Mechanical Strength and Stiffness of Biodegradable and Titanium Osteofixation Systems

Gerrit J. Buijs, DMD, Eduard B. van der Houwen, MSc,†*
Boudewijn Stegenga, DMD, MSc, PhD,‡
Rudulf R.M. Bos, DMD, PhD,§
and Gijsbertus J. Verkerke, MSc, PhD‖

Purpose: To present relevant mechanical data to simplify the selection of an osteofixation system for situations requiring immobilization in oral and maxillofacial surgery.

Materials and Methods: Seven biodegradable and 2 titanium osteofixation systems were investigated. The plates and screws were fixed to 2 polymethylmethacrylate (PMMA) blocks to simulate bone segments. The plates and screws were subjected to tensile, side bending, and torsion tests. During tensile tests, the strength of the osteofixation system was monitored. The stiffness was calculated for the tensile, side bending, and torsion tests.

Results: The 2 titanium systems (1.5 mm and 2.0 mm) presented significantly higher tensile strength and stiffness compared with the 7 biodegradable systems (2.0 mm, 2.1 mm, and 2.5 mm). The 2.0 mm titanium system showed significantly higher side bending and torsion stiffness than the other 8 systems.

Conclusion: Based on the results of the current study, it can be concluded that the titanium osteofixation systems were (significantly) stronger and stiffer than the biodegradable systems. The BioSorb FX (Linvatec Biomaterials Ltd, Tampere, Finland), LactoSorb (Walter Lorenz Surgical Inc, Jacksonville, FL), and Inion (Inion Ltd, Tampere, Finland) 2.5 mm systems have high mechanical device strength and stiffness compared with the investigated biodegradable osteofixation systems. With the cross-sectional surface taken into account, the Biosorb FX system (with its subtle design) proves to be the far more superior system. The Resorb X (Gebrüder Martin GmbH & Co, Tuttlingen, Germany) and MacroPore (MacroPore Biosurgery Inc, Memphis, TN) systems present to be, at least from a mechanical point of view, the least strong and stiff systems in the test.

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Sufficient revascularization, anatomic reduction, and proper immobilization of bone segments are essential aspects of the healing of fractures and osteotomies.[1,2] Immobilization of bone fragments is currently obtained by the use of osteofixation plates and screws.[3,4] The plates and screws are applied subperiosteally to secure sufficient revascularization.[2] These fixation devices must withstand the local deforming forces that are exerted through the maxillofacial muscles.

Currently, titanium fixation systems are successfully used to realize adequate immobilization.[5] These

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*PhD Student, Department of Oral and Maxillofacial Surgery, University Medical Center Groningen, University of Groningen, Groningen, The Netherlands.

†PhD Student, Department of BioMedical Engineering, University Medical Center Groningen, University of Groningen, Groningen, The Netherlands.

‡Professor, Department of Oral and Maxillofacial Surgery, University Medical Center Groningen, University of Groningen, Groningen, The Netherlands.

§Professor, Department of Oral and Maxillofacial Surgery, University Medical Center Groningen, University of Groningen, Groningen, The Netherlands.

‖Professor, Department of BioMedical Engineering, University Medical Center Groningen, University of Groningen, Groningen, The Netherlands; and the Department of Biomechanical Engineering, University of Twente, Enschede, The Netherlands.

Address correspondence and reprint requests to Dr Buijs: Department of Oral and Maxillofacial Surgery, University Medical Center Groningen, University of Groningen, Hanzeplein 1, PO Box 30.001, 9700 RB Groningen, The Netherlands; e-mail: g.j.buijs@kchir.umcg.nl

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systems, however, have several disadvantages: *1*) the need for a second intervention to remove the devices, if indicated[6-8]; *2*) interference with imaging or radiotherapeutic techniques[9-11]; *3*) possible growth disturbance or mutagenic effects[9,10,12-14]; *4*) brain damage[13,15]; and *5*) thermal sensitivity.[16]

Biodegradable "dissolving" fixation systems could reduce the problems associated with titanium systems.[17] However, these systems are mechanically weaker than titanium systems because of the use of biodegradable polymers. Moreover, adverse reactions to the degradation products have been reported.[18-21] Despite these disadvantages, there is a continuous drive to explore fixation devices that will degrade when bone healing has occurred.[22] The question as to whether biodegradable systems are proper alternatives to titanium systems has been the subject of research for decades.[23] Nevertheless, the mechanical properties of biodegradable systems have hardly been objectively compared in the scientific literature. In addition, many biodegradable fixation systems with a great variety of dimensions and co-polymer compositions are commercially available. As a result, the mechanical characteristics differ substantially, which consequently hampers surgeons in their selection of an adequate fixation system for a specific situation.[24] Determining the different mechanical properties of titanium and biodegradable osteofixation systems could support the procedure of finding the right fixation system for the right situation.[25]

Objectives

The objective of this study was to present relevant mechanical data to simplify the selection of an osteofixation system for situations requiring immobilization in oral and maxillofacial surgery.

