, and any interpretation in terms of greater pain susceptibility in orthodontically treated individuals would be speculative.

The higher prevalence of corrective lens use in the orthodontic group may reflect craniofacial developmental differences, although this observation requires further investigation. Previous studies have described associations between mandibular deviation and ocular convergence [39], correlations between visual function and dental occlusion [40], and altered visual parameters in orthodontic or TMD patients [41]. Neuroanatomical and functional pathways tightly connect vision and the stomatognathic system [42], and relationships have been proposed between occlusal features and ocular convergence deficits [39], myopia [43], and pericranial or cervical muscle activity [44–46]. While a developmental relationship between the visual system and the stomatognathic apparatus is plausible, these correlations are likely complex and not reducible to simple causal models [47]. In this context, our findings do not support a causal link between orthodontic treatment and the need for eyeglasses. It may be hypothesized that the visual and stomatognathic systems interact during growth; however, the present data do not allow any inference on the direction or nature of this relationship, and the difference in corrective lens use did not remain significant after correction for multiple comparisons.

The most striking findings concern the biomechanical variables of the cranio-cervico-hyoid system. Dysfunction of hyoid mobility and of the C0–C1 and C2–C3 segments was significantly more frequent in the ortho group, with moderate to high effect sizes. The composite variable “at least one dysfunction” was present in 74% of orthodontic subjects and in 50% of controls, supporting an association between orthodontic history and restricted passive mobility. Importantly, these associations remained significant after stringent correction for multiple testing.

The clinical meaning of these differences, however, should be interpreted with caution. Statistical significance reflects the consistency of the between-group difference in prevalence, not its clinical magnitude. The biomechanical outcomes were binary palpatory judgements of restricted passive mobility, recorded without quantification of the amount of restriction, without established thresholds for clinically relevant restriction, and without formal reliability testing. Moreover, restricted mobility was also common among untreated

controls (approximately one third to one half for each segment), and in the present sample it was not accompanied by differences in pain intensity, functional impact, central sensitization, or psychological distress that remained significant after correction for multiple comparisons. The present findings therefore describe a difference in the prevalence of a clinical sign, whose symptomatic and functional relevance remains to be established.

Our results align with previous literature describing the structural and functional relationships between cervical and hyoid posture and the stomatognathic system, as well as cephalometric changes in craniocervical posture and hyoid bone position following orthodontic treatment [48–51]. These findings are consistent with the concept of a close interdependence between mandibular position, cervical and head posture, and hyoid biomechanics. As a hypothesis, mandibular advancement and the resulting change in occlusion might modify the biomechanical balance of the cranio-cervico-hyoid junction, for example, through changes in suprahyoid and infrahyoid muscle length, hyoid position, or head posture. However, the present study did not measure muscle activity, hyoid position, airway dimensions, or cervical posture, nor did it assess changes longitudinally during treatment; these mechanisms therefore remain hypotheses to be tested rather than explanations supported by the present data.

An additional observation was the higher frequency of sports practice among orthodontic subjects, despite no differences in BMI or weight. This paradoxical association may reflect lifestyle differences not captured by BMI or may simply be a sample-size artifact. Nonetheless, it highlights the importance of considering behavioral and environmental factors alongside clinical and biomechanical outcomes.

Because all treated participants had been corrected to Class I occlusion, whereas all controls retained their Class II division 1 malocclusion, treatment history and current occlusal status completely overlapped in this sample. Consequently, the observed differences may reflect (i) the mandibular advancement treatment itself, (ii) the resulting change in occlusal relationship, (iii) pre-existing differences between women who did and did not receive treatment, or a combination of these, and these components cannot be disentangled with the present design. Moreover, the cross-sectional nature of the study prevents any causal interpretation. In particular, the absence of standardized information on baseline malocclusion severity, vertical skeletal and dental pattern, respiratory pattern, specific appliance design retention phase, and exact time elapsed since treatment completion limits the possibility of attributing the findings directly to mandibular advancement treatment. Therefore, the present results should be interpreted as exploratory associations observed in young adult women with Class II division 1 malocclusion and a history of mandibular advancement treatment, rather than as evidence of treatment-related effects.

Overall, the findings suggest a possible association between previous mandibular advancement treatment and altered biomechanics of the cranio-cervico-hyoid complex; differences in pain perception and functional impact were small and not robust to correction for multiple comparisons. However, because the timing and characteristics of previous treatment were not consistently available, it is not possible to determine whether these differences reflect persistent post-treatment changes, pre-existing individual predispositions, the corrected occlusal relationship itself, or other unmeasured factors.

