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Fixation methods in sagittal split ramus osteotomy: a systematic review on in vitro biomechanical assessments

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Abstract. The aim of this systematic review was to assess the stability of rigid internal fixation (RIF) techniques in sagittal split ramus osteotomy (SSRO) based on in vitro biomechanical assessments, with particular interest in large mandibular advancements. In general, RIF methods can be divided into three groups: bicortical screws, miniplates, and a combination of the two. An electronic search of the PubMed, CINAHL, and Embase databases was performed, and studies published between January 2003 and March 2018 were screened for inclusion. Comparative studies with an in vitro experimental design, using biomechanical assessments to measure the stability of RIF methods in SSRO, were included. Of 104 unique studies identified in the initial search, 24 were included. Twenty-two of these 24 studies analyzed an advancement of the mandible of 7 mm or less. The use of a single four-hole or six-hole miniplate was less stable than the use of bicortical screws, hybrid techniques, double miniplates, or grid plates. Two studies analyzed advancements of 10 mm, for which two miniplates placed in parallel and a grid plate showed most stability. Although there was agreement between studies with regard to results, more biomechanical studies are required to quantify the stability of fixation methods in larger mandibular advancements.

Key words: sagittal split ramus osteotomy; mandibular advancement; jaw fixation techniques.

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The sagittal split ramus osteotomy (SSRO) is a commonly performed procedure in oral and maxillofacial surgery practice. It can be performed as a single treatment or in combination with a Le Fort I osteotomy, depending on the specific indication. With the SSRO, a sagittal split is performed in the mandible, creating two proximal and one distal segment. The distal segment of the mandible can subsequently be set back or advanced in relation to the proximal segments.

In contrast to the restoration of a traumatic fracture in which bone fragments are stabilized at the fracture site, advancement of the distal SSRO segment will result in bony gaps across the osteotomy site. Stability in SSRO is therefore all the more determined by fixation techniques. Since the introduction of rigid internal fixation (RIF) in SSRO by Spiessl in

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1974[1], different techniques have been applied to stabilize the proximal and distal segments.

In general, miniplates, bicortical screws, or a combination of the two (hybrid) are the RIF techniques most used (Fig. 1). Each fixation technique has its advocates, and its application is mostly dependent on professional experience and preference. The use of bicortical screws in the stabilization of SSRO is the most cost-effective technique, with lower costs in comparison to the use of miniplates and with a similar operating time. In addition, the placement of bicortical screws is considered the most predictable way to achieve fixation of mandibular osteotomy segments[2]. The use of miniplates in the fixation of SSRO has other benefits. Miniplates can be placed without the need for an extraoral incision, which avoids visible scarring of the skin. Moreover, because monocortical screws are used, damage to the inferior alveolar nerve is less likely. Another advantage is that in the case of malposition during surgery, readjustments can be made more easily when compared with the use of bicortical screws. This may also be beneficial in teaching surgical trainees[3].

The function of RIF is to achieve stability between the bony fragments in the early postoperative phase. In a review on the stability of bicortical screws in SSRO, Ochs concluded that the use of three bicortical screws is the most rigid way to fixate a sagittal split osteotomy[2], referring to several in vitro studies in which biomechanical assessments were used to test the stability of a fixation method[4,5].

In a review on the use of miniplates in SSRO, Stoelinga and Borstlap[3] referred to an in vitro study on sheep mandibles in which no differences in stability were found between the use of a miniplate or bicortical screws[6]. The authors questioned the clinical relevance of an in vitro design in testing stability, since patients will be limited in chewing forces during masticatory function due to oedema and haematoma and will be instructed not to chew solid foods in the first weeks after surgery. Stoelinga and Borstlap urged for a clinical experimental set-up, in which a randomized controlled trial had to be conducted to test stability and other possible relevant differences between miniplates and bicortical screws in SSRO fixation[3].

In a recent clinical systematic review and meta-analysis on postoperative skeletal stability after SSRO in patients treated with either miniplates or bicortical screws, no significant difference was found between the two treatment modalities[7]. However, the study was limited by the number of comparative clinical studies included, of which only one was a randomized controlled trial.

In another systematic review, the relapse rate after SSRO advancement surgery with different types of RIF was evaluated[8]. This review included a large number of clinical trials, most of which were retrospective. Long- and short-term relapse rates were compared between miniplates, titanium bicortical screws, and resorbable bicortical screws. A greater number of studies reported higher long-term skeletal relapse rates for patients treated with titanium or resorbable bicortical screws than for patients treated with miniplates. The authors also concluded that advancements of 6–7 mm or more predispose the patient to horizontal relapse[8]. Despite these observations, the application of large mandibular advancements with SSRO in oral maxillofacial surgery is increasing. For example, in patients with obstructive sleep apnoea (OSA), maxillomandibular advancement with large mandibular advancements has been demonstrated to be a safe and highly effective treatment modality[9,10].

Although prospective comparative clinical studies on the stability of fixation techniques in SSRO are low in number, several in vitro studies investigating modifications of the described fixation techniques have been conducted in recent years. Despite differences in experimental design when compared to clinical studies, in vitro biomechanical studies represent a useful instrument to enhance knowledge on the biomechanical characteristics of fixation techniques used in SSRO. The rigidity of the hardware can be objectified. Different fixation techniques can be tested and optimized under standardized condi-