Materials and Methods

The specimens to be investigated were 7 commercially available biodegradable (5 × 2.0 mm, 1 × 2.1

Table 1. CHARACTERISTICS OF INCLUDED OSTEOFIXATION SYSTEMS

Brand Name	Manufacturer	Composition	Sterility	Screw Diameter* (mm)	Screw Length* (mm)	Plate Length* (mm)	Plate Width* (mm)	Plate Thickness* (mm)
Biodegradable Systems								
BioSorb FX	Linvatec Biomaterials Ltd. (Tampere, Finland)	SR 70L/30DL PLA	Sterile	2.0	6.0	25.5	5.5	1.3
Resorb X	Gebrüder Martin GmbH & Co (Tuttlingen, Germany)	100 DL-Lactide	Sterile	2.1	7.0	26.0	6.0	1.1
Inion 2.0 mm	Inion Ltd (Tampere, Finland)	LDL Lactide/ TMC/PGA	Sterile	2.0	7.0	28.0	7.0	1.3
Inion 2.5 mm	Inion Ltd (Tampere, Finland)	LDL Lactide/ TMC/PGA	Sterile	2.5	6.0	32.0	8.5	1.6
LactoSorb	Walter Lorenz Surgical Inc (Jacksonville, FL)	82 PLLA/18 PGA	Sterile	2.0	7.0	28.5	7.0	1.3
Polymax	Mathys Medical Ltd (Bettlach Switzerland)	70L/30DL PLA	Sterile	2.0	6.0	28.0	6.0	1.3
MacroPore	MacroPore BioSurgery Inc (Memphis, TN)	70L/30DL PLA	Expired	2.0	6.0	25.0	6.7	1.2
Titanium Systems								
KLS Martin	Gebrüder Martin GmbH & Co (Tuttlingen, Germany)	Titanium (pure)	Sterile	1.5	6.0	18.5	3.5	0.6
KLS Martin	Gebrüder Martin GmbH & Co (Tuttlingen, Germany)	Titanium (pure)	Sterile	2.0	6.0	25.5	5.0	1.0

*According to the specifications of the manufacturers.

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mm, and 1 × 2.5 mm) and 2 commonly used commercially available titanium (1.5 mm and 2.0 mm) osteofixation systems. The general characteristics of the included plates and screws are summarized in Table 1. The nonsterile titanium plates and screws were sterilized in our department in the usual manner. The manufacturers of the biodegradable systems supplied sterile implants, with the exception of the MacroPore implants (MacroPore Biosurgery Inc, Memphis, TN), for which the expiration date had passed (average, 6 to 12 months). The plates under investigation were 4-hole extended plates. Eighteen plates and 72 screws of each system were subjected to 3 different mechanical tests.

The osteofixation plates and screws were fixed to 2 polymethylmethacrylate (PMMA) blocks that simulated bone segments. There was no interfragmentary contact to simulate the most unfavorable clinical situation. Two screws were inserted in both PMMA blocks according to the instructions of the individual manufacturer (with prescribed burs and taps). The applied torque for inserting the screws was measured to check whether it was comparable to the clinically applied torque ("hand tight") defined in a previous study.[26] The holes were irrigated with saline before insertion of the screws, to simulate the in situ lubrication. The 2 PMMA blocks, linked by the osteofixation device (1 plate and 4 screws) were restored in a water tank containing water at 37.2°C for 24 hours to simulate the relaxation of biodegradable screws at body temperature.[27] The tests were performed in another tank containing water at the same temperature to simulate body temperature. Saline was not used because of possible corrosion of the test and environment set-up. Omitting the use of saline was expected not to be of influence to the test results.

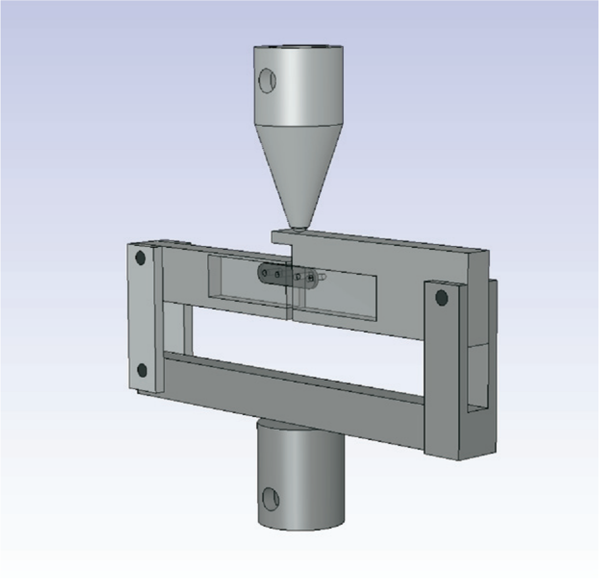

FIGURE 2. Side bending test set-up.

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The plates and screws were subjected to tensile, side bending, and torsion tests. The tensile test was performed as a standard loading test (Fig 1). Side bending tests were performed to simulate an in vivo bilateral sagittal split osteotomy (BSSO) situation (Fig 2). Torsion tests were performed to subject the osteofixation devices to high torque to simulate the most unfavorable situation (Fig 3). The 2 PMMA

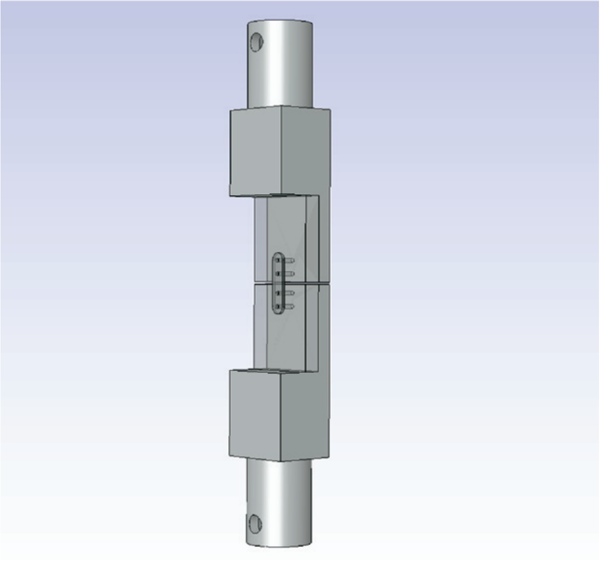

FIGURE 1. Tensile test set-up.

