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Three-dimensional evaluation of mandibular midline distraction: A systematic review

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ABSTRACT

Objective

To provide a literature overview on mandibular midline distraction (MMD) using three-dimensional (3D) imaging analysis techniques. Regarding different distractor types, the focus was on changes in position and/or morphology of the mandibular condyle and temporomandibular joint (TMJ), skeletal effects, dental effects, soft tissue effects and biomechanical and masticatory effects specifically on the mandible and TMJ.

Methods

Studies up to March 27 2017 were included, in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement guidelines, using Embase, Medline OvidSP, Web-of-science, Scopus, Cochrane and Google Scholar.

Results

Thirty-one full-text papers were assessed for eligibility and 15 met inclusion criteria: prospective (2), retrospective (2), case-report (1) and computational analysis (10). All included studies were graded low (level 4-5) on quality of evidence using Oxford Centre for Evidence-Based Medicine criteria.

Conclusion

There is a limited number of studies available, with low level of evidence and small sample sizes. Bone-borne distractor seems preferable when taking skeletal effects into account. Tooth-borne distraction leads to significant dental tipping. Hybrid distractor combined with parasymphyseal step osteotomy seemed to be most stable under functional masticatory loads. The effects of chewing appeared to be marginal during the latency period. No permanent TMJ symptoms were reported and little is known about soft tissue effects.

INTRODUCTION

Transverse mandibular and maxillary discrepancies manifest in anterior and posterior crowding, and can be prominent in patients with developmental disorders and congenital deformities (e.g. Treacher-Collins, Apert, Crouzon, Nager). Traditionally, transverse discrepancies were treated with orthodontic appliances and/or tooth extractions. However, in the early 1990s distraction was introduced for the facial skeleton and new treatment options became available (McCarthy et al., 1992; Guerrero et al., 1997; Koudstaal et al., 2005). With this technique, both osteogenesis and histogenesis are induced.

Mandibular midline distraction (MMD) is used as a surgical technique to widen the mandible. An osteotomy is performed in the midline of the mandible and a distractor is attached on both sides of the osteotomy. Distractors can be attached to the bone (bone-borne), the teeth (tooth-borne) or a combination of both (hybrid). Following surgery, a latency period of 5-7 days is respected to allow initial soft callus formation. The distractor is activated at a specific rhythm and rate, depending on the distraction site and preferences of the surgeon or orthodontist.

Indications for MMD are mandibular anterior or posterior crowding (Guerrero et al., 1997), uni- and bilateral crossbite (King et al., 2004), V-shape of the mandible, severe (maxillary-) mandibular transverse deficiency and impacted anterior teeth with inadequate space and tipped teeth (Proffit et al., 2003). In certain cases both the maxilla and the mandible need widening and bimaxillary expansion (BiMEx) is indicated. BiMEx is a combination of surgically assisted rapid maxillary expansion (SARME) and MMD (Weil et al., 1997; Del Santo et al., 2000; De Gijt et al., 2012).

The mandible is a curved bone, which on both sides terminates at the temporomandibular joint (TMJ). The TMJ is surrounded by a soft tissue envelope and allows the mandible to perform rotational, translational, and horizontal movements. The attachment and activation of the distractor creates different vectors in three-dimensional (3D) planes. The biomechanical properties of the distractors themselves are important as they may influence the outcome of distraction in the long-term, and have their respective influence on the TMJ (Mommaerts, 2001; Conley and Legan, 2003; Mommaerts et al., 2005; Gunbay et al., 2009).

Until now, research on MMD has focused largely on conventional methods including dental cast models and posterior-anterior cephalograms (De Gijt et al., 2012). However, imaging techniques and software have become more sophisticated. This makes it possible to analyse bony and soft tissue structures more accurately. In addition, in contrast to conventional radiographs, it is possible to perform 3D measurements of bony and soft tissue structures on 3D reconstruction models using cone beam computed tomography (CBCT). This technique results in less radiation exposure than the multislice computed tomography (MSCT), generating highly realistic facial and skeletal information compared with 2D radiographs. Finite element method (FEM) studies can analyse stress distribution during MMD in the mandible and the TMJ.

The main objective of this study was to provide a literature overview on MMD using 3D imaging analysis techniques. Regarding different distractor types, the focus was on the changes in position and/or morphology of mandibular condyle and TMJ, skeletal effects, dental effects, soft tissue effects and biomechanical and masticatory effects specifically on the mandible and the TMJ.

METHODS

Protocol and registration

The methods for the analysis were described and registered as a protocol in the International Prospective Register of Systematic Reviews (PROSPERO) under the number of registration: CRD42014010010. The Medical Ethics Committee of Erasmus MC - University Medical Center Rotterdam, Rotterdam, the Netherlands, approved the research protocol (approval number: MEC-2014-343).

Search strategy

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement was used as a guideline for this systematic review (Moher et al., 2009). An electronic search up to March 27 2017 was performed using the following electronic databases:

- Embase;
- Medline OvidSP;
- Web-of-science;
- Scopus;
- Cochrane;
- Google Scholar.

The search strategy used a defined combination of keywords for each of above databases *(Appendix I)*. References of the included studies were hand-searched for other relevant studies in order to complete the search.

Inclusion criteria

Randomized controlled trials (RCT), controlled clinical trials (CCT), case series and finite element method (FEM) studies were included in this review. Adolescent- or adult-aged subjects who underwent a MMD, all types of distractors (bone-, tooth-borne or bone-and-tooth borne hybrid distractors) and all types of 3D imaging analysis techniques were included. The search strategy was restricted to English-language publications, and animal studies were excluded. There was no restriction of sample size and follow-up period in the case series.

Data extraction and analysis

After performing the search strategy, all duplicates were removed. Two authors (AG and JPG) independently made a selection, based on title and abstract when available. Papers were excluded if the study groups included congenital (craniofacial) deformities, mental retardation and history of radiation therapy in the area of interest. If the paper appeared to match with the inclusion criteria or when the abstract was lacking information or missing, the full-text paper was obtained. Each selected full-text paper was then completely reviewed independently by both authors in accordance with all the inclusion criteria, and then included or rejected. Included studies were graded on quality of evidence using the Oxford Centre for Evidence-Based Medicine (OCEBM) criteria (OCEBM, 2011). The included studies were scored on the origin of the study, study design, sample size, age range, gender, length of follow-up, 3D imaging analysis technique, 3D imaging software, type of osteotomy, type of distractor, latency period, distraction rate/gap, consolidation period and treatment outcome *(Table I)*.