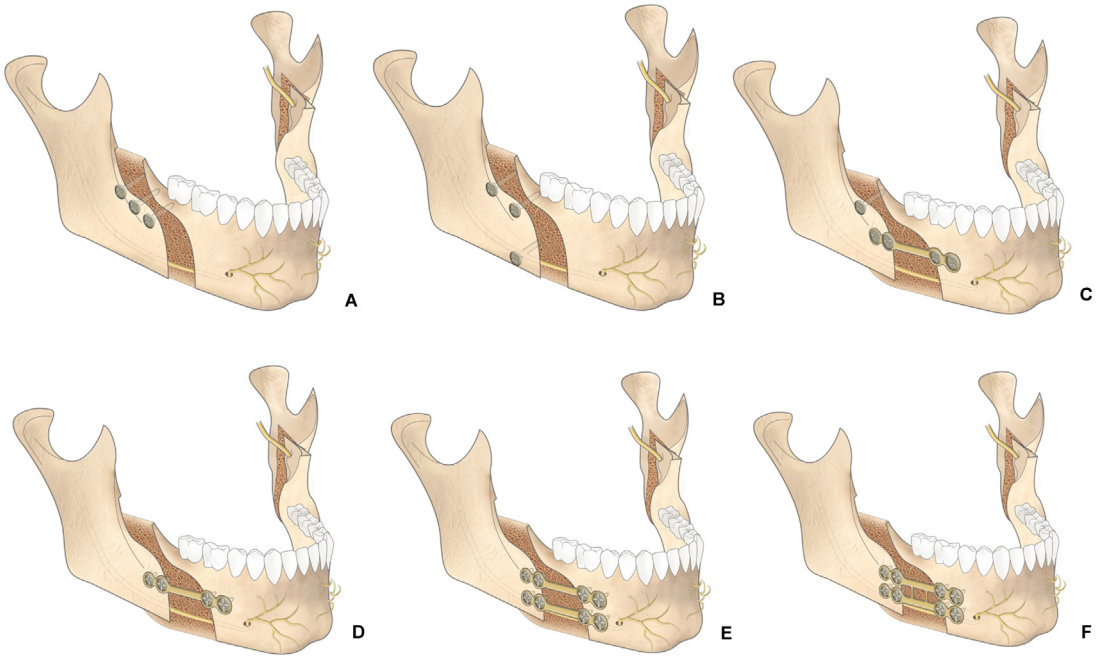

Fig. 1. Six fixation methods for the mandible following sagittal split ramus osteotomy (SSRO) with advancement: (A) three bicortical screws placed linearly, (B) three bicortical screws placed in an inverted-L pattern, (C) hybrid fixation, (D) one four-hole straight miniplate, (E) two straight miniplates placed parallel to each other, (F) grid plate.

tions in a controlled and safe manner. Before new fixation techniques are used in a clinical setting, a solid biomechanical basis is vital.

This article reviews the contemporary literature on new developments in and current perceptions of RIF methods for the stabilization of SSRO based on in vitro biomechanical assessments, with specific interest in large mandibular advancements.

The purpose of this study was to identify the most stable fixation techniques according to in vitro biomechanical assessments.

Materials and methods

This systematic review was structured in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. In vitro studies evaluating the stability of RIF techniques with SSRO were acquired after a search in the PubMed, CINAHL, and Embase databases. The electronic search was restricted to studies published in the English language between January 2003 and March 2018. Since both Ochs (2003)[2] and Stoelinga and Borstlap (2003)[3] have published comprehensive overviews regarding the use of bicortical screws and miniplates, 2003 was chosen as the first year of inclusion for this review.

The following key words were used in the search: sagittal split ramus osteotomy; mandibular advancement; sagittal split osteotomy; SSRO; sagittal ramus osteotomy; bilateral sagittal split osteotomy; BSSO; jaw fixation techniques; miniplate; plate; bicortical screw; screw; rigid internal fixation; in vitro; biomechanical; polyurethane; replica; synthetic; cadaver; human; animal; and sheep. Articles written in English were selected. The reference lists of identified articles were scanned manually for further eligible studies that had not been captured in the database search. A detailed overview of the search strategy is given in the **Supplementary Material** (Appendix A).

Titles and abstracts were screened for inclusion against the following criteria: (1) in vitro comparative studies concerning mandibular advancement by sagittal split osteotomy surgery, (2) use of biomechanical tests to compare the stability of multiple RIF methods, (3) use of (hemi) mandibles (cadaveric human or animal) or replica (hemi)mandibles for the tests. Comparative studies that used other material as mandibular substitutes were excluded.

Data concerning the stability of fixation methods measured in loading resistance (in newtons) were extracted from the included studies. The methodological quality of each individual study was weighted on the basis of randomization, standardization, and outcomes.

Results

The initial search returned 189 records. A total of 133 publications were unique. Of these publications, 104 were published from 2003 onwards. Based on title and abstract, full-text documents were acquired for 28 studies that were possibly eligible[11–38]. After full-text analysis, four articles did not meet the previously stated inclusion criteria[35–38], thus 24 studies could be included[11–34] (Fig. 2).

Most studies did not describe the use of randomization[11,12,14–17,20–22,24–27,29,30,32]. Other studies made use of randomization, although a detailed report of this process was missing[13,18,19,23,28,31,33,34]. Fixation of the RIF methods in SSRO was standardized with the use of an acrylic or resin guide[11,12,15,17–22,25]. One study described the use of standardization without a detailed description[32]. The other articles did not report on the process of standardization in the fixation of RIF methods[13,14,16,23,24,26–31,33,34]. Most studies made comparisons of original data[11–15,18–24,26–34], while three articles used the outcomes from earlier studies for comparison with new measurements[16,17,25].

The objective of all included studies was the measurement of load resistance of the fixated mandibles, with the load applied by a loading machine. The linear non-cyclical force necessary to develop a displacement was evaluated in an in vitro testing environment.

Different outcome values were used in the included studies. In some studies, stability was assessed by the measurement of peak/yield load, which is the load at which permanent deformation starts[12,14,17,22,24–26,29,34]. Other studies measured the load necessary for a specific amount of displacement in millimetres[11,13,15,16,19–21,23,27,31], all of which measured loading resistance at 3 mm displacement. Another

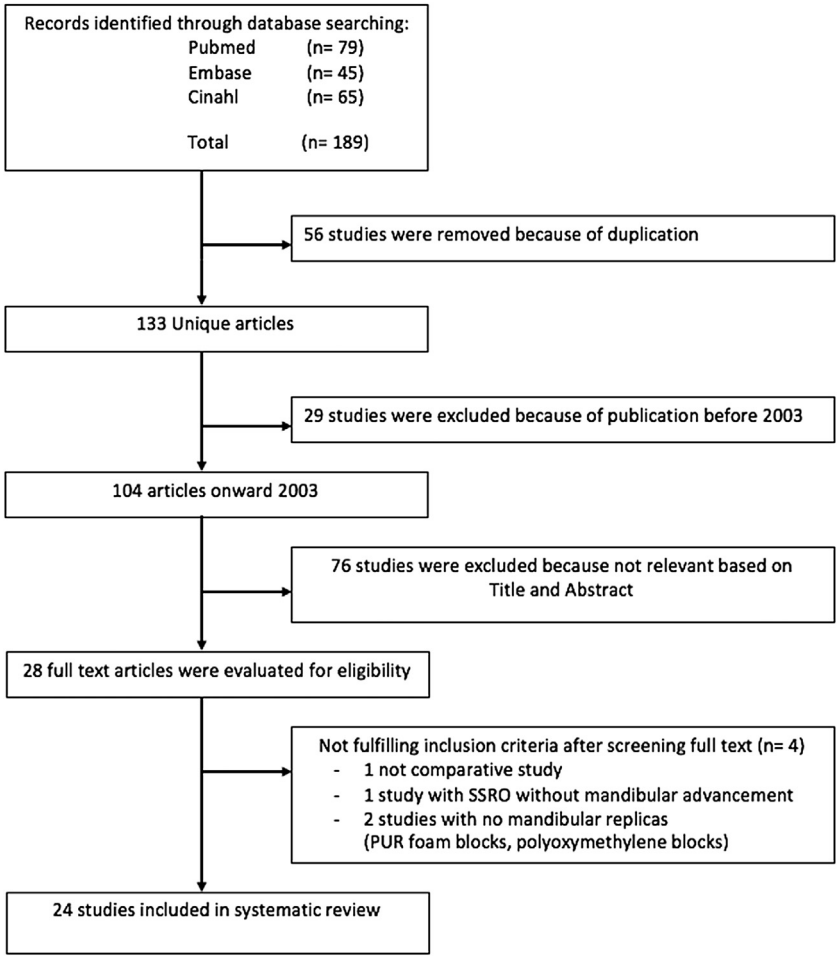

Fig. 2. Study selection procedure.

group of studies used standardized loads in newtons, which were based on studies that had observed postoperative occlusal forces[28,30,32,33]. Regarding the size of the mandibular advancement, most of the in vitro studies used an advancement of 5 mm to test the different fixation methods[11,12,14,15,17–20,22,27–34]. Three studies used an advancement of 7 mm[24–26], whereas two other studies used an advancement of 10 mm[21,23].