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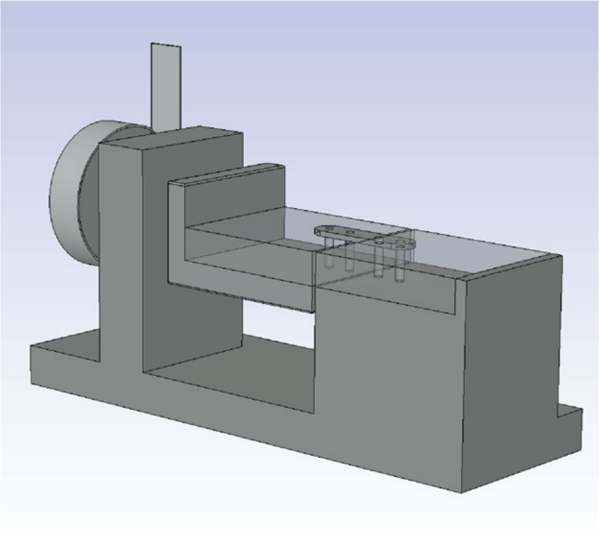

FIGURE 3. Torsion test set-up.

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Table 2. APPLIED TORQUE OF INSERTED OSTEOFIXATION SCREWS

Test	System	Mean	SD
Tensile	BioSorb FX	81.23	0.41
	Inion 2.0	74.29	0.31
	Inion 2.5	156.81	0.76
	LactoSorb	97.96	0.48
	MacroPore	62.42	0.47
	Polymax	57.05	0.58
	ResorbX	56.13	0.23
	Titanium 1.5	251.21	1.54
	Titanium 2.0	369.84	1.09
Side Bending	BioSorb FX	81.50	0.57
	Inion 2.0	74.40	0.54
	Inion 2.5	157.24	0.35
	LactoSorb	97.63	0.32
	MacroPore	62.17	0.75
	Polymax	56.83	0.23
	ResorbX	55.90	0.26
	Titanium 1.5	248.23	0.70
	Titanium 2.0	370.20	1.02
Torsion	BioSorb FX	80.93	0.43
	Inion 2.0	74.50	0.83
	Inion 2.5	156.80	0.76
	LactoSorb	97.88	0.56
	MacroPore	62.21	0.45
	Polymax	57.46	0.41
	ResorbX	55.91	0.30
	Titanium 1.5	248.53	1.36
	Titanium 2.0	367.96	1.97

NOTE. Mean = mNm.

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blocks, linked by the osteofixation device, were mounted in a test machine (Zwick/Roell TC-FR2, 5TS.D09, 2.5 kN Test machine; force accuracy, 0.2%; positioning accuracy, 0.0001 mm; Zwick/Roell Nederland, Venlo, The Netherlands). Regarding the tensile tests, the 2 PMMA blocks and thus the osteofixation plate were subjected to a tensile force with a constant speed of 5 mm/minute until fracture occurred (according to the standard American Society for Testing and Materials D638M). For the side bending test, the 2 PMMA blocks were supported at their ends, whereas the plates were loaded in the center of the construction with a constant speed of 30 mm/minute (with this speed the outer fibers were loaded as fast as the fibers of the osteofixation system in the tensile test) until the plate was bent 30 degrees. For the torsion test, the 2 PMMA blocks were twisted along the long axis of the osteofixation system with a constant speed of 90 degrees/minute (with this speed the outer fibers were loaded as fast as the fibers of the osteofixation system in the tensile test) until the plate was turned 160 degrees.

During testing, the applied force was recorded by the load cell of the test machine. Both force and displacement were measured with a sample frequency of 500 Hz and graphically presented in force-displacement diagrams. During tensile tests, the strength of the osteofixation system was monitored. The stiffness was calculated for the tensile, side bending, and torsion tests by linking the Fmax 25% and Fmax 75% points (to exclude inaccuracies of the start and end of the curves) of the maximum force on the force-displacement curves and determining the direction-coefficients of the curves.

Statistical Analysis

Statistical Package of Social Sciences (SPSS Inc, Chicago, IL; version 12.0) was used to analyze the data. Mean and standard deviation were calculated to describe the data. To determine whether there were significant differences between the biodegradable and the titanium osteofixation systems in *1*) tensile strength and stiffness, *2*) side bending stiffness, and *3*) torsion stiffness, the maximum values were subjected to a 1-way analysis of variance (ANOVA). A correction for multiple testing was performed according to Dunnet T3 (equal variances not assumed). Differences were considered to be significant when *P* was less than .05 for all tests.

Results

The torques used to insert the screws of the 9 osteofixation systems regarding the tensile, side bending, and torsion tests are outlined in Table 2. Mean torques as well as the standard deviations for each system in all 3 tests were nearly similar.

The mean tensile strength and stiffness of the 9 osteofixation systems are graphically presented in Figures 4 and 5, respectively. The 2 titanium systems (1.5 mm and 2.0 mm) presented significantly higher tensile strength and stiffness compared with the biodegradable systems (2.0 mm, 2.1 mm, and 2.5 mm). Regarding the biodegradable systems, the BioSorb FX, (Linvatec Biomaterials Ltd, Tampere, Finland), Inion 2.5 mm (Inion Ltd, Tampere, Finland), and LactoSorb (Walter Lorenz Surgical Inc, Jacksonville, FL) systems presented a significantly higher tensile strength whereas the BioSorb FX and LactoSorb systems presented a significantly higher tensile stiffness compared with the other biodegradable systems. The differences between the systems are outlined in Table 3. The standard deviations for the systems regarding the tensile strength and stiffness were small. A summary of the descriptive statistics is presented in Table 4.