Table I. Included studies.

Author	Year	Title	Origin	OCEBM level of evidence	Study design	3D imaging analysis technique
Bianchi et al.	2017	Soft, hard-tissues and pharyngeal airway volume changes following maxillo-mandibular transverse osteodistraction: Computed tomography and three-dimensional laser scanner evaluation	Italy	4	Prospective CS	CT, facial scan
Singh et al.	2016	Biomechanical Effects of Novel Osteotomy Approaches on Mandibular Expansion: A Three-Dimensional Finite Element Analysis	China	5	Computational study	FEM
Savoldelli et al.	2012	Comparison of stress distribution in the temporomandibular joint during jaw closing before and after symphyseal distraction: a finite element study	France	5	Computational study	FEM
Kim et al.	2012	A finite element study on the effects ofmidsymphyseal distraction osteogenesis on the mandible and articular disc	South Korea	5	Computational study	FEM

Table I. Included studies. (continued)

Author	Year	Title	Origin	OCEBM level of evidence	Study design	3D imaging analysis technique
Boccaccio et al.	2011	Analysis of the performance of different orthodontic devices for mandibular symphyseal distraction osteogenesis	Italy	5	Computational study	FEM
Seeberger et al.	2011	Changes in the mandibular and dento-alveolar structures by the use of tooth borne mandibular symphyseal distraction devices	Germany	4	Retrospective CS	CT
Gunbay et al.	2009	Effects of transmandibular symphyseal distraction on teeth, bone, and temporomandibular joint	Turkey	4	Retrospective CS	CT
Landes et al.	2008	Prospective changes to condylar position in symphyseal distraction osteogenesis	Germany	4	Prospective CS	(3D)CT
Boccaccio et al. *a*	2008	Effects of aging on the latency period in mandibular distraction osteogenesis: a computational mechanobiological analysis	Italy	5	Computational study	FEM
Boccaccio et al. *b*	2008	Tissue differentiation and bone regeneration in an osteotomized mandible: a computational analysis of the latency period	Italy	5	Computational study	FEM
Gökalp	2008	Effects of symphyseal distraction osteogenesis on the temporomandibular joint seen with magnetic resonance imaging and computerized tomography	Turkey	4	Case report	MSCT, MRI
Boccaccio et al. *c*	2008	Comparison of different orthodontic devices for mandibular symphyseal distraction osteogenesis: a finite element study	Italy	5	Computational study	FEM
Boccaccio et al.	2007	The influence of expansion rates on mandibular distraction osteogenesis: a computational analysis	Italy	5	Computational study	FEM
Boccaccio et al.	2006	Mechanical behavior of an osteotomized mandible with distraction orthodontic devices	Italy	5	Computational study	FEM
Basciftci et al.	2004	Biomechanical evaluation of mandibular midline distraction osteogenesis by using the finite element method	Turkey	5	Computational study	FEM

Abbreviations: 3D, three-dimensional; CS, case series; CT, computed tomography; FEM, finite element method; MRI, magnetic resonance imaging; MSCT, multislice computed tomography; OCEBM, Oxford Centre for Evidence-Based Medicine.

The included studies were divided into two main group; a 'clinical' (morphological) group and a 'FEM' (biomechanical) group. The objective for the 'clinical' group was to evaluate whether MMD provokes changes in position and/or morphology of mandibular condyle and TMJ, skeletal effects, dental effects, soft tissue effects, using 3D imaging analysis techniques. The objective of the 'FEM' group was to evaluate the distraction, masticatory effects and latency period, stress distribution and displacement of mandibular segments following MMD, using FEM.

RESULTS

The electronic database search results yielded 757 citations (Embase, 148; Medline OvidSP, 144; Web-of-science, 130; Scopus, 197; Cochrane, 3 and Google Scholar 135). After correction for duplicates, 330 citations remained. Four papers were identified through a manual search of reference lists.

All of the 334 papers were screened by title and abstract. 303 papers were excluded for different reasons, including papers with other topics than MMD; MMD, but not analysed by 3D imaging analysis techniques; and animal studies. The remaining 31 papers were screened using the full-text paper. Of this selection another 16 papers were excluded for different reasons, including papers with other topics than MMD; not analysed by 3D imaging analysis techniques; animal studies; non-English-language papers; and presentations of meetings. Fifteen studies were therefore included *(Fig. I; Table I)*. Of this selection, only 5 studies (Landes et al., 2008; Gökalp, 2008; Gunbay et al., 2009; Seeberger et al., 2011; Bianchi et al., 2017) met the OCEBM criteria for level 4 evidence as a case series. The remaining 10 studies (Basciftci et al., 2004; Boccaccio et al., 2006; Boccaccio et al., 2007; Boccaccio 2008a, 2008b, 2008c; Boccaccio et al., 2011; Kim et al., 2012; Savoldelli et al., 2012; Singh et al., 2016) met the OCEBM criteria for level 5 evidence as mechanism-based reasoning *(Table I)*.

Clinical group

This group consists of five studies (Landes et al., 2008; Gökalp, 2008; Gunbay et al., 2009; Seeberger et al., 2011; Bianchi et al., 2017). In this group, the ages of all the patients (*n* = 55) ranged from 14.3 to 43 years (32 female, 23 male), with a mean age of 21.9 years. The follow-up period depended on the objective of the study and ranged from 3 months (Landes et al., 2008; Seeberger et al., 2011) post-operatively to 48 months (Gunbay et al., 2009; Bianchi et al., 2017) post-consolidaton *(Table II)*.

Table II. Patient characteristics of included studies in the 'clinical group'.

Author	Year	Study design	3D imaging analysis technique	Sample size (*n*)	Age range, mean (years)	Gender (F/M)	Follow-up period
Bianchi et al.	2017	Prospective CS	CT, facial scan	19	18-36, 26.3	11/8	24-48
Seeberger et al.	2011	Retrospective CS	CT	19	15-43, 27.1	12/7	3
Gunbay et al.	2009	Retrospective CS	CT	7	14.3-22.5, 16.2	3/4	36-48
Landes et al.	2008	Prospective CS	(3D)CT	9	15-43, 24.7	5/4	3-24
Gökalp	2008	Case report	MSCT, MRI	1	15, 15	1/-	6

Abbreviations: 3D, three-dimensional; CS, case series; CT, computed tomography; MRI, magnetic resonance imaging; MSCT, multislice computed tomography.