The selected studies were divided into three groups according to the mandibular material used and placed in chronological order.

Polyurethane mandibles

Eighteen of the included studies used synthetic (polyurethane) material mandibles for the biomechanical tests. Thirteen studies used hemimandibles (Table 1) and five studies tested complete mandibles (Table 2). Three manufacturers produced the polyurethane mandibles: Nacional Ossos (Jaú, Sao Paulo, Brazil), Synbone (Malans, Switzerland), and Sawbones, Pacific Research Laboratories, Inc. (Vashon Island, WA, USA). The hemimandibles made by Nacional Ossos consisted of a solid polyurethane material[11,12,14,17–22]. The mandibles or hemimandibles made by Synbone[13,15,16,24–28] and Sawbones[23] consisted of polyurethane with a medullar and cortical structure. A sagittal split osteotomy was performed in all studies.

Hemimandibles

Brasileiro et al. (2009) studied the biomechanical properties of three different fixation techniques for mandibular stabilization after SSRO[11]. Twenty specimens per group were tested with lateral or vertical forces. The authors concluded that the use of three bicortical screws provided the greatest stability after vertical loading. No significant difference between bicortical screws and a hybrid construction was seen with lateral loading. The authors also concluded that the addition of a bicortical screw to a miniplate significantly optimized the resistance of the fixation.

Sato et al. (2010) compared the stability of three different configurations of bicortical screw fixation to fixation with a single miniplate[12]. Three bicortical screws in an inverted-L arrangement or linear arrangement placed at 90° were the most resistant fixation methods. The group with the linear arrangement of 60° was less resistant, although more resistant than the miniplate group.

Ribeiro-Junior (2010) compared nine different fixation techniques[13]. All hemimandibles were subjected to SSRO with the help of an acrylic resin matrix to demarcate the path of the saw cut. The results showed that the addition of a bicortical screw next to a miniplate resulted in significantly greater stability, including greater stability compared to two miniplates placed parallel to each other, although this was not significantly more stable than the use of three bicortical screws. The stability of two miniplates was similar to that of three bicortical screws. The authors also concluded that locking miniplates presented better performance in bone fixation than conventional miniplates, although this conclusion was not based on significant results.

Scaf de Molon et al. (2011) compared the diameter size of self-tapping titanium bicortical screws with regard to fixation stability[14]. The stability of SSRO fixation did not differ significantly with the use of screws of 2.0 mm or 1.5 mm in diameter. The authors concluded that screws of 1.5 mm diameter appear to be safe for clinical use.

Hwang et al. (2012) evaluated the effect of the number and geometry of resorbable (polylactic acid copolymer) bicortical screws[15]. The authors concluded that fixation with three resorbable bicortical screws fixed in the retromolar area and the mandibular angle could provide better stability than a titanium miniplate and also similar stability to the use of four or five resorbable bicortical screws.

Ribeiro Junior et al. (2012) studied the stability of three different miniplates with locking or non-locking fixation material[16]. In this study, no significant differences were found between fixation methods with locking material and the same methods with non-locking material. Furthermore, in the comparison between all groups, the use of a six-hole sagittal locking plate (double-Y shaped) showed greater resistance than a six-hole straight miniplate and fixation with a four-hole standard miniplate with non-locking screws.

Sato et al. (2012) compared the stability of the hybrid technique with two other fixation methods[17]. In the biomechanical tests, the hybrid technique was more stable than single miniplate fixation. However, three bicortical screws in an inverted-L configuration performed better regarding stability than the hybrid fixation.

Pereira Filho et al. (2013) evaluated the biomechanical stability of a custom-made bone plate compared to regular methods used for fixation of SSRO[18]. The authors concluded that the inverted-L fixation method provided greater stability than the use of a miniplate or a custom-made bone plate. The maximum loading forces were significantly higher for the inverted-L group and showed the least resistance in the custom-made bone plate group.

Oguz et al. (2015) evaluated six different RIF methods[19]. At 3 mm displacement, the four-hole miniplate + bicortical screw and the grid miniplate showed significantly more resistance force than the use of a locking plate, 2.0 mm miniplate, or a six-hole miniplate.

Lima et al. (2015) performed biomechanical loading tests to compare cannulated bicortical screws with bicortical screws with a solid core[20]. Cannulated screws could carry significantly more load before 1 mm of displacement was reached than solid-core screws. However, there was no difference in loading resistance between groups at more than 1 mm of mandibular displacement.

De Oliveira et al. (2016) conducted biomechanical tests on 60 synthetic hemimandibles after SSRO[21]. The distal part of the mandible was advanced with counterclockwise rotation with the help of acrylic guides to standardize repositioning. The authors concluded that a grid plate or two miniplates provided the greatest stability in the fixation of the hemimandibles, followed by a hybrid fixation or a four-hole miniplate with locking material. The least stable groups were the hemimandibles fixated with four-hole or six-hole straight miniplates.

Vieira Santos et al. (2017) compared four different fixation methods, with locking or non-locking material, modelled in two different SSRO designs[22]. The osteotomy performed in the first group had a right angle below the two molars, which descended perpendicular to the base area of the mandible. In the second group, the SSRO was performed without the right angle and descended in a straight line to the anterior base area of the mandible. Overall there was no significant difference between the two SSRO designs regarding mechanical resistance, although the use of a single miniplate performed better in the group without a right angle in the SSRO. Furthermore, on comparison between groups, the use of a locking miniplate with bicortical screw offered more mechanical resistance than the use of a single locking or non-locking four-hole miniplate.

Klein et al. (2017) tested six fixation methods modelled with two different mandibular advancement methods, namely 10-mm straight advancement and 10-mm advancement with 20° counterclockwise rotation[23]. Overall, more stability was

Table 1. Polyurethane hemimandibles.