Mean side bending stiffness of the 9 osteofixation systems is plotted in Figure 6. The 2.0 mm titanium system showed significantly higher side bending stiffness compared with the other 8 systems. The 1.5 mm

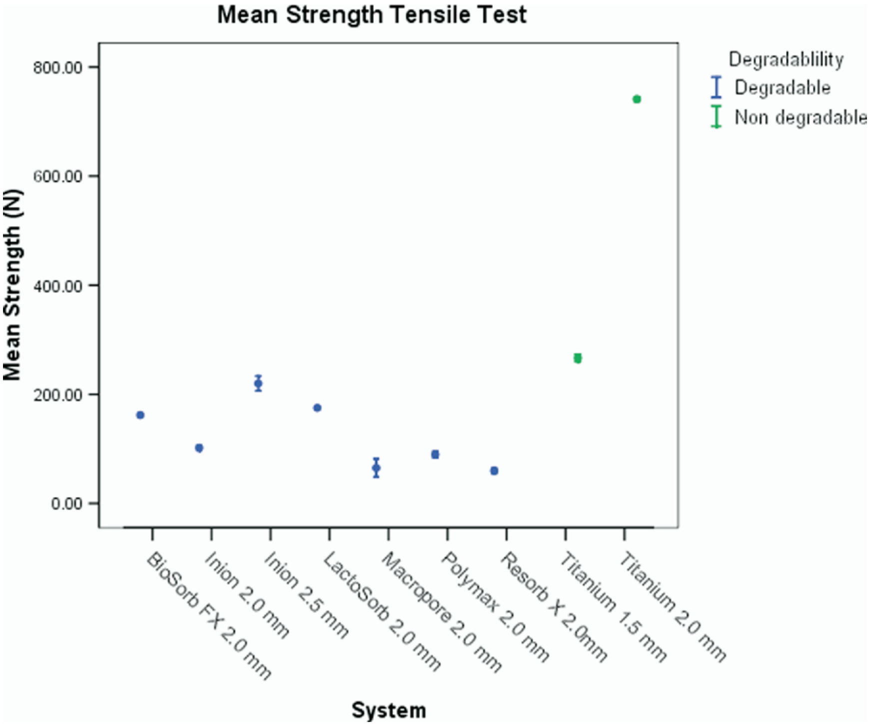

FIGURE 4. Mean tensile strength organized by system. Points in figure represent mean strength. Bars represent the standard deviation of the mean strength.

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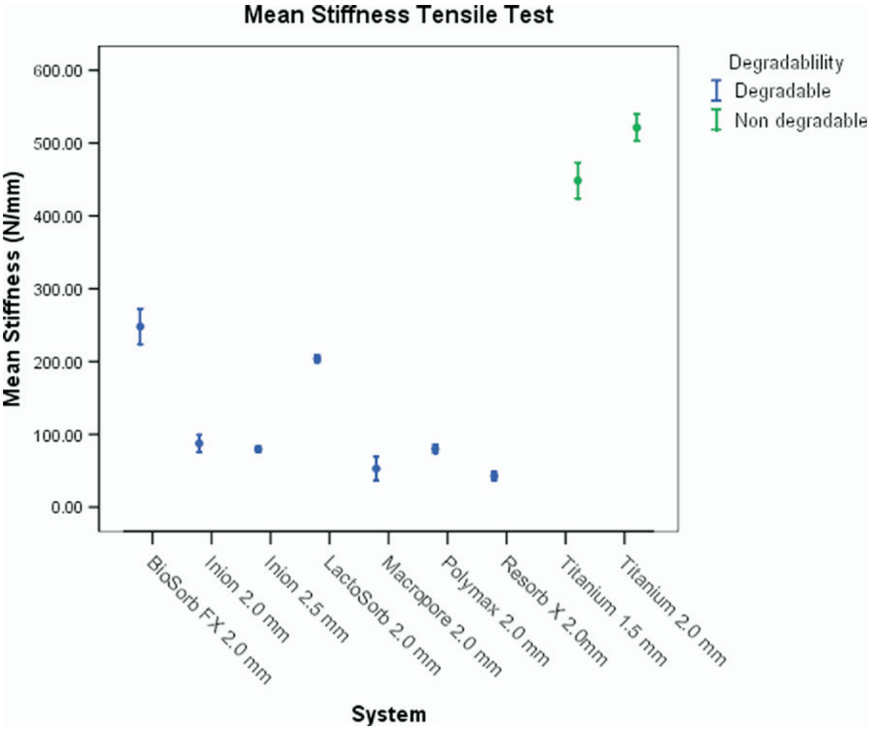

FIGURE 5. Mean tensile stiffness organized by system. Points in figure represent mean stiffness. Bars represent the standard deviation of the mean stiffness.

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Table 3. SIGNIFICANCE BETWEEN OSTEOFIXATION SYSTEMS IN TENSILE TEST

System	BioSorb FX 2.0 mm	Inion 2.0 mm	Inion 2.5 mm	LactoSorb 2.0 mm	MacroPore 2.0 mm	Polymax 2.0 mm	Resorb X 2.1 mm	Titanium 1.5 mm	Titanium 2.0 mm
BioSorb FX 2.0 mm	XXXX	S	S	S	S	S	S	S	S
Inion 2.0 mm	*S*	XXXX	S	S	S	NS	S	S	S
Inion 2.5 mm	*S*	*NS*	XXXX	S	S	S	S	S	S
LactoSorb 2.0 mm	*NS*	*S*	*S*	XXXX	S	S	S	S	S
MacroPore 2.0 mm	*S*	*NS*	*NS*	*S*	XXXX	NS	NS	S	S
Polymax 2.0 mm	*S*	*NS*	*NS*	*S*	*NS*	XXXX	S	S	S
Resorb X 2.1 mm	*S*	*S*	*S*	*S*	*NS*	*S*	XXXX	S	S
Titanium 1.5 mm	*S*	*S*	*S*	*S*	*S*	*S*	*S*	XXXX	S
Titanium 2.0 mm	*S*	*S*	*S*	*S*	*S*	*S*	*S*	*S*	XXXX

NOTE. *Underline* indicates tensile strength; *italic* indicates tensile stiffness.
Abbreviations: S, significant; NS, nonsignificant.