Surgical intervention and distraction

In 4 studies (Landes et al., 2008; Gökalp, 2008; Gunbay et al., 2009; Seeberger et al., 2011) a midsymphyseal osteotomy was performed between the mandibular central incisors. A step osteotomy between the canine and lateral incisor was performed in 1 study (Bianchi et al., 2017). Bone-borne, tooth-borne and hybrid distractors were used. SARME was performed simultaneously in four studies (Landes et al., 2008; Gökalp, 2008; Seeberger et al., 2011; Bianchi et al., 2017). See *Table III* for additional baseline information of the studies.

Table III. Surgical intervention and distraction in the 'clinical group'.

Author	Year	Osteotomy, anaesthesia	Distractor type	Latency period (days)	Distraction rate (mm/day)	Consolidation period (months)	Additional surgery
Bianchi et al.	2017	Step MSO, GA	Bone-borne	7	1	2	SARME
Seeberger et al.	2011	Vertical MSO, ND	Tooth-borne	7	0.4	3	SARME
Gunbay et al.	2009	Vertical MSO, LA	Bone-borne	7	1	1	-
Landes et al.	2008	Step MSO, GA	Bone-borne	5	0.6	3	SARME
Gökalp	2008	Vertical MSO, GA	Tooth-borne	5	1	6	SARME

Abbreviations: GA, general anaesthesia; LA, local anaesthesia; MSO, midsymphyseal osteotomy; ND, not described; SARME, surgically assisted rapid maxillary expansion.

3D imaging analysis method

The following 3D imaging techniques were reported: 3D computed tomography (3DCT) (Landes et al., 2008), computed tomography (CT) (Gunbay et al., 2009; Seeberger et al., 2011; Bianchi et al., 2017), MSCT (Gökalp, 2008), magnetic resonance imaging (MRI) (Gökalp, 2008) and facial scan (Bianchi et al., 2017). These scans were performed pre-operatively in all studies (Landes et al., 2008; Gökalp, 2008; Gunbay et al., 2009; Seeberger et al., 2011; Bianchi et al., 2017), at end of distraction (Gunbay et al., 2009), after completion of postoperative orthodontic treatment (Bianchi et al., 2017) and postoperatively at 3 months (Landes et al., 2008; Seeberger et al., 2011), 6 months (Gökalp, 2008) and 36 months (Gunbay et al., 2009).

There were various analysis methods applied for evaluating the mandibular condyle position. Most studies evaluated the mandibular condyle position by measuring the inter-condylar distance (Landes et al., 2008; Gökalp, 2008; Bianchi et al., 2017), condylar axis (Landes et al., 2008; Gökalp, 2008; Gunbay et al., 2009) and mandibular axis (Seeberger et al., 2011). Two studies analysed the TMJ region (Landes et al., 2008; Gökalp, 2008). Landes et al. measured lateral and inner distances from the condylar surface to the mandibular fossa on the coronal plane of the (3D)CT scan (Landes et al., 2008). Landes et al., Seeberger et al. and Bianchi et al. measured the distance between the condyles (Landes et al., 2008; Seeberger et al., 2011; Bianchi et al., 2017). Gökalp evaluated the disc positions of the condyle and the glenoid fossa on bilateral sagittal MRI scans for both closed and open positions of the mouth (Gökalp, 2008).

For evaluating skeletal effects, Seeberger et al. measured the inter mental foramen distance and mandibular tilting (Seeberger et al., 2011). Bianchi et al. measured the distance from the genial tubercle to the hyoid bone, length of the hyoid bone to basal skull plane, mandibular body length, bigonial width, ramal angle and ramus length (Bianchi et al., 2017).

For evaluating the dental effects, inter first molar crown (Seeberger et al., 2011; Bianchi et al., 2017), inter first molar root (Seeberger et al., 2011; Bianchi et al., 2017), inter first premolar crown (Seeberger et al., 2011; Bianchi et al., 2017) and inter first premolar root distances were measured (Seeberger et al., 2011; Bianchi et al., 2017). These were measured using the buccal cusps and the lingual root apices. Bianchi et al. added measurements of inter occlusal distances for the second molar, first molar, second premolar, first premolar and canine (Bianchi et al., 2017). Landes et al. measured the inter-canine distance by using the dental cavum midpoint of the left and right inferior canine on the axial plane of the (3D)CT scan (Landes et al., 2008). Only Seeberger et al. performed measurements of first molar and first premolar angulation (Seeberger et al., 2011).

With regards to the soft tissue effects, Bianchi et al. examined morphological changes as shell-to-shell deviation (clearance vector map) and represented regional changes as a pseudo-colour map on the facial scan. Linear/angular measurements were performed using 17 landmarks taken from classical anthropometry, and axial/sagittal cross sections were also obtained (Bianchi et al., 2017) *(Table IV)*.

Table IV. 3D imaging analysis method in the 'clinical group'.

Author	Year	3D imaging analysis technique	Period, phase	Reported analysis objects and methods
Bianchi et al.	2017	CT, facial scan	ND, pre-OP ND, post-OP OT	Measurement of LMH, LHYO, GOGNR, GOGNL, ID, GOGO, RA°, ARGOR, ARGOL, IOSMD, IOFMD, IOSPMD, IOFPMD, IOCD, IFMCD, IFPMCD, IFMRD, IFPMRD on CT scan. Linear and angular measurements using 17 facial landmarks taken from classical anthropometry on facial scan.
Seeberger et al.	2011	CT	1 week, pre-OP 3 months, post-OP	Measurement of ID, IFMCD, IFPMCD, IFMRD, IFPMRD, FMA°, FPMA°, IMFD and MT° on 3D reconstruction of CT scan.
Gunbay et al.	2009	CT	ND, pre-OP ND, end of distraction 36 months, post-OP	Measurement of DLRC° on CT scans.
Landes et al.	2008	(3D)CT	Same day, pre-OP 3 months, post-OP	Measurement of ID, DLRC° and ICD on axial plane of (3D)CT scan. Measurement of CSTFCD, CSTFLD and CSTFMD on coronal plane of (3D)CT scan.
Gökalp	2008	MSCT, MRI	ND, pre-OP 6 months, post-OP	Measurement of PRMPC° on axial plane of MSCT scan. Disc positions of condyle and glenoid fossa in closed and open position of the mouth evaluated on bilateral sagittal MRI scans of TMJ.