Study	Year (Ref.)	Type of RIF	Study sample, *n*	Biomechanical assessment model	Application of load	Advancement	Mean peak load	Mean load at 3 mm displacement	Significance
1	Brasileiro et al. 2009[11]	(1) 4-hole minipl + sc (2) 4-hole minipl + sc + BiCoSc (hybrid) (3) 3 BiCoSc inverted-L	60 (30/30)	2-point model	(a) Vertical loading incisal edge (b) Lateral loading, lateral surface of first molar	5 mm		(1a) 4.0 N (1b) 9.8 N (2a) 5.8 N (2b) 12.7 N (3a) 10.1 N (3b) 12.1 N	Significant (3) > 1, 2 vertical loading No significant difference for lateral loading
2	Sato et al. 2010[12]	(1) 3 BiCoSc linearly at 90° (2) 3 BiCoSc linearly at 60° (3) 3 BiCoSc inverted-L (4) 4-hole minipl + sc (5) Uncut hemimandible (control)	50	2-point model	First molar	5 mm	(1) 258.9 N (2) 191.5 N (3) 277.5 N (4) 41.9 N (5) 772.2 N		Significant (5) > 1, 2, 3, 4 (1, 3) > 2, 4 (2) > 4
3	Ribeiro-Junior et al. 2010[13]	(1) 4-hole minipl + sc (2) 4-hole locking minipl + sc (3) 4-hole minipl + sc + BiCoSc (hybrid) (4) 4-hole locking minipl + sc + BiCoSc (hybrid) (5) 6-hole minipl + sc (6) 6-hole locking minipl + sc (7) 2 × 4-hole minipl + sc (8) 2 × 4-hole locking minipl + sc (9) 3 BiCoSc inverted-L	45	3-point model according to Armstrong et al.[41]	Second molar	4 mm		(1) 49.2 N (2) 55.2 N (3) 183.4 N (4) 193.2 N (5) 46.8 N (6) 46.6 N (7) 145.0 N (8) 150.0 N (9) 178.0 N	Significant (4) > 1, 2, 5, 6, 7, 8 (3) > 1, 2, 5, 6, 7 (9) > 1, 2, 5, 6 (8) > 1, 2, 5, 6 (7) > 1, 2, 5, 6
4	Scaf de Molon et al. 2011[14]	(1) 3 BiCoSc inverted-L 1.5 mm diameter (2) 3 BiCoSc inverted-L 2.0 mm diameter	20	2-point model	Incisal edge	5 mm	(1) 185.0 N (2) 233.0 N		Not significant

5	Hwang et al. 2012[15]	(1) 4-hole minipl + sc (2) 3 resorbable BiCoSc linear (3) 2 resorbable BiCoSc, in retromolar area and 1 in mandibular body (4) 2 resorbable BiCoSc in retromolar area and 1 in mandibular angle (5) 3 resorbable BiCoSc retromolar area and 1 in mandibular body (6) 3 resorbable BiCoSc in retromolar area and 1 in mandibular angle (7) 3 resorbable BiCoSc in retromolar area, 1 in mandibular angle, 1 in mandibular body	35	2-point model	First molar	5 mm		(1) 10.5 N (2) 22.9 N (3) 27.7 N (4) 31.0 N (5) 33.0 N (6) 35.7 N (7) 39.2 N	Significant (7) > 1, 2 (3, 4, 5, 6) > 1
6	Ribeiro-Junior et al. 2012[16]	(1) 4-hole minipl + sc (2) 4-hole locking minipl + locking sc (3) 6-hole minipl + sc (4) 6-hole locking minipl + locking sc (5) 6-hole sagittal minipl + sc (horizontal double-Y design) (6) 6-hole locking sagittal minipl + locking sc (horizontal double-Y design)	30	3-point model according to Armstrong et al.[41]	Second molar	4 mm		(1) 49.2 N[a,13] (2) 55.2 N[a,13] (3) 46.8 N[a,13] (4) 46.6 N[a,13] (5) 64.0 N (6) 85.2 N	Significant (6) > 1, 3, 4
7	Sato et al. 2012[17]	(1) 4-hole minipl + sc + BiCoSc (hybrid) (2) 3 BiCoSc inverted-L (3) 4-hole minipl + sc	30	2-point model	First molar region	5 mm	(1) 188.4 N (2) 277.5 N[a] (Sato 2010) (3) 41.9 N[a,12]		Significant 2 > 1 > 3
8	Pereira Filho et al. 2013[18]	(1) 3 BiCoSc inverted-L (2) 4-hole minipl + sc (3) 8-hole sagittal minipl + sc (tuning-fork shaped)	30	2-point model	Between first and second molar	5 mm	Max load until 10 mm displacement: (1) 87.3 N (2) 51.9 N (3) 35.6 N		Significant 1 > 2 > 3
9	Oguz et al. 2015[19]	(1) 2 × 4-hole minipl + sc (2) 4-hole minipl + sc (3) 4-hole minipl + sc + BiCoSc (hybrid) (4) 8-hole gridpl + sc (5) 4-hole locking minipl + locking sc (6) 6-hole minipl + sc	60	2-point model	Premolar region	5 mm		(1) 32.1 N (2) 16.9 N (3) 40.9 N (4) 38.1 N (5) 24.6 N (6) 21.0 N	Significant (3) > 1, 2, 5, 6 (4) > 2, 5, 6 (1) > 2, 6

Table 1 (*Continued*)

Study	Year (Ref.)	Type of RIF	Study sample, *n*	Biomechanical assessment model	Application of load	Advancement	Mean peak load	Mean load at 3 mm displacement	Significance
10	Lima et al. 2015[20]	(1) 3 cannulated BiCoSc inverted-L (2) 3 solid-core BiCoSc inverted-L	20	2-point model	First molar region	5 mm		(1) 64.9 N (2) 49.2 N	Not significant Although significant at 1 mm displacement, 1 > 2
11	De Oliveira et al. 2016[21]	(1) 4-hole minipl + sc (2) 6-hole minipl + sc (3) 2 × 4-hole minipl + sc (4) 8-hole gridpl + sc (5) 4-hole minipl + sc + BiCoSc (hybrid) (6) 4-hole locking minipl + sc	60	2-point model	Between canine and first premolar	8 mm upper border 11 mm lower border		(1) 6.8 N (2) 5.8 N (3) 25.7 N (4) 24.2 N (5) 12.8 N (6) 15.2 N	Significant (3, 4) > 5, 6 > 1, 2
12	Vieira Santos et al. 2017[22]	2 sagittal split osteotomies: (A) right angle between osteotomy, (B) no angle osteotomy: (1) 4-hole minipl + sc (2) 4-hole minipl + sc + BiCoSc (hybrid) (3) 4-hole locking minipl + sc (4) 4-hole locking minipl + sc + BiCoSc (hybrid)	40	2-point model	First molar region	5 mm	(1) 106.7 N (2) 145.0 N (3) 105.0 N (4) 162.7 N	(1a) 81.7 N (1b) 130.7 N (2a) 131.2 N (2b) 158.8 N (3a) 68.4 N (3b) 141.6 N (4a) 136.6 N (4b) 188.9 N	No significant differences in peak load SSRO A or B Significant 4 > 1, 2 1b > 1a 3b > 3a
13	Klein et al. 2017[23]	2 sagittal split osteotomies: (A) 10 mm advancement, (B) 10 mm advancement with 20° counterclockwise rotation; 6 subgroups each: (1) 4-hole minipl + sc (2) 2 × 4-hole minipl + sc (3) 6-hole double-Y sagittal plate + sc (4) 4-hole locking minipl + sc (5) 2 × 4-hole locking minipl + sc (6) 6-hole double-Y sagittal locking plate + sc	60	3-point model according to Ribeiro-Junior et al.[13]	First molar region	SSRO group (a): 10 mm SSRO group (b): 9 mm upper border, 12 mm lower border		(1a) 44.3 N (1b) 33.0 N (2a) 105.9 N (2b) 93.0 N (3a) 59.9 N (3b) 50.5 N (4a) 53.5 N (4b) 41.1 N (5a) 127.1 N (5b) 110.3 N (6a) 66.6 N (6b) 56.9 N	Significant SSRO (a) > SSRO (b) for subgroups 1, 3, 4 Between subgroups: SSRO (a): (2, 5) > 1, 3, 4, 6 (6) > 1, 4 (3) > 1 SSRO (b): (5) > 1, 3, 4, 6 (2) > 1, 3, 4 (6) > 1, 4 (3) > 1

