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Original Article

BIOMECHANICS OF BONE BLOCK GRAFT MODELS OF DIFFERENT GEOMETRY

BIOMECÂNICA DE MODELOS DE ENXERTOS ÓSSEOS EM BLOCO DE GEOMETRIAS DIFERENTES

Cláudio Henrique Barbieri[1], *Luiz Garcia-Mandarano Filho*[2]

1. Division of Hand and Upper Limb Surgery, Department of Biomechanics, Medicine and Rehabilitation of the Locomotor Apparatus, Faculdade de Medicina de Ribeirão Preto, Universidade de São Paulo, SP, Brazil.
2. Hospital Universitário da Faculdade de Medicina de Ribeirão Preto, Universidade de São Paulo, Ribeirão Preto, SP, Brazil.

ABSTRACT

Objective: To evaluate the mechanical behavior of different geometry bone block grafts in wooden models. Methods: Constructs with rectangular (G1) and trapezoidal (G2) profile "grafts", fixed with 3.5 mm 8-hole dynamic compression plates were submitted to non-destructive bending, with the load applied alternately on the same surface as that of the plate fixation (upper) and on the opposite surface (lower), and torsion tests. A 50 N maximum load for bending and a 5º maximum deformation for torsion were considered. Rigidity (N/mm) was recorded for the former and torque (N.m) was recorded for the latter. Results: Rigidity was consistently higher in G2 than in G1, but not significantly so for all comparisons. The exception was for the load applied on the same surface of plate fixation, significantly higher in G1 than in G2. Torque was higher in G1, but not significantly so. Conclusion: The two different-profile "grafts" present a similar mechanical behavior and can be indistinctly used in clinical practice. ***Level of evidence V, specialist´s opinion based on basic studies.***

Keywords: Internal fixation of fractures. Bone transplantation. Complications. Pseudarthrosis.

RESUMO

Objetivo: Avaliar o comportamento mecânico de enxertos ósseos em blocos com geometrias diferentes usando modelos de madeira. Métodos: Montagens com "enxertos" de perfil retangular (G1) e trapezoidal (G2), fixadas com placas de compressão dinâmica de 3,5 mm e oito orifícios, foram submetidas a ensaios não destrutivos de flexão, com a carga aplicada alternativamente na mesma superfície de fixação da placa (superior), na superfície oposta (inferior) e de torsão. Foram consideradas uma carga máxima de 50 N para a flexão e uma deformação máxima de 5º para a torsão. Foram registrados o desvio (mm) e a rigidez (N/mm) para o primeiro e o torque (N.m) para o segundo. Resultados: A rigidez foi consistentemente maior em G2 que em G1, mas não significantemente para todas as comparações. A exceção foi para a carga aplicada na mesma superfície da fixação com a placa, significantemente maior em G1 que em G2. O torque foi mais elevado em G1, mas não significantemente. Conclusão: Os dois "enxertos" de perfis diferentes apresentam comportamento mecânico semelhante, podendo ser utilizados indistintamente na prática clínica. ***Nível de evidência V; opinião de especialista baseada em matérias básicas.***

Descritores: *Fixação interna de fraturas. Enxerto ósseo. Complicações. Pseudoartrose.*

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INTRODUCTION

Despite the advances of the modern orthopaedic surgery, it is still a challenging issue to reconstruct and preserve limbs affected by the loss of a large portion of their frame. This is particularly true for the forearm bones, where massive bone loss of various causes compromises the delicate pronation-supination mechanism, with negative reflex over function.

Among other techniques, the bone block graft represents an adequate solution for the critical-sized defects of the forearm bones, since it provides both biological tissue and mechanical stability, two fundamental requirements for a good outcome. The bone block graft is understood as the tricorticocancellous (TCC) graft from the iliac crest as described by Nicoll[1] and used with small modifications by many other authors.[2,3] The TCC bone block graft completely takes up and heals in about four to six months.[4]

The use of the TCC bone block graft requires that the recipient site be adequately prepared, beginning with the removal of all devitalized bone and soft tissue. The recipient bone ends are usually regularized perpendicularly to the long axis, in order to provide full and easy adaptation of the graft, also prepared with contact surfaces perpendicular to its long axis. This seems to be the most adequate graft geometry for the situation, since it greatly

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The study was conducted at the Laboratory of Bioengineering of Faculdade de Medicina de Ribeirão Preto, Ribeirão Preto, SP, Brazil