Abbreviations: 3D, three-dimensional; ARGOL, ramus length left; ARGOR, ramus length right; CSTFCD, condyle surface to fossa cranial distance; CSTFLD, condyle surface to fossa lateral distance; CSTFMD, condyle surface to fossa median distance; CT, computed tomography; DLRC°, distolateral rotation of condyle; FMA°, first molar angle; FPMA°, first premolar angle; GOGNL, mandibular body length left; GOGNR, mandibular body length right; GOGO, bigonial width; ICD, inter canine distance; ID, inter condylar distance; IFMCD, inter first molar crown distance; IFMRD, inter first molar root distance; IFPMCD, inter first premolar crown distance; IFPMRD, inter first premolar root distance; IMFD, inter mental foramen distance; IOCD, inter occlusal canine distance; IOFMD, inter occlusal first molar distance; IOFPMD, inter occlusal first premolar distance; IOSMD, inter occlusal second molar distance; IOSPMD, inter occlusal second premolar distance; LHYO, hyoid bone to basal skull plane length; LMH, genial tubercle to hyoid bone distance; MRI, magnetic resonance imaging; MSCT, multislice computed tomography; MT°, mandibular tilt; OP, operative; OT, orthodontic treatment; PRMPC°, posterolateral rotation of the medial pole of condyle; RA°, ramal angle; TMJ, temporomandibular joint.

Treatment outcome

In all cases the distraction was successful and the desired expansion was achieved. Regarding mandibular condylar position, a distolateral movement was found in two studies (Landes et al., 2008; Gunbay et al., 2009). This was between 2.5 and 3° in the study of Gunbay et al., whereas Landes et al. observed a distolateral movement of

0.028° (Landes et al., 2008; Gunbay et al., 2009). In the same Landes et al. study, the vertical lateral, cranial and median distances to the fossa remained unchanged with no angulation of the condyles in the coronal plane (Landes et al., 2008). Gökalp reported a bilateral posterolateral rotation of -1° (right) and -9° (left) of the medial pole of the condyles with an unchanged disc position of the TMJ (Gökalp, 2008). Lateral condylar displacement was analysed in three studies (Landes et al., 2008; Seeberger et al., 2011; Bianchi et al., 2017). In the study of Seeberger et al. the intercondylar distance changed insignificantly for 0.67 ± 1.67 mm, while Landes et al. observed a significant mean decrease of -1.0 ± 0.1 mm (Landes et al., 2008; Seeberger et al., 2011). Bianchi et al. also reported a decrease for the intercondylar distance of -1.83 ± 0.11 mm, however this was not significant (Bianchi et al., 2017). There were only three cases of transient TMJ symptoms reported of all the patients in the 'clinical' group (Gunbay et al., 2009). No permanent TMJ symptoms were described.

With regards to the skeletal effects, Seeberger et al. observed a significant increase in the inter mental foramen distance and a significant tilting of the mandibular corpus, with v-shaped rotation (Seeberger et al., 2011). Bianchi et al. reported a significant decrease of 21.43% for the genial tubercle of the mandible to the hyoid bone distance. The ramal angle decreased insignificantly and there was evidence of a slight increase of the mandibular body length (Bianchi et al., 2017).

Concerning dental effects, Seeberger et al. observed a significant increase of the inter- first molar, inter- first premolar crown and root distance, and a significant lateral angulation on the tooth-borne distractor fixation level for all first molars and premolars (Seeberger et al., 2011). Landes et al. observed a significant increase in inter canine distance of 3.8 ± 0.18 mm (Landes et al., 2008). Bianchi et al. reported a significant increase in inter canine distance of 4.89 ± 1.96 mm, inter first premolar distance of 5.48 ± 1.89 mm and inter second premolar distance of 4.69 ± 3.78 mm. There was no significant increase for the intermolar distances. The mean expansion at the level of the root apices of the first premolars was 3.01 ± 0.83 mm and of the first molars was 3.35 ± 1.11 mm, which were both significant (Bianchi et al., 2017).

When evaluating the soft tissue effects for MMD, Bianchi et al. observed major post-operative changes in the lower lip and chin. MMD did not cause any vertical or horizontal asymmetry. There were statistical significant differences demonstrated for the sagittal projection of the cheilion, labialis inferior, pogonion points and enlargement of the mouth and chin. The axial sections through pogonion showed a forward displacement of the chin with enlargement after MMD *(Table V)*.

Table V. Treatment outcome in the 'clinical group'.

Author	Year	3D imaging analysis technique	Distractor type (months)	Follow-up period (*n*)	Sample size	Reported outcome changes (distance, mm; angle/rotation, °)	
Bianchi et al.	2017	CT, facial scan	Bone-borne	24-48	19	LMH:	2.08 ± 0.07*
						LHYO:	0.13 ± 0.28
						GOGNR:	1.61 ± 0.63
						GOGNL:	1.81 ± 0.36
						ID:	-1.83 ± 0.11
						GOGO:	0.12 ± 0.23
						RA°:	-2.31 ± 0.61
						ARGOR:	0.21 ± 0.15
						ARGOL:	0.06 ± 0.25
						IOSMD:	2.15 ± 0.88
						IOFMD:	4.01 ± 1.33
						IOSPMD:	4.69 ± 3.78*
						IOFPMD:	5.48 ± 1.89*
						IOCD:	4.89 ± 1.96*
						IFMCD:	4.59 ± 1.94
						IFPMCD:	5.44 ± 1.61*
						IFMRD:	3.35 ± 1.11*
						IFPMRD:	3.01 ± 0.83*
						Major post-operative changes in the lower lip and chin. No vertical or horizontal asymmetry. Statistical significance in the sagittal projection of cheilion, labialis inferior, pogonion points and enlargement of mouth and chin. Forward displacement of the chin with enlargement on axial sections through pogonion.	
Seeberger et al.	2011	CT	Tooth-borne	3	19	ID:	0.67 ± 1.67
						IFMCD:	4.9 ± 1.30*
						IFPMCD:	4.83 ± 1.63*
						IFMRD:	2.60 ± 2.05*
						IFPMRD:	2.93 ± 1.84*
						FMA°:	2.63 ± 1.75*
						FPMA°:	3.32 ± 1.57*
						IMFD:	2.67 ± 1.18*
						MT°:	2.30 ± 1.97*

Table V. Treatment outcome in the 'clinical group'. (continued)