RIF, rigid internal fixation; minipl, miniplate; sc, monocortical screws; BiCoSc, bicortical screw; gridpl, grid plate.

[a] Results of earlier studies were used for comparison.

Table 2. Complete polyurethane mandibles.

Study	Year (Ref.)	Type of RIF	Study sample, *n*	Biomechanical assessment model	Application of load	Advancement	Mean yield load	Mean load at 3 mm displacement	Significance
1	Peterson et al. 2005[24]	(1) 3 BiCoSc inverted-L (2) 4-hole straight minipl + sc (3) 6-hole curved minipl + sc (4) 4-hole adjustable slide minipl + sc (5) Complete uncut mandible (control)	50 (25/25)	2-point model	(a) Incisal edge (b) Contralateral between first and second molar	7 mm	(1a) 143.3 N (1b) 352.4 N (2a) 43.9 N (2b) 220.8 N (3a) 48.0 N (3b) 210.0 N (4a) 27.7 N (4b) 345.2 N (5a) 517.9 N (5b) 890.8 N		Significant (5) > 1, 2, 3, 4 (1a) > 2a, 4a (1b, 4b) > 2b, 3b
2	Van Sickels et al. 2005[25]	(1) 3 BiCoSc inverted-L (2) 4-hole adjustable slide plate (3) 4-hole adjustable slide plate with BiCoSc (4) 4-hole adjustable slide plate with 2 BiCoSc (5) 4-hole adjustable slide plate with 3 BiCoSc (6) Complete uncut mandible (control)	60 (30/30)	2-point model	(a) Incisal edge (b) Contralateral first molar	7 mm	(1a) 143.3 N[a,24] (1b) 352.4 N[a,24] (2a) 27.7 N[a,24] (2b) 345.2 N[a,24] (3a) 70.4 N (3b) 185.2 N (4a) 104.6 N (4b) 238.7 N (5a) 130.1 N (5b) 274.9 N (6a) 517.9 N[a,24] (6b) 890.8 N[a,24]		Significant (6) > 1, 2, 3, 4, 5 (1a, 5a) > 2a, 3a, 4a
3	Aymach et al. 2011[26]	(1) Straight 6-hole minipl + 4 sc (2) 2 straight 6-hole minipl + 8 sc (3) 8-hole T-shaped minipl + 6 sc[b]	18	2-point model	Incisal edge	7 mm	(1) 12.2 N (2) 34.2 N (3) 31.3 N		Significant (2, 3) > 1
4	Sener et al. 2012[27]	(1) 2 × 4-hole minipl + sc placed parallel (2) 2 × 4-hole minipl + sc placed parallel with an oblique connection (3) 2 × 4-hole minipl + sc placed parallel with a connection oblique and at both ends	15	3-point model according to Armstrong et al.[41]	Double-sided wire, mandibular angle	5 mm		(1) 14.8 N (2) 19.6 N (3) 19.4 N	Significant (2, 3) > 1
5	Ulu et al. 2018[28]	(1) 4-hole miniplate + sc (2) 3 BiCoSc inverted-L (3) 4-hole resorbable miniplate + sc (4) 3 resorbable BiCoSc inverted-L	16	Custom-made 6-point model	Double-sided wire, mandibular angle	5 mm		120 Newton (1) 0.40 mm (2) 0.35 mm (3) 0.43 mm (4) 0.85 mm 240 Newton (1) 0.83 mm (2) 0.62 mm (3) 0.86 mm (4) 1.08 mm	Significant (2) > 3, 4 (1, 3) > 4

RIF, rigid internal fixation; minipl, miniplate; sc, monocortical screws; BiCoSc, bicortical screw.
[a] Results of earlier studies were used for comparison.
[b] Aymach et al.[26] used a modified SSRO in the third group.

Table 3. Sheep hemimandibles.

Study	Year (Ref.)	Type of RIF	Study sample, *n*	Biomechanical assessment model	Application of load	Advancement	Mean peak load	Mean load at 3 mm displacement	Significance
1	Gomes et al. 2003[29]	(1) 3 BiCoSc in inverted-L (2) 3 resorbable BiCoSc in inverted-L	20	2-point model	Between last two molar teeth	5 mm	(1) 180.9 N (2) 163.5 N		Not significant
2	Dolanmaz et al. 2004[30,a]	(1) Titanium 4-hole minipl + sc (2) Resorbable 4-hole minipl + sc	12	3-point model	Wire, mandibular angle	5 mm		10 Newton (1) 0.01 mm (2) 0.04 mm 50 Newton (1) 0.06 mm (2) 0.13 mm 100 Newton (1) 0.12 mm (2) 0.23 mm	Significant difference at 10–50 N 1 > 2
3	Özden et al. 2006[31]	(1) 1 BiCoSc (2) 2 BiCoSc in vertical pattern (3) 2 BiCoSc in linear pattern (4) 3 BiCoSc inverted backward-L (5) 3 BiCoSc inverted-L (6) 4-hole minipl + sc (7) 4-hole minipl (oblique placed) + 2 BiCoSc in proximal segment + 2 sc distal segment of plate (8) 4-hole minipl (oblique placed) + sc (9) 4-hole minipl (oblique placed) + 2 BiCoSc in prox segment + 2 sc distal segment of plate + 1 additional BiCoSc in prox segment of mandible (10) 3 resorbable BiCoSc inverted-L	50	3-point model, according to Armstrong et al.[41]	Mandibular angle	5 mm		(1) 9.6 N (2) 497.7 N (3) 268.4 N (4) 778.5 N (5) 495.5 N (6) 222.8 N (7) 452.3 N (8) 283.5 N (9) 789.0 N (10) 510.9 N	Significant (4, 9) > 1, 2, 3, 5, 6, 7, 8, 10 (2, 5, 7, 10) > 1, 3, 6, 8 (8) > 1, 6 (3, 6) > 1
4	Cilasun et al. 2006[32,a]	(1) 3 BiCoSc in inverted-L (2) 3 resorbable BiCoSc in inverted-L	20	3-point model according to Dolanmaz et al.[30]	Wire, mandibular angle	5 mm		10 Newton (1) 0.84 mm (2) 0.70 mm 50 Newton (1) 3.10 mm (2) 2.36 mm 100 Newton (1) 5.15 mm (2) 4.19 mm	Not significant