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Table 4. SUMMARY OF DESCRIPTIVE STATISTICS TENSILE TEST

System	Mean^	SD^	95% Confidence Interval Lower Bound^	95% Confidence Interval Upper Bound^
Tensile strength				
BioSorb FX 2.0 mm	162.00	3.18	155.16	168.85
Inion 2.0 mm	101.98	5.11	95.13	108.82
Inion 2.5 mm	219.82	13.43	212.98	226.67
LactoSorb 2.0 mm	175.17	2.40	168.33	182.02
MacroPore 2.0 mm	65.07	16.92	58.23	71.92
Polymax 2.0 mm	89.68	5.52	82.84	96.53
Resorb X 2.1 mm	59.87	4.73	53.02	66.71
Titanium 1.5 mm	266.71	6.74	259.86	273.55
Titanium 2.0 mm	741.21	4.08	734.36	748.05
Tensile stiffness				
System	Mean*	SD*	Lower Bound*	Upper Bound*
BioSorb FX 2.0 mm	248.00	24.28	235.57	260.43
Inion 2.0 mm	87.56	11.66	75.12	99.99
Inion 2.5 mm	79.52	3.74	67.09	91.95
LactoSorb 2.0 mm	203.78	4.82	191.34	216.21
MacroPore 2.0 mm	52.87	16.57	40.44	65.31
Polymax 2.0 mm	80.08	5.74	67.65	92.51
Resorb X 2.1 mm	42.86	5.82	30.44	55.30
Titanium 1.5 mm	448.56	24.68	436.12	460.99
Titanium 2.0 mm	521.27	18.56	508.84	533.70

^in N.
*in N/mm.
Abbreviation: SD, standard deviation.

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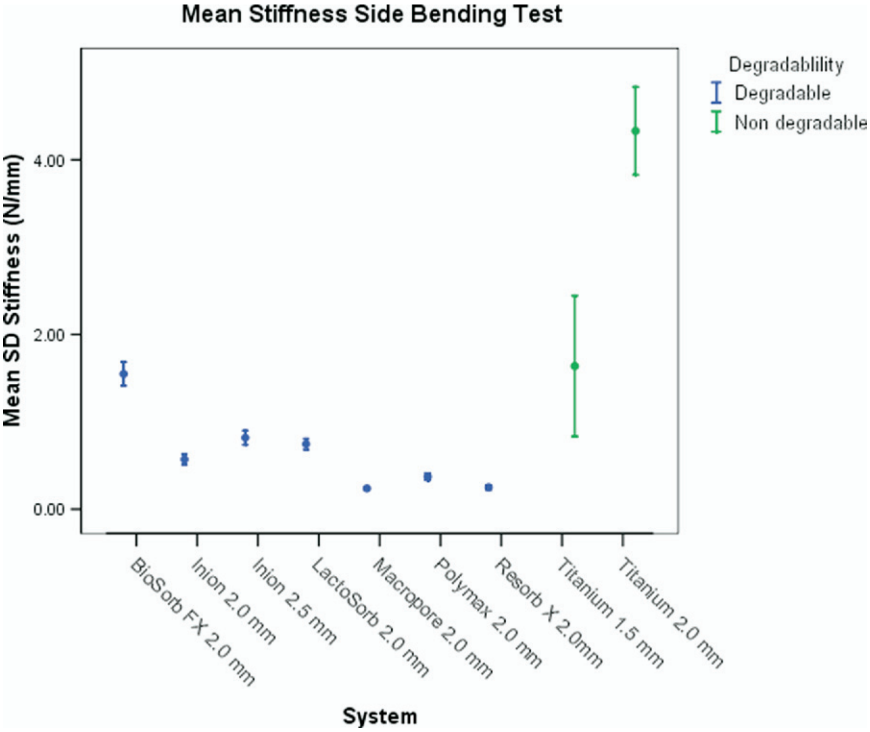

FIGURE 6. Mean side bending stiffness organized by system. Points in figure represent mean stiffness. Bars represent the standard deviation of the mean stiffness.

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titanium and the BioSorb FX system presented a nearly similar mean side bending stiffness. The side bending stiffness of the BioSorb FX system was significantly higher compared with the other 6 biodegradable systems, whereas significance was not reached for the 1.5 mm titanium system, mainly because of the large standard deviation of the mean of the 1.5 mm titanium system (Table 5). The nonsignificant results

Table 5. SIGNIFICANCE BETWEEN OSTEOFIXATION SYSTEMS IN STIFFNESS TEST

System	BioSorb FX 2.0 mm	Inion 2.0 mm	Inion 2.5 mm	LactoSorb 2.0 mm	MacroPore 2.0 mm	Polymax 2.0 mm	Resorb X 2.1 mm	Titanium 1.5 mm	Titanium 2.0 mm
BioSorb FX 2.0 mm	XXXX	S	S	S	S	S	S	NS	S
Inion 2.0 mm	*S*	XXXX	S	S	S	S	S	NS	S
Inion 2.5 mm	*S*	*S*	XXXX	NS	S	S	S	NS	S
LactoSorb 2.0 mm	*S*	*NS*	*S*	XXXX	S	S	S	NS	S
MacroPore 2.0 mm	*S*	*S*	*S*	*S*	XXXX	S	NS	NS	S
Polymax 2.0 mm	*NS*	*S*	*S*	*S*	*S*	XXXX	S	NS	S
Resorb X 2.1 mm	*S*	*S*	*S*	*S*	*S*	*S*	XXXX	NS	S
Titanium 1.5 mm	*S*	*S*	*S*	*S*	*NS*	*S*	*S*	XXXX	S
Titanium 2.0 mm	*S*	*S*	*S*	*S*	*S*	*S*	*S*	*S*	XXXX

NOTE. *Underline* indicates side bending stiffness; *italic* indicates torsion stiffness.
Abbreviations: S, significant; NS, nonsignificant.