Author	Year	3D imaging analysis technique	Distractor type (months)	Follow-up period (*n*)	Sample size	Reported outcome changes (distance, mm; angle/rotation, °)	
Gunbay et al.	2009	CT	Bone-borne	36-48	7	DLRC°:	2.5 – 3
						TMJS:	3 (transient)
Landes et al.	2008	(3D)CT	Bone-borne	3	9	ID:	-1.0 ± 1.1*
						DLRC°:	0.028 ± 4.34
						ICD:	3.8 ± 0.18*
						CSTFLD:	0.4 ± 0.5
						CSTFCD:	0.4 ± 0.5
						CSTFMD:	0.4 ± 0.3
Gökalp	2008	MSCT, MRI	Tooth-borne	6	1	PRMPC°:	-1° (right)
							-9° (left)

Abbreviations: *, significant $P < 0.05$; 3D, three-dimensional; ARGOL, ramus length left; ARGOR, ramus length right; CSTFCD, condyle surface to fossa cranial distance; CSTFLD, condyle surface to fossa lateral distance; CSTFMD, condyle surface to fossa median distance; CT, computed tomography; DLRC°, distolateral rotation of condyle; FMA°, first molar angle; FPMA°, first premolar angle; GOGNL, mandibular body length left; GOGNR, mandibular body length right; GOGO, bigonial width; ICD, inter canine distance; ID, inter condylar distance; IFMCD, inter first molar crown distance; IFMRD, inter first molar root distance; IFPMCD, inter first premolar crown distance; IFPMRD, inter first premolar root distance; IMFD, inter mental foramen distance; IOCD, inter occlusal canine distance; IOFMD, inter occlusal first molar distance; IOFPMD, inter occlusal first premolar distance; IOSMD, inter occlusal second molar distance; IOSPMD, inter occlusal second premolar distance; LHYO, hyoid bone to basal skull plane length; LMH, genial tubercle to hyoid bone distance; MRI, magnetic resonance imaging; MSCT, multislice computed tomography; MT°, mandibular tilt; OP, operative; OT, orthodontic treatment; PRMPC°, posterolateral rotation of the medial pole of condyle; RA°, ramal angle; TMJS, temporomandibular joint symptoms.

FEM group

This group consists of ten studies (Basciftci et al., 2004; Boccaccio et al., 2006; Boccaccio et al., 2007; Boccaccio 2008a, 2008b, 2008c; Boccaccio et al., 2011; Kim et al., 2012; Savoldelli et al., 2012; Singh et al., 2016).

Only three studies (Basciftci et al., 2004; Kim et al., 2012; Savoldelli et al., 2012) reported the origin of the geometric data for the FEM model, which were obtained from healthy volunteers. The age of these volunteers ($n = 3$, all male) ranged from 22 to 30 years, with a mean age of 26.3 years *(Table VI)*.

Distraction

Various analysing methods were applied for evaluating the distraction. In nine FEM simulations, a vertical midsymphyseal osteotomy was performed (Basciftci et al., 2004; Boccaccio et al., 2006; Boccaccio et al., 2007; Boccaccio 2008a, 2008b, 2008c; Boccaccio et al., 2011; Kim et al., 2012; Savoldelli et al., 2012). Only one FEM

Table VI. Patient characteristics of included studies in the 'FEM group'.

Author	Year	Study design	3D imaging analysis technique	Sample size (*n*)	Age (years)	Gender (F/M)
Singh et al.	2016	Computational study	FEM	1	ND	ND
Savoldelli et al.	2012	Computational study	FEM	1	30	M
Kim et al.	2012	Computational study	FEM	1	27	M
Boccaccio et al.	2011	Computational study	FEM	1	ND	ND
Boccaccio et al. *a*	2008	Computational study	FEM	1	ND	ND
Boccaccio et al. *b*	2008	Computational study	FEM	1	ND	ND
Boccaccio et al. *c*	2008	Computational study	FEM	1	ND	ND
Boccaccio et al.	2007	Computational study	FEM	1	ND	ND
Boccaccio et al.	2006	Computational study	FEM	1	ND	ND
Basciftci et al.	2004	Computational study	FEM	1	22	M

Abbreviations: 3D, three-dimensional; FEM, finite element method; ND, not described.

simulation performed three types of osteotomy, including a midsymphyseal, angulated midsymphyseal and parasymphyseal step osteotomy (Singh et al., 2016). Various types of distractors were analysed in these simulations, bone-borne (Basciftci et al., 2004; Boccaccio 2008c; Boccaccio et al., 2011; Kim et al., 2012; Savoldelli et al., 2012; Singh et al., 2016), tooth-borne (Boccaccio et al., 2006; Boccaccio et al., 2007; Boccaccio 2008a, 2008b, 2008c; Boccaccio et al., 2011; Kim et al., 2012; Singh et al., 2016) and hybrid distractors (Basciftci et al., 2004; Boccaccio 2008c; Boccaccio et al., 2011; Kim et al., 2012; Singh et al., 2016). The simulated distraction gaps were 2 mm (Boccaccio 2008a, 2008b, 2008c), 6 mm (Boccaccio et al., 2006; Boccaccio et al., 2007), 7 mm (Boccaccio et al., 2011), 8 mm (Kim et al., 2012) and 10 mm (Basciftci et al., 2004; Savoldelli et al., 2012). Singh et al. used a 6-day distraction period with a frequency of one distraction per day, however the size of the distraction gap was not described (Singh et al., 2016) *(Table VII)*.

Masticatory effects and latency period

Boccaccio et al. showed that parasitic rotations of the mandible arms may counteract arch expansion due to mastication forces. There was a significant effect of the mastication forces on mechanical response using the tooth-borne distractor (Boccaccio et al., 2006). The same author observed that the hybrid distractor provided the most stable situation at the distraction gap. The tooth-borne distractor showed similar displacement, but had less stability under mastication forces (Boccaccio et al., 2011). These findings are in line with Singh et al. who presented that the hybrid distractor combined with a parasymphyseal step osteotomy permits reduction in the parasitic rotations produced by mastication forces (Singh et al., 2016). In another study Boccaccio et al. showed that the mandibular arch displacements were less than 10% different from the distraction gap for tooth-borne and

Table VII. Distraction in the 'FEM group'.