5	Oguz et al. 2011[33 a]	(1) Titanium 4-hole minipl + sc (2) Titanium 4-hole locking minipl + locking sc	20	3-point model according to Dolanmaz et al.[30]	Wire, mandibular angle	5 mm	20 Newton (1) 1.51 mm (2) 1.48 mm 120 Newton (1) 5.32 mm (2) 5.07 mm	Not significant
6	De Olivera et al. 2012[34]	(1) 3 BiCoSc inverted-L30 (2) 2 BiCoSc horizontally placed with 4-hole minipl + sc (hybrid) (3) 2 × 4-hole minipl + sc		2-point model	Second molar	5 mm	(1) 119.6 N (2) 107.8 N (3) 115.7 N	Not significant

RIF, rigid internal fixation; minipl, miniplate; sc, monocortical screws; BiCoSc, bicortical screw; prox, proximal.
[a] These studies used standardized loads in Newton to compare displacement in millimetres.

observed in the group without counter-clockwise rotation. The straight group showed significantly better mechanical resistance for a single locking or non-locking miniplate and a double-Y design non-locking plate. Furthermore, regarding the tested fixation methods, the authors concluded that double miniplates showed the greatest mechanical stability, followed by one double-Y design plate and then a single miniplate.

Complete mandibles

Peterson et al. (2005) compared four different fixation methods[24]. Regarding the incisal yield load, the inverted-L group showed significantly higher values than the four-hole straight and four-hole slide miniplate groups. However, for molar loading, the inverted-L group and the slide plate group resisted more loading than the curved six-hole plate group and the four-hole straight miniplate group.

Van Sickels et al. (2005) tested the biomechanical stability of five fixation techniques with the use of molar and incisal loading[25]. There was no significant difference between the fixation groups for the molar loads. The inverted-L group, with or without the combination of a slide miniplate, showed greater resistance for incisal loads than the single slide plate group. The authors concluded that a single adjustable slide plate with or with out additional bicortical screw is resistant to torsional loading in the molar region. However, with an advancement of 7 mm, two or three additional bicortical screws are necessary to supplement a slide miniplate in order to provide the same resistance to loading as seen with three bicortical screws in an inverted-L pattern.

Aymach et al. (2011) described a model that consisted of a T-shaped miniplate and a modified SSRO (MSSRO) with a buccal step placed adjacent to the mandibular second molar area[26]. Comparisons were made between this model and two other groups in which a standard SSRO was performed and fixated with either one six-hole miniplate with four monocortical screws or two six-hole miniplates with eight screws. The MSSRO group and the SSRO group with two miniplates showed more resistance to vertical loading than the SSRO group with one miniplate. The authors advocated the advantages of MSSRO because of the possible prevention of condylar segment rotation, good clinical results, and a two-point fixation effect with a single construct. However, it is also a more sensitive technique with the potential for unfavourable splits.

Sener et al. (2012) wanted to identify the most appropriate design of a custom-made stainless steel miniplate[27]. The groups with connections between two parallel plates were shown to be more resistant than the groups with non-connecting miniplates. The authors concluded that the test model with the oblique plate combining the parallel plates was the most appropriate model because it can be manipulated more easily than a similar model with two extra vertical connections added, yet with comparable stability.

Ulu et al. (2018) compared resorbable (poly-l-lactic acid/polyglycolic acid (PLLA/PGA)) fixation material with titanium[28]. Bicortical screws in an inverted-L configuration and single four-hole miniplates were used to compare the two materials. Three titanium bicortical screws in an inverted-L was the most stable fixation. The use of resorbable bicortical screws was less stable than a single titanium or resorbable miniplate. The two plate fixation types performed similarly regarding stability.

Sheep hemimandibles

Six of the 24 included studies used fresh adult sheep hemimandibles for biomechanical evaluation[29–34] (Table 3). All mandibles were stripped of all soft tissue and sectioned along the anterior midline. Afterwards, a sagittal split osteotomy was carried out. In order to adapt the hemimandibles correctly to the biomechanical testing unit, the coronoid processes were removed.

Gomes et al. (2003) evaluated the strength of titanium versus resorbable (polylactic acid copolymer) bicortical screws[29]. No significant difference was found between the two groups. The authors concluded that resorbable material would be a feasible alternative for RIF, although a larger number of studies comparing resorbable with titanium material have to be conducted. Consistent outcomes are needed in order to promote support for the use of resorbable systems.

Dolanmaz et al. (2004) tested the stability of resorbable (PLLA/PGA) and conventional miniplates[30]. In that study, displacement in millimetres was compared for standardized loads to a maximum force of 140 newtons. There was a significant difference in displacement values in the force range 10–50 N, indicating less stability in the resorbable fixation group. In the force range 50–140 N, there was a trend towards higher displacement values with the use of resorbable miniplates, however this was not significant.

Özden et al. (2006) tested 10 different fixation methods on stability[31]. The authors concluded that the use of three titanium bicortical screws in an inverted−L configuration was the fixation technique with the greatest resistance. The use of a miniplate placed obliquely and fixed with two bicortical screws in the proximal plate segment was a more stable configuration than miniplates with monocortical screws.

Cilasun et al. (2006) compared groups with resorbable (PLLA/PGA) and titanium bicortical screws[32]. The authors concluded that there was no difference in stability between resorbable and titanium bicortical screws.

Oguz et al. (2011) compared the stability of standard and locking miniplates[33]. No significant differences were found between the conventional miniplate group and the locking plate group. The authors concluded similar stability for conventional and locking systems.

De Olivera et al. (2012) tested three different fixation techniques: three bicortical screws in an inverted−L configuration, a miniplate with the addition of two bicortical screws, and two miniplates placed in parallel[34]. The maximum force in vertical loads needed to introduce instability into the system was recorded for all groups. No significant differences were found. The authors concluded no differences in stability between the groups.

Discussion

Comparison of the in vitro studies included in this review was complicated by the differences in study design regarding the model for biomechanical assessment, characteristics of the mandibular samples, amount of mandibular advancement, and location of mandibular loading. Despite the differences in experimental set-up of the studies, there was some definite concurrence in the results. Three bicortical screws in an inverted-L configuration gave the best loading resistance in studies evaluating up to 7 mm of mandibular advancement. The use of a single straight four-hole or six-hole miniplate was less stable than the use of bicortical screws, hybrid methods, double miniplates, or eight-hole grid plates. Two studies investigated an advancement of 10 mm, in which double miniplates or grid plates achieved the best results; however there was no comparison with three bicortical screws in these studies.