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Table 6. SUMMARY OF DESCRIPTIVE STATISTICS TORSION AND BENDING TEST

System	Mean*	SD*	95% Confidence Interval Lower Bound*	95% Confidence Interval Upper Bound*
Side bending stiffness				
BioSorb FX 2.0 mm	1.55	0.13	1.28	1.81
Inion 2.0 mm	0.57	0.06	0.31	0.84
Inion 2.5 mm	0.82	0.08	0.55	1.08
LactoSorb 2.0 mm	0.75	0.06	0.48	1.01
MacroPore 2.0 mm	0.24	0.02	-0.03	0.50
Polymax 2.0 mm	0.37	0.04	0.11	0.64
Resorb X 2.1 mm	0.25	0.03	-0.02	0.52
Titanium 1.5 mm	1.64	0.81	1.37	1.90
Titanium 2.0 mm	4.33	0.50	4.07	4.60
Torsion stiffness				
BioSorb FX 2.0 mm	0.96	0.10	0.80	1.12
Inion 2.0 mm	0.67	0.05	0.52	0.84
Inion 2.5 mm	2.36	0.12	2.20	2.53
LactoSorb 2.0 mm	0.56	0.04	0.40	0.73
MacroPore 2.0 mm	1.27	0.14	1.10	1.43
Polymax 2.0 mm	0.86	0.08	0.70	1.02
Resorb X 2.1 mm	0.32	0.04	0.16	0.48
Titanium 1.5 mm	1.34	0.08	1.18	1.50
Titanium 2.0 mm	4.17	0.54	4.00	4.33

*in N/mm.

Abbreviation: SD, standard deviation.

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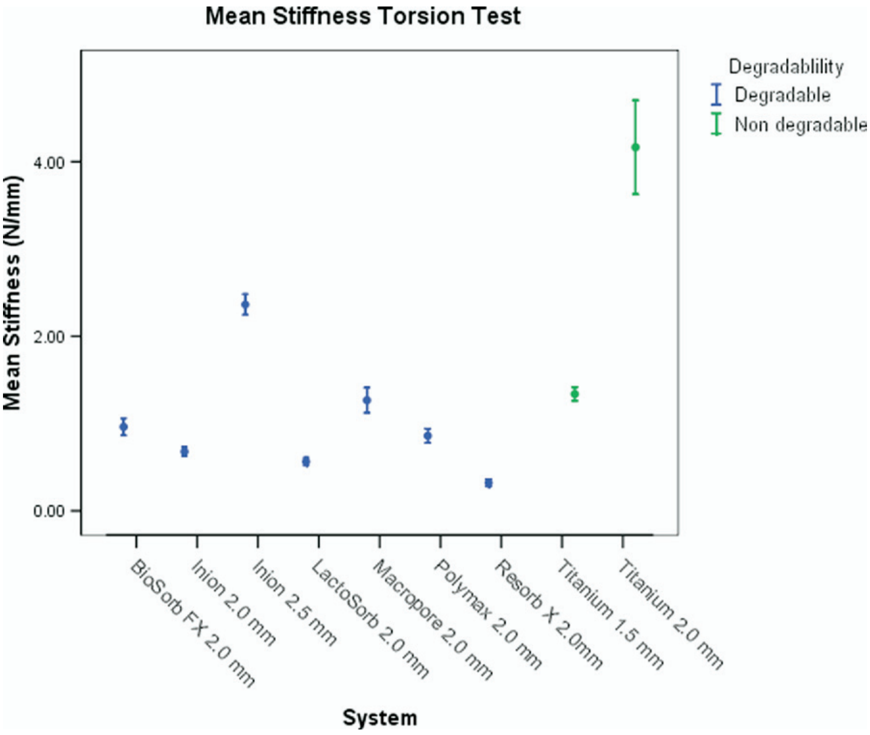

FIGURE 7. Mean torsion stiffness organized by system. Points in figure represent mean stiffness. Bars represent the standard deviation of the mean stiffness.

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were additionally illustrated by the 95% confidence interval of the 1.5 mm titanium system, which overlaps the interval of the BioSorb FX system. The standard deviations of the biodegradable systems were small, while the 2.0 mm titanium system also showed a higher standard deviation (Table 6).

The mean torsion stiffness of the 9 osteofixation systems is graphically plotted in Figure 7. As presented with the side bending stiffness, the torsion stiffness of the 2.0 mm titanium system was significantly higher compared with the remaining systems. The standard deviations of the biodegradable and 1.5 mm titanium systems were small, particularly compared with the standard deviation of the 2.0 mm titanium system. The mean torsion stiffness for the 1.5 mm titanium and 2.0 mm MacroPore system was nearly equal, showing nonsignificance between these 2 systems. The Inion 2.5 mm system presented by far the highest torsion stiffness of the biodegradable systems. Comparisons of the differences between the 9 osteofixation systems are outlined in Table 5. Table 6 presents a summary of the descriptive statistics of the side bending and torsion tests.