Author	Year	Osteotomy	Distraction gap (mm)	Distractor type	Masticatory loads in model
Singh et al.	2016	Vertical MSO	ND	Bone-borne	Yes
		Angulated MSO		Tooth-borne	Yes
		Parasymphyseal SO		Hybrid	Yes
Savoldelli et al.	2012	Vertical MSO	10	Bone-borne	Yes
Kim et al.	2012	Vertical MSO	8	Bone-borne	Yes
				Tooth-borne	Yes
				Hybrid	Yes
Boccaccio et al.	2011	Vertical MSO	7	Bone-borne	Yes
				Tooth-borne	Yes
				Hybrid	Yes
Boccaccio et al. *a*	2008	Vertical MSO	2	Tooth-borne	Yes
Boccaccio et al. *b*	2008	Vertical MSO	2	Tooth-borne	Yes
Boccaccio et al. *c*	2008	Vertical MSO	2	Bone-borne	Yes
				Tooth-borne	Yes
				Hybrid	Yes
Boccaccio et al.	2007	Vertical MSO	6	Tooth-borne	Yes
Boccaccio et al.	2006	Vertical MSO	6	Tooth-borne	Yes
Basciftci et al.	2004	Vertical MSO	10	Bone-borne	No
				Hybrid	No

Abbreviations: MSO, midsymphyseal osteotomy; ND, not described; SO, step osteotomy.

hybrid distractors. The hybrid distractor was the most stable under mastication forces (Boccaccio 2008c). The same author simulated the effects of aging on the latency period before starting the distraction with a tooth-borne distractor. The results showed an optimal latency period duration of 5-6 days for young (up to 20 years old) patients, 7-8 days for adult (about 55 years old) patients and 9-10 days for the elder (more than 70 years old) patients. Mastication forces appeared to have a rather marginally influence on this (Boccaccio 2008a). Related to this outcome, the same author simulated two different mastication loads in another study. There was a full mastication load and a mastication load reduced by 70%. The results showed that both intramembranous and endochondral ossification are predicted to occur for the full mastication loading in the osteotomized region, while for the reduced mastication loading mainly intramembranous ossification is predicted. The results showed bony bridges between both sides of the bone callus after a latency period of 7-8 days (Boccaccio 2008b). Concerning this outcome, the same author reported previously that lower distraction rate of 0.6 mm/day leads to greater amounts of bony bridging. Subsequently, it was reported that distraction rates higher than 1.2 mm/day could lead to low quality of bone callus (Boccaccio et al., 2007).

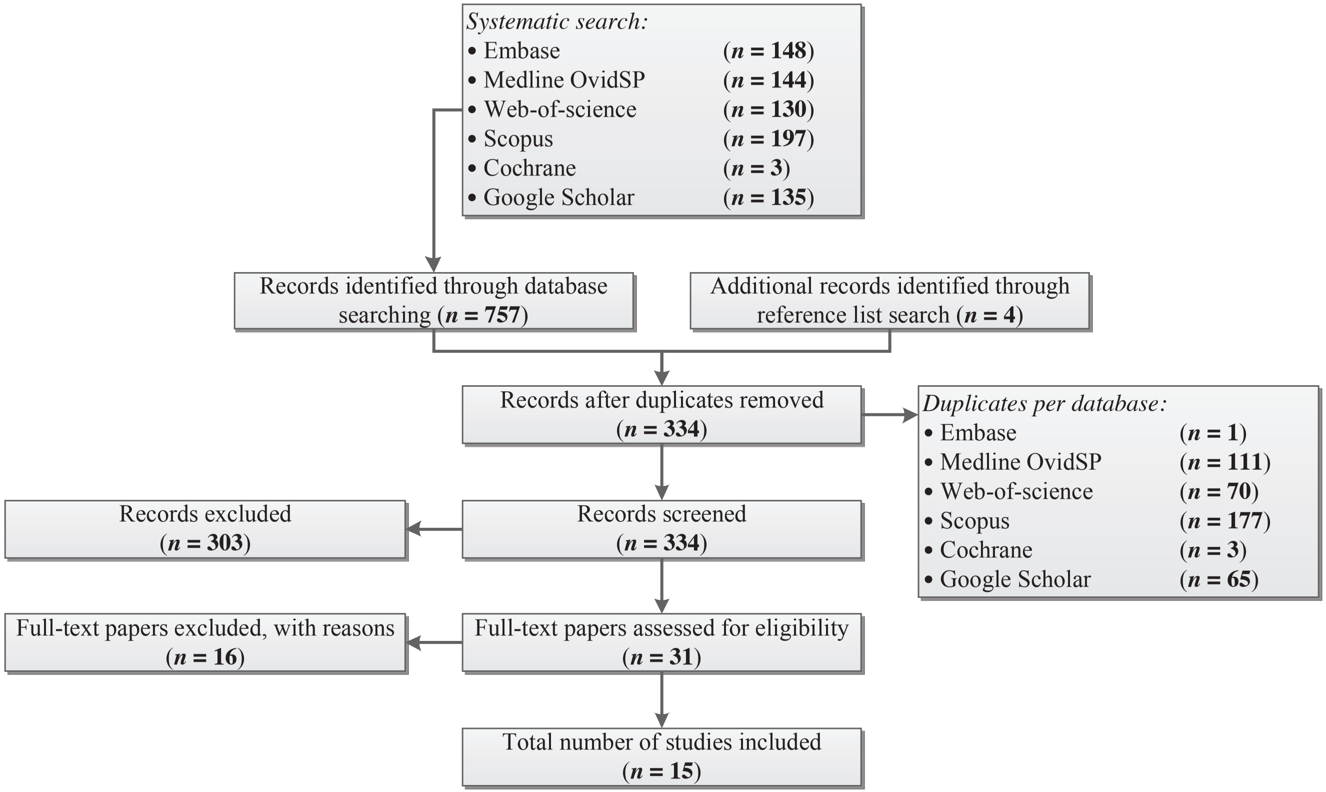

Figure I. Data extraction flowchart, according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA).

Stress distribution and displacement of mandibular segments

In all FEM simulations the distraction was successful and the desired expansion was achieved. Each mandibular segment showed a different pattern of stress distribution and displacement dependent on the type of distractor.

Area contiguous to the distractor

Only two studies (Basciftci et al., 2004; Kim et al., 2012) reported the stress distribution in the area contiguous to the distractor. Basciftci et al. observed a low stress distribution using the bone-borne or hybrid distractor in the area contiguous to the distractor (Basciftci et al., 2004). Kim et al. however, observed high stress distribution using a bone-borne distractor in the same area (Kim et al., 2012).

Dental arch and alveolar process

In the study by Kim et al. the tooth-borne distractor showed most expansion at the dental arch, followed by the hybrid distractor and the bone-borne distractor. In comparison with the hybrid distractor and bone-borne distractor, the tooth-borne distractor showed high levels of stress distribution, and displaced the alveolar process and basal bone area from incisor region to premolar region in a parallel fashion. However, the bone-borne distractor showed a decrease in lateral displacement from the anterior to posterior part (Kim et al., 2012). This outcome is in concordance with Basciftci et al. who observed a nonparallel separation of the dentoalveolar complex from anterior to posterior part using the bone-borne distractor (Basciftci et al., 2004).

Boccaccio et al. reported that expansion of the dental arch appeared to be more significant for the tooth-borne distractor and hybrid distractor than for the bone-borne distractor (Boccaccio et al., 2011). This outcome is in line with Singh et al. who demonstrated a maximum stress distribution on the root using the tooth-borne distractor with a parasymphyseal step osteotomy. The same author showed that the amount of bone displacement in parasymphyseal step osteotomy using the hybrid distractor was maximum and consistent, including a significant increase of intercanine, interpremolar and intermolar distance (Singh et al., 2016).

Corpus, gonion and ramus

Basciftci et al. observed minimal displacement of the ramal and gonion regions using the bone-borne or hybrid distractor. There was a high stress distribution observed in the ramal region (Basciftci et al., 2004). In contrast to this outcome, Kim et al. observed a low stress distribution with the bone-borne distractor and a more even stress distribution with the hybrid distractor in the mandibular body and ramal region, while the tooth-borne distractor showed a higher stress distribution (Kim et al., 2012).

Condyle and articular disc

Basciftci et al. observed the highest stress distribution below the condylar area using the bone-borne or hybrid distractor, while there was a minimal condylar displacement (Basciftci et al., 2004). This is in concordance with Kim et al., who observed a high level of stress distribution with the bone-borne, tooth-borne and hybrid distractor in the condylar neck area, with minimal condylar displacement. In the articular disc, the tooth-borne distractor showed the highest stress distribution, followed by the hybrid and bone-borne distractor (Kim et al., 2012). In contrast to these outcomes, Savoldelli et al. observed a similar stress distribution on the condylar surfaces and in articular discs before and after MMD with the bone-borne distractor (Savoldelli et al., 2012).

DISCUSSION

This systematic review represents an overview of the literature on studies of MMD using 3D imaging analysis techniques. Unfortunately, no RCT's and CCT's were found. Using the inclusion criteria, 15 potentially relevant papers were found of which five were clinical studies (Landes et al., 2008; Gökalp, 2008; Gunbay et al., 2009; Seeberger et al., 2011; Bianchi et al., 2017) and ten were FEM studies (Basciftci et al., 2004; Boccaccio et al., 2006; Boccaccio et al., 2007; Boccaccio 2008a, 2008b, 2008c; Boccaccio et al., 2011; Kim et al., 2012; Savoldelli et al., 2012; Singh et al., 2016). The wide variety of outcome variables limited the opportunity to review the literature using the systematic method and a meta-analysis of the data was not possible. The majority of the reported studies were FEM models, leading to a low level of evidence (OCEBM, 2011). FEM models of the human masticatory system are useful in identifying and predicting stress distributions in anatomical structures. However, the human mandible is not symmetric and there are many individual differences.

Changes in position and/or morphology of mandibular condyle and TMJ

The effect of MMD on the condyles and TMJ is closely related to the rigidity of the distractor. Each type of distractor has different fixation points and therefore causes a different amount of force with a different vector on the mandible, and thus on the condyle and the TMJ.

With regards to condylar rotation, a distolateral rotation was found in two studies (Landes et al., 2008; Gunbay et al., 2009). An explanation for this finding might be that the intercondylar distance decreased in the Landes et al. study, and a distolateral rotation occurred. However, both authors used different distractors. Landes et al. used an axially high rigid distractor (The Modus, Medartis, Basel, Switzerland), while Gunbay et al. used an axially low rigid distractor (TMD, Surgi-Tec NV, Bruges, Belgium) which may have influenced the outcome. Furthermore, Landes et al. analysed the rotational movement after 3 months of consolidation, while Gunbay et al. analysed directly after distraction, not taking the adaptation of the condyles into account. Both analyses were performed using CT scans. An inconspicuous bilateral posterolateral rotation was reported for the medial pole of the condyles on the axial CT plane, with an unchanged disc position of the TMJ on the sagittal MRI plane (Gökalp, 2008). This rotation was asymmetric and without clinical symptoms for the patient, indicating adaptability of the condyle. This outcome should be adopted cautiously, considering this was a case-report with a short follow-up of 6 months.

Regarding intercondylar distance, both an increase and a decrease was found. Seeberger et al. observed an insignificant increase using a tooth-borne distractor, while Landes et al. observed a significant decrease and Bianchi et al. an insignificant decrease using a bone-borne distractor (Landes et al., 2008; Seeberger et al., 2011; Bianchi et al., 2017). Theoretically, tooth-borne distractors exert their force mainly on a dentoalveolar level, and lead to a combination of increased vertical angle and more posterolateral widening when compared with bone-borne distractors, which exert their force anteriorly on a basal bone level and would create anterolateral expansion. Based on this, tooth-borne distractors could lead to a greater lateral displacement of the posterior part of the mandible and increased intercondylar distance, with an increase in stress distribution in the TMJ. However, in an FEM study Kim et al. observed minimal condylar displacement using a tooth-borne distractor, with an increased stress distribution in the articular disc (Kim et al., 2012). The observed decrease in intercondylar distance may be due the combination of the bone-borne distractor fixation points and the soft tissue envelope surrounding the posterior part of the mandible, especially the TMJ. This soft tissue envelope could form sufficient resistance in the posterior part of the mandible, because bone-borne distractors apply their force anteriorly of the mandible. This is also supported by the high levels of stress distribution in the condylar area with minimal condylar displacement, observed by Basciftci et al. and Kim et al. with the bone-borne distractor in a FEM study (Basciftci et al., 2004; Kim et al., 2012). However, Basciftci et al. did not consider the mastication forces and soft tissues in the TMJ. Kim et al. did consider the mastication forces, and the analysis was only based on the left side of the mandible without taking into account the soft tissues in the TMJ. Since humans are not symmetrical, the conclusion must be interpreted with some care. In contrast, Savoldelli et al. generated an FEM model with a complete masticatory system before and after MMD, during jaw closing, using a bone-borne distractor, including the soft tissues in the TMJ. There was a similar stress distribution observed on the condylar surfaces and in the articular discs before and after MMD. Their study suggests that anatomical changes in the TMJ should not predispose to long-term tissue fatigue. There was an absence of permanent clinical TMJ symptoms after MMD (Savoldelli et al., 2012). This is supported by Gunbay et al., who reported three transient cases of TMJ symptoms, which were all only mild TMJ pain, and resolved after the distraction period (Gunbay et al., 2009). Overall, no permanent clinical TMJ symptoms were found in this systematic review. It can be assumed that MMD does not lead to permanent clinical TMJ symptoms. However, this assumption is mostly based on FEM studies and with only a small number of clinical studies with relatively short follow-up periods and small sample sizes.