Study design

Most of the studies used polyurethane synthetic hemimandibles for biomechanical testing[11–28]. Ease in standardization, low cost, and ready availability are important reasons why investigators show preference for this model[19]. Also, comparable results have been observed in pull-out strength tests of titanium bone screws when comparing fresh-frozen human cadaveric mandibles to polyurethane replicas[39], supporting their use in the evaluation of the biomechanical performance of RIF systems. In some studies the mandible replicas were made of solid polyurethane[11,12,14,17–22]. These models simulate the external cortex of the human mandible; however internally there is no differentiation between cortical and cancellous bone. Although it increases the rigidity, it has the disadvantage of decreasing the impact of the anatomical details of the human mandible. Other studies used complete polyurethane mandibles with a dense outer layer resembling cortical bone and a porous inner layer that mimics cancellous bone, which is closer to the human anatomy[24–27]. Also, in contrast to most studies that used hemimandibles, this model would be more realistic because of a contralateral side supporting the ipsilateral side of the mandible. The use of polyurethane mandibles is advocated in biomechanical research because of the ability to identify trends in experiments, although direct extrapolation to the clinical situation cannot be made[40].

Other studies used sheep hemimandibles for biomechanical testing[29–34]. The use of sheep models in biomechanical evaluation has been recommended because of their similarity to the human mandible in terms of form, size, and structure[29]. However, the use of sheep mandibles led to considerable variability in results between samples within a fixation group. Four of the six sheep model studies included did not show significant differences between fixation groups, which could be explained by this large range of variation[29,32–34]. A possible reason for this could be the differences in size and bone density between different sheep mandibles. Although the use of human cadaveric mandibles in biomechanical testing would be the most appropriate model as a replica for the clinical situation, it also has the disadvantage of variable size and bone density, which complicates standardization of a study. Furthermore, ethical, practical, and financial issues are well-known difficulties in study designs using human specimens[39].

With regard to the experimental design, different mechanical testing models were used in the studies included. One technique of biomechanical assessment was based on a cantilevered beam model, in which the proximal part of the jaw was fixated and loading was exerted on the distal part. This two-point model was used in various studies for biomechanical assessment[11,12,14,15,17–22,24–26,29,34]. However, other authors consider that the two-point model is inaccurate in mimicking masticatory function. Armstrong et al. introduced the use of a three-point loading model and reported its ability to reproduce the loads on the masticatory system accurately[41]. Other studies have implemented this technique[13,16,23,27,31]. In the three-point biomechanical model, both the proximal and distal hemimandible were fixated and a vertical compression load was applied on the distal segment of the hemimandible, representing a food bolus. Although the experimental model is more complex, it remains theoretical and a two-dimensional representation of the clinical situation. Dolanmaz et al. introduced an alternative version of the three-point biomechanical model, in which the distal part was fixed and the proximal condylar bearing part was able to rotate around the axis[30]. Furthermore, a steel wire was positioned distal to the osteotomy, with an upward direction of the force to establish a maximum possible biting force vector. This technique was also applied by others[32,33]. In order to achieve more realistic results, Ulu et al.[28] used a custom-made six-point biomechanical model. This complete mandible model allowed more mandibular movement by lack of condylar and symphyseal fixation in comparison to the three-point model.

Another variable in the biomechanical assessments was observed in the location of the vertical loading. For this purpose, studies used the incisal edge[11,14,26], premolar region[19,21], or molar region[11–13,15–18,20,22,23,29,34]. Other studies used both incisal loading and first molar loading, which showed higher yield loads for molar loading than incisal loading, naturally explained by the shorter arm of the cantilever model[24,25].

Bicortical screw fixation

Regarding the fixation methods, the bicortical screws were used in different configurations and amounts, and were made of different materials. Two studies did not observe significant differences in rigidity between titanium screws and resorbable screws placed in an inverted-L pattern[29,32]. This, is in contrast to other findings in which titanium screws performed better for load resistance than resorbable screws, both placed in an inverted-L pattern[28,31].

No difference in the stability of three bicortical screws of 1.5 mm or 2.0 mm diameter was observed[14]. Bicortical screws of 1.5 mm provided the same stability and required less availability of space, thereby reducing bone damage. These results are in accordance with earlier findings in which no differences in stability were observed between bicortical screws of 2.0 mm or 2.7 mm in diameter[42].

For fixation of SSRO, cannulated bicortical screws were at least as stable in biomechanical tests as regularly used solid-core bicortical screws[20]. Due to the hollow inner part, the use of cannulated screws could prevent possible inferior alveolar nerve compression. However, the number of clinical studies on the use of these screws in maxillofacial surgery is limited.

Regarding the configuration of bicortical screws, one study found that the use of three bicortical screws in an inverted-L pattern (Fig. 1B) and three bicortical screws placed linearly at a 90° angle (Fig. 1A) performed better for stability when compared to three bicortical screws placed linearly at a 60° angle[12]. This in contrast to the results of another study, in which no difference in load resistance was found between bicortical screws inserted at an angle of 60° or 90° [43]. A clinically relevant advantage of the bicortical screws placed at a 60° angle is the ability to use a transoral approach. This avoids the need for a percutaneous approach[2,12,43].

The use of three bicortical screws in inverted-L pattern has been described as the gold standard for stabilization of a SSRO[25]. In some of the in vitro studies included, the bicortical screws in an inverted-L pattern proved overall to be significantly more stable to vertical loading than any other type of fixation[11,17,18,28]. In other included studies, some fixation methods were used that showed similar results in terms of stability as the three bicortical screws in an inverted-L pattern[12,13,15,25,28,34]. Each in vitro study with a comparison between three bicortical screws in an inverted-L pattern versus a single titanium four-hole miniplate showed significantly greater resistance to vertical loading for the bicortical screws groups[11–13,15,18,24,31].

Although the use of bicortical screws could be recommended based on rigidity, anatomical limitations, such as tooth position, location of the inferior alveolar nerve, and thin alveolar walls after the extraction of third molars, can make their use inconvenient[34]. In addition, other disadvantages can be pointed out, such as the risk of compression of the inferior alveolar nerve between bone segments, the possibility of condylar torque, the need for a possible extraoral approach, and the difficulty of removing bicortical screws in the case of infection or other complications that require removal[12]. Nevertheless, according to a systematic review on common complications associated with SSRO, the need for removal of titanium bicortical screws occurs markedly less often than the need for removal of titanium miniplates[44].

Miniplate fixation

Regarding miniplate fixation, different types of miniplate were assessed. The titanium miniplates used varied in size, shape, type, and number. The standard titanium miniplate used in SSRO has four or six holes[3]. No significant differences were reported on comparison of load resistance for these two types of plate[13,16,19,21]. In all of these studies, other types of fixation method performed better for stability than both of these standard miniplates.