Several limitations must therefore be acknowledged. Participants were recruited from a university dental clinic, and selection bias cannot be excluded. Although both groups shared the same initial diagnosis of Class II division 1 malocclusion and all treated participants had undergone mandibular advancement with a MAD for 6–12 months, baseline malocclusion severity was not quantified; the specific appliance design, retention, post-treatment follow-up time, and treatment stability were incompletely documented. Vertical craniofacial characteristics, including open bite or deep bite tendency, mandibular plane

inclination, lower facial height, and residual vertical discrepancies, were not systematically assessed, despite their potential influence on muscle tone, fascial tension, hyoid position, and head posture. Respiratory pattern and airway-related variables were also not evaluated, although nasal or oral breathing may affect craniofacial development, cervical posture, hyoid position, airway function, and neuromuscular balance. The narrow age range (18–30 years) also limited the assessment of age-related trends. In addition, no *a priori* sample size calculation was performed, so the study may have been underpowered for secondary outcomes and subgroup analyses. Furthermore, since all treated participants reached Class I occlusion while all controls remained in Class II division 1, current occlusal status was fully confounded with treatment history and could not be adjusted for; beyond Angle classification, no standardized orthodontic outcome assessment was available, leaving open the possibility of residual confounding due to baseline malocclusion severity. The cross-sectional design also precludes causal inference, since, among patients with Class II division 1 malocclusion, those predisposed to cranio-cervico-hyoid dysfunction may have been more likely to receive orthodontic treatment. Although the agreement between subjective measures, such as VAS and FIQR, and objective biomechanical findings supports the internal consistency of the results, subjective outcomes may still introduce variability. Finally, intra- and inter-rater reliability of the biomechanical assessment was not formally tested; although all evaluations were performed by a single trained examiner blinded to group allocation and study purpose, the absence of reliability data limits reproducibility. Despite the application of corrections for multiple comparisons, both type I and type II errors remain possible. Future longitudinal studies with larger samples should include pre-treatment and post-treatment assessments; standardized documentation of the mandibular advancement technique (appliance type) and treatment duration; retention status and time since treatment completion; skeletal (sagittal and vertical) pattern; airway and respiratory characteristics; and repeated biomechanical measurements by blinded examiners, with formal testing of intra- and inter-examiner reliability. Such designs, ideally including an untreated Class II group followed over the same period, are required to clarify causal mechanisms and the clinical relevance of these findings.

Finally, the present findings should not be interpreted as an indication to modify, delay, or avoid orthodontic mandibular advancement in clinical practice. The study was hypothesis-generating, and its results, which describe associations observed after treatment that cannot be attributed to the treatment itself, do not provide a basis for treatment decisions.

5. Conclusions

Among young women with a diagnosis of Class II division 1 malocclusion, those with a history of orthodontic treatment and resultant correction to Class I demonstrated a higher prevalence of restricted passive cranio-cervico-hyoid mobility than untreated women who remained Class II division 1. Because treatment history and current occlusion were completely confounded, the findings cannot establish whether the observed differences are attributable to mandibular advancement, occlusal correction, or other pre-existing factors. These findings are hypothesis-generating and require confirmation in longitudinal studies including pre-treatment assessment.

6. Clinical Relevance

The findings of this exploratory cross-sectional study suggest that young women with Class II division 1 malocclusion treated with mandibular advancement may present altered passive mobility of the cranio-cervico-hyoid complex after treatment completion. These alterations, particularly reduced mobility of the hyoid bone and upper cervical segments,

were more frequent in orthodontically treated participants and remained statistically robust after correction for multiple comparisons.

From a clinical standpoint, these results suggest that cranio-cervico-hyoid functional assessment could be considered in research protocols and in the follow-up of patients reporting cervical, orofacial, or functional complaints; they do not support any modification of the indications for orthodontic mandibular advancement. However, because total treatment duration and appliance type were not consistently documented, and because retention history, exact time since treatment completion, initial malocclusion severity, vertical skeletal pattern, respiratory pattern, and standardized treatment outcomes were not fully characterized, the present findings should not be interpreted as evidence of a causal or long-term effect of orthodontic treatment. Rather, they should be considered hypothesis-generating and warrant confirmation in longitudinal studies with standardized orthodontic outcome assessment, retention data, and reliability-tested biomechanical measures.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/bioengineering13111249/s1>, Table S1: STROBE Statement Checklist.

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Abbreviations

VAS	visual analogue scale.
CSI	central sensitization inventory
DASS-42	Depression-anxiety-stress scale-42
FIQR	Fibromyalgia Impact Questionnaire-Revised
TMD	Temporomandibular disorders
ROM	range of motion
CMD	craniomandibular dysfunction
CCD	craniocervical dysfunction

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