Skeletal effects

With regards to skeletal effects, there was a significant increase of the inter mental foramen distance and a significant tilting of the mandibular corpus with V-shaped rotation observed following MMD using a tooth-borne distractor (Seeberger et al., 2011). This outcome disagrees with the results of Kim et al., who observed a displacement of the alveolar process and basal bone area in a parallel way from incisor region to premolar region, with a notable displacement on the ramus (Kim et al., 2012). However, this outcome was based on a FEM model, with the described limitations. Bianchi et al. reported an insignificant decrease in the ramal angle and a significant decrease of 21.43% for the genial tubercle of the mandible to the hyoid bone distance (Bianchi et al., 2017). These findings were obtained using a bone-borne distractor.

Overall, bone-borne distractors cause a more proportionate expansion in vertical direction compared with the hybrid and tooth-borne distractors (Gunbay et al., 2009; Seeberger et al., 2011). Bone-borne distractors apply their force mostly at the mandibular basal level compared to tooth-borne distractors. This is in line with Kim et al. and Boccaccio et al., who observed more expansion in the alveolar process area and dental arch with the tooth-borne distractor than with the hybrid and bone-borne distractor (Boccaccio et al., 2011; Kim et al., 2012).

These findings suggest that, in terms of skeletal effect, the bone-borne distractor is preferable. However, it should be noted that a second surgical procedure is needed to remove this distractor, which is not the case for a tooth-borne distractor.

Dental effects

Three studies (Landes et al., 2008; Seeberger et al., 2011; Bianchi et al., 2017) reported the inter dental distances following MMD. Landes et al. and Bianchi et al. showed a significant change of the inter canine distance. However, both authors used a different type of distractor (Landes et al., 2008; Bianchi et al., 2017). Seeberger et al. and Bianchi et al. measured the inter first molar crown, inter first molar root, inter first premolar crown and inter first premolar root distances (Seeberger et al., 2011; Bianchi et al., 2017). Except the inter first molar crown distance in the Bianchi et al. study, all of these distances changed significantly in both studies (Seeberger et al., 2011; Bianchi et al., 2017). Both studies used a different type of distractor and Seeberger et al. reported a relatively short follow-up period of 3 months, which makes it difficult to compare (Seeberger et al., 2011; Bianchi et al., 2017). Longer follow-up periods are needed to analyse the dental stability taking relapse and remodelling into account. Concerning dental angulation, data are sparse due to different influencing factors such as type of distractor, widening of the hemimandible, orthodontic treatment and availability of 3D imaging analysis techniques. Only one study reported on dental angulation following MMD, which was a significant lateral angulation on the tooth-borne distractor fixation level of all first molars and premolars (2.63° and 3.32° respectively) (Seeberger et al., 2011). It can be concluded that the tooth-borne distractor leads to significant dental tipping, which could affect the dental stability negatively in the long-term.

Soft tissue effects

Only one study (Bianchi et al., 2017) reported soft tissue effects following MMD. Major post-operative changes in the lower lip and chin were observed. MMD did not cause any vertical or horizontal asymmetry. There was statistical significance demonstrated in the sagittal projection of the cheilion, labialis inferior, pogonion points and enlargement of the mouth and chin. The axial sections through the pogonion showed a forward displacement of the chin with enlargement after MMD. It should be considered that dental movements due to the orthodontic treatment may have an influence on these findings, especially for the lower lip projection. There was an insignificant increase in mandibular body length, which could be an explanation for the chin projection. However, in this study simultaneous SARME was performed, which complicates the interpretation of the soft tissue effects isolated for MMD.

It can be assumed that MMD leads to soft tissue changes specifically for the lower lip and chin projection, but it should be noted that this assumption is based on only one study.

Biomechanical and masticatory effects specifically on the mandible and the TMJ

Biomechanical and masticatory effects together constitute an important role in MMD. The hybrid distractor seems to be the most stable under functional masticatory loads (Boccaccio et al., 2011), specifically combined with a parasymphyseal step osteotomy (Singh et al., 2016). The magnitude of these masticatory loads seems to have a marginal influence on the optimal latency period with the use of a tooth-borne distractor (Boccaccio 2008a). However, these masticatory loads can influence bone callus formation in the distraction gap (Boccaccio 2008b), where high distraction rates could lead to low quality bone callus (Boccaccio et al., 2007). These outcomes could support healthcare professionals in their choice of distractor type and lead to safer control of distraction.

The effect of chewing on the latency period appears to be marginal. However, this assumption is based on FEM models using various distraction gaps. Moreover, not all FEM models take into account the complete in vivo situation, including the masticatory loads and TMJ. This complicates the comparison of these outcomes. Mastication loads could be influenced by the possible strengthening of these masticatory muscles, while dental contact between the maxilla and the mandible could influence these mastication loads. Also, MMD is often combined with SARME, and there are no FEM models available simulating this situation.

CONCLUSION

There has been a limited number of studies performed on MMD using 3D imaging analysis techniques. Most of these papers are FEM studies and characterized by a low level of evidence. Clinical studies on the (long-term) 3D biomechanical effects of MMD are sparse, and with relatively small sample sizes. There is inconsistency between the effects and the clinical relevance of the distractor types. The bone-borne distractor seems preferable when taking skeletal effects into account. Tooth-borne distraction leads to significant dental tipping, theoretically increasing the risk of relapse. The hybrid distractor combined with a parasymphyseal step osteotomy seems to be the most stable under functional masticatory loads. The effect of chewing appeared to be marginal during the latency period. From these studies, it can be concluded that MMD does not result in clinical permanent TMJ symptoms. However, possible long-term effects on the TMJ are not clarified yet because long-term follow-up studies are lacking. In addition, little is known about the soft tissue effects of MMD. More clinical studies with large case series, using 3D imaging analysis techniques, are needed to clarify long-term morphological 3D aspects of MMD.

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