Discussion

The differences in strength and stiffness can be explained by many different factors, including dimension (1.5 mm, 2.0 mm, 2.1 mm, and 2.5 mm), (copolymer) compositions, geometry of the plates and screws, ageing of the plates and screws, and methods to sterilize and manufacture the plates and screws. Because the differences between the osteofixation systems are multifactorial, it remains difficult to pose (a) specific reason(s).

The maxillofacial muscles exert high forces in different directions.[2] Consequently, it is difficult to simulate the in situ conditions in in vitro situations. To obtain clinically valuable information regarding the selection of an osteofixation system, the tensile strength and stiffness, side bending stiffness, and torsion stiffness were investigated as mentioned above. Adequate tensile strength and stiffness of an osteofixation system is essential for fixation of fractures and osteotomies. The osteofixation system is inevitably exposed to tensile forces when adequately repositioned bone segments are exposed to local deforming forces.[28,29] The side bending test has been performed to simulate the BSSO of the mandible.[30] The BSSO procedure is often performed in oral and maxillofacial surgery.[4] The torsion test was used to simulate the torsion forces that are developed in the area between the 2 canine teeth when a median fracture of the mandible is present. These torsion forces, however, are predominantly counteracted by the interfragmentary fracture segments.[31] A second argument to subject the osteofixation system to the torsion test is that torsional forces are extraordinarily destructive for osteofixation systems. During torsion of the PMMA blocks, they were prevented from moving along the long axis of the system to additionally load the system to tensile forces. This simulates the most unfavorable in situ situation imaginable. Another important aspect of simulating the in situ situation was to test the system as it is used and applied in the clinic. The plates and screws were fixed with prescribed burs and taps. Fixing the plates with corresponding screws will provide more clinically relevant information rather than fix the plates with metal screws.[25] In this way, information on the entire system's (device) mechanical characteristics was obtained.

Stiffness was calculated in all 3 tests (tensile, side bending, and torsion), while the strength is reported in just 1 case (tensile test). The stiffness of an osteofixation system is a more clinically applicable characteristic.[32] Contrary to stiffness, the maximum strength will only become relevant when the bone segments are separated more than a few millimeters, which inherently results in compromised bone healing. Enlargement of the healing period is the result, and loosening of the screws and plates or infection is possible.[32] Stiffness was calculated from the raw data as described in the Materials and Methods section. Determining the 25% Fmax and 75% Fmax point, as well as the corresponding displacement, implies loss of accuracy because of the limited sample frequency (500 Hz). This results in higher relative standard deviations when comparing the tensile strength.

The small standard deviations regarding the tensile strength (predominantly the titanium systems) elucidate that the method of testing and the test hardware were properly designed regarding reproducibility. However, the high standard deviations concerning the stiffness of the titanium systems in both the torsion (titanium 2.0 mm) and side bending (titanium 1.5 and 2.0 mm) tests did not support the assumption of proper method and hardware design. The explanation for these phenomena could be the measurement imprecision mentioned above or the variety in mechanical properties of the specimens of each system.

Another eye-catching point is that the torsion and side bending stiffness of the 1.5 mm titanium system and 4 (BioSorb FX, Inion 2.0, Inion 2.5, and LactoSorb) of the biodegradable systems that were nearly in the same range of stiffness. This is most probably a result of the smaller dimensions of the 1.5 mm titanium system. Table 4 shows significant differences between the side bending stiffness of the biodegradable systems (caused by the small standard deviations) while the differences between the 1.5 mm titanium and the biodegradable systems were not significant.

Titanium osteofixation systems were (significantly) stronger and stiffer than biodegradable systems. Despite the favorable mechanical properties of these systems compared with the biodegradable systems, the question arises whether the biodegradable systems pose adequate resistance to the local deforming forces to achieve adequate bone healing in patients.[33] After all, the disappearance of a fixation system when bone union of the bone segments has been obtained is still very appealing. The question mentioned above can only be answered through well-designed randomized clinical trials that compare biodegradable and titanium osteofixation systems. The present study, however, provides well-founded information to help surgeons select a mechanically potent bone fixation system for restoring, fixing, and stabilizing bone segments in specific situations in the maxillofacial area. The objective of this study was to present relevant mechanical data to simplify the selection of an osteofixation system for situations requiring immobilization in oral and maxillofacial surgery. This study has presented that the tensile strength and stiffness of both titanium systems were significantly higher than the biodegradable systems, whereas the differences between the biodegradable systems also showed significance in most cases with regard to tensile strength as well as stiffness. Moreover, it showed that the side bending stiffness of the titanium 2.0 mm was significantly higher than the 8 remaining systems. The BioSorb FX also showed high side bending stiffness in comparison to the other biodegradable systems, with both Resorb X and MacroPore at the lower side. Finally, this study has shown that the torsion stiffness of the titanium 2.0 mm system was high compared with the other systems. Based on the results of the current study, it can be concluded the BioSorb FX, Inion 2.5, and LactoSorb systems represent the higher strength and stiffnesses among the investigated biodegradable osteofixation systems. With the cross-sectional surface taken into account, the BioSorb FX system (with its subtle design) proved to be the far more strong and stiff system. The Resorb X and MacroPore systems are, at least from a mechanical point of view, the least strong and stiff systems in the test.[26]