An altered design of the six-hole miniplate, a double-Y-shaped plate, was evaluated in two studies[16,23]. This plate design significantly improved stability in comparison with the conventional six-hole miniplate[16] and four-hole miniplate[23]. However, the use of two miniplates parallel to each other was shown to be more stable than the double-Y-shaped plate[23].

The use of two miniplates (Fig. 1E) provided more stability than a single miniplate[13,19,21,23,26]. When comparing two miniplates with a grid plate (Fig. 1F), two studies observed similar stability[19,21]. However in another study, two miniplates set parallel to each other performed less well with regard to resistance than two groups with different designs of grid plate[27].

The results of a polyurethane model study showed better stability for the hybrid group with locking miniscrews than for the group with two miniplates; however, regarding stability, the two groups were similar to the group with three bicortical screws in an inverted-L[13]. This is in contrast to a sheep model study, in which comparable stability was demonstrated for all three fixation methods[34].

Another comparison was made with the use of locking miniplates[13,16,19,21–23,33]. In contrast to conventional systems, locking

screws are locked to the plate and inserted into the bone at the same time, which may increase primary stability[33]. Despite these theoretical advantages[21], the results of comparative biomechanical studies are inconsistent. Most of the studies included did not find significant differences when comparing various fixation methods with either conventional or locking hardware[13,16,22,23,33]. Despite these results, two of these studies concluded that the locking material showed better performance[13,23]. Only one study found significantly better performance for one four-hole locking plate in comparison to a conventional four-hole or six-hole miniplate[21]. In a comparison of the stress distribution in SSRO using finite element analysis, the use of one four-hole locking miniplate resulted in a more spread load distribution than the use of a conventional plate[45].

Resorbable materials have been developed with the aim of avoiding the possible requirement for removal that may occur with titanium hardware. Despite this advantage, titanium miniplates were shown to be more stable than resorbable alternatives, with less expense, operating time, and complexity of the operation technique[30]. Promising new developments could possibly change this situation. In a more recent study, resorbable PLLA/PGA miniplates had the same stability as titanium miniplates[28].

Hybrid fixation

The combination of a miniplate with one or more bicortical screws is also known as the hybrid fixation method. The most common hybrid fixation consists of a four-hole miniplate and an additional bicortical screw positioned posterior to the miniplate and below the upper mandibular border, which significantly adds to stability in comparison with a single miniplate alone[11,13,17,19,21]. Alongside its stability, the use of the hybrid method is supported by the possibility of intraoral access for the placement of one bicortical screw in the retromolar region[13]. Also, the risk of damage to the surrounding structures during insertion is low, since it is placed in the third molar region, and in most patients this tooth has already been removed. In one study there was a strong tendency for the hybrid option alongside the grid plate to have the higher values for resistance forces[19]. In another study, three bicortical screws performed better in vertical resistance forces, however in lateral resistance forces, the hybrid option was comparable in stability[11].

Altered designs of the hybrid model have also been evaluated, such as the use of three bicortical screws in combination with a miniplate[31]. This model did not show significantly greater stability than the single use of three bicortical screws and was associated with increased costs; furthermore, the need for transcutaneous access for bicortical screw placement in the inferior border of the mandible remained. This result is comparable to that of the study by Van Sickels et al.[25] in which the authors concluded that ''two or three bicortical screws were necessary to be added to a plate to achieve the same stability as the sole use of three bicortical screws''.

Large mandibular advancements

Rigid fixation with bicortical screws in large mandibular advancements (10 mm or more) cannot always be achieved because of the limited bony overlap between the proximal and distal bone fragments. In these instances, hybrid techniques and multiple points of fixation are often advisable[2]. Two studies observed better stability with two miniplates placed parallel to each other than one conventional four-hole miniplate in an SSRO advancement of 10 mm[21,23]. One of these studies concluded that results regarding stability were better with two miniplates or a grid plate in comparison with a hybrid fixation[21]. Counterclockwise rotation was performed in both studies. Counterclockwise rotation of the occlusal plane provides optimal volume of the airways, which is a beneficial effect especially in the case of patients with OSA. However, this movement also results in more stress on the fixation by stretching of the suprahyoid and infrahyoid muscles. Despite this, better stabilization was observed for large advancement without counterclockwise rotation[23]. Biomechanical studies are lacking for advancements of 10 mm or larger. The outcomes of biomechanical assessments concerning advancements of 5 mm are not representative of large advancements. The stress distribution of forces could be different for larger advancements. These differences in force distribution could affect the stability of the fixation techniques. It is possible that more contact points with the bone, as occurs with double miniplates with eight monocortical fixation contacts, could be more important for stability in large advancements than bicortical fixation.

Clinical extrapolation

Although the importance of the biomechanical studies as fundamental research has been acknowledged, the extrapolation of resistance forces measured in these studies to clinical values is more complex. Different biomechanical models have endeavoured to mimic masticatory function, however all of these models remain theoretical. Important determinants in the in vivo situation, for example, support by the soft tissues and muscles, have not been taken into account.

Some studies theorized the amount of resistance that is needed for a stable fixation[24,25,30,32], based on studies investigating the biting forces of healthy people and orthognathic surgery patients[46–48]. Peterson et al.[24] made the assumption that the resistance loads of perioperative biting forces should fall within the range of 250 N for molar loading and 125 N for incisal loading. Two studies on biting forces compared healthy people with patients with prognathism before and after SSRO surgery[46,47]. In both studies, the healthy group had a stronger bite force than the prognathic patients measured both preoperatively and postoperatively. Six to eight weeks after surgery, the patients had lower bite forces than preoperatively[47,48]. Six months after surgery, the bite forces had surpassed the preoperative values[46,48]. Although the studies made an assumption of the necessary amount of resistance load, it must be noted that these were based on orthognathic fixation of mandibular setback and mandibular angle fracture patients[24,25,30,32].

In conclusion, this systematic review found heterogeneity between biomechanical assessment studies comparing RIF methods. This indicates the need for more standardization in these in vitro studies. The use of consistent replicas, such as polyurethane mandibles, tested in a three-point model is recommended. Also, measurement of 3 mm displacement is clinically of more relevance than the use of peak load. Since patients are not allowed to chew solid food in the first weeks after the operation, excess chewing forces are less relevant.

Despite the diversity in study design, some concurrence was seen in the results for relatively small SSRO advancements. The use of three bicortical screws, double miniplates, grid plates, or hybrid materials improved stability in comparison to the use of a single miniplate. Furthermore, this review highlights the very limited number of biomechanical assessment studies on larger mandibular advancements. With a

higher tendency for relapse in larger advancements[8] and a growing indication for such advancements in oral and maxillofacial surgery, for example for the treatment of OSA, more fundamental and clinical research is necessary in order to provide an evidence-based choice for the use of fixation methods in larger advancements.

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None.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.ijom.2018.06.013.

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