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References

1. Bowers DG Jr, Lynch JB: Management of facial fractures. South Med J 70:910, 1977
2. Harle F, Champy M, Terry BC: Atlas of Craniomaxillofacial Osteosynthesis. Ed 1. New York, Thieme, 1999, pp 3-7
3. Luhr HG: The development of modern osteosynthesis. Mund Kiefer Gesichtschir 1:84, 2000 (suppl 4)
4. Stoelinga PJ, Borstlap WA: The fixation of sagittal split osteotomies with miniplates: The versatility of a technique. J Oral Maxillofac Surg 61:1471, 2003
5. Matthews NS, Khambay BS, Ayoub AF, et al: Preliminary assessment of skeletal stability after sagittal split mandibular advancement using a bioresorbable fixation system. Br J Oral Maxillofac Surg 41:179, 2003
6. Bostman O: Economic considerations on avoiding implant removals after fracture fixation by using absorbable devices. Scand J Soc Med 22:41, 1994
7. Juutilainen T, Patiala H, Ruuskanen M, et al: Comparison of costs in ankle fractures treated with absorbable or metallic fixation devices. Arch Orthop Trauma Surg 116:204, 1997
8. Rokkanen PU, Bostman O, Hirvensalo E, et al: Bioabsorbable fixation in orthopaedic surgery and traumatology. Biomaterials 21:2607, 2000
9. Goldstein JA: The use of bioresorbable material in craniofacial surgery. Clin Plast Surg 28:653, 2001
10. Peltoniemi HH, Ahovuo J, Tulamo RM, et al: Biodegradable and titanium plating in experimental craniotomies: A radiographic follow-up study. J Craniofac Surg 8:446, 1997
11. Rozema FR, Levendag PC, Bos RR, et al: Influence of resorbable poly(L-lactide) bone plates and screws on the dose distributions of radiotherapy beams. Int J Oral Maxillofac Surg 19:374, 1990
12. Penman HG, Ring PA: Osteosarcoma in association with total hip replacement. J Bone Joint Surg Br 66:632, 1984
13. Yaremchuk MJ, Posnick JC: Resolving controversies related to plate and screw fixation in the growing craniofacial skeleton. J Craniofac Surg 6:525, 1995
14. Yerit KC, Hainich S, Turhani D, et al: Stability of biodegradable implants in treatment of mandibular fractures. Plast Reconstr Surg 115:1863, 2005
15. Ghali GE, Sinn DP, Tantipasawasin S: Management of nonsyndromic craniosynostosis. Atlas Oral Maxillofac Surg Clin North Am 10:1, 2002
16. Suuronen R, Laine P, Pohjonen T, et al: Sagittal ramus osteotomies fixed with biodegradable screws: A preliminary report. J Oral Maxillofac Surg 52:715, 1994
17. Suuronen R, Kallela I, Lindqvist C: Bioabsorbable plates and screws: Current state of the art in facial fracture repair. J Craniomaxillofac Trauma 6:19, 2000
18. Bostman OM, Pihlajamaki HK: Adverse tissue reactions to bioabsorbable fixation devices. Clin Orthop Relat Res 2:216, 2000
19. Bostman O, Hirvensalo E, Makinen J, et al: Foreign-body reactions to fracture fixation implants of biodegradable synthetic polymers. J Bone Joint Surg Br 72:592, 1990
20. Bergsma JE, de Bruijn WC, Rozema FR, et al: Late degradation tissue response to poly(L-lactide) bone plates and screws. Biomaterials 16:25, 1995
21. Bergsma EJ, Rozema FR, Bos RR, et al: Foreign body reactions to resorbable poly(L-lactide) bone plates and screws used for the fixation of unstable zygomatic fractures. J Oral Maxillofac Surg 51:666, 1993
22. Cheung LK, Chow LK, Chiu WK: A randomized controlled trial of resorbable versus titanium fixation for orthognathic surgery. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 98:386, 2004
23. Turvey TA, Bell RB, Tejera TJ, et al: The use of self-reinforced biodegradable bone plates and screws in orthognathic surgery. J Oral Maxillofac Surg 60:59, 2002
24. Edwards TJ, David DJ: A comparative study of miniplates used in the treatment of mandibular fractures. Plast Reconstr Surg 97:1150, 1996

25. Buijs GJ, Stegenga B, Bos RR: Efficacy and safety of biodegradable osteofixation devices in oral and maxillofacial surgery: A systematic review. J Dent Res 85:980, 2006
26. Buijs GJ, Houwen EBvd, Stegenga B, et al: Torsion strength of biodegradable and titanium screws: A comparison. J Oral Maxillofac Surg 65:2142, 2007
27. Shetty V, Caputo AA, Kelso I: Torsion-axial force characteristics of SR-PLLA screws. J Craniomaxillofac Surg 25:19, 1997
28. Champy M, Lodde JP, Jaeger JH, et al: Mandibular osteosynthesis according to the Michelet technic I. Biomechanical bases. Rev Stomatol Chir Maxillofac 77:569, 1976
29. Ralph JP, Caputo AA: Analysis of stress patterns in the human mandible. J Dent Res 54:814, 1975
30. Dolanmaz D, Uckan S, Isik K, et al: Comparison of stability of absorbable and titanium plate and screw fixation for sagittal split ramus osteotomy. Br J Oral Maxillofac Surg 42:127, 2004
31. Tams J, van Loon JP, Rozema FR, et al: A three-dimensional study of loads across the fracture for different fracture sites of the mandible. Br J Oral Maxillofac Surg 34:400, 1996
32. Engroff SL, Blanchaert RH Jr, Von Fraunhofer JA: Mandibulotomy fixation: A laboratory analysis. J Oral Maxillofac Surg 61:1297, 2003
33. Cox T, Kohn MW, Impelluso T: Computerized analysis of resorbable polymer plates and screws for the rigid fixation of mandibular angle fractures. J Oral Maxillofac Surg 61:481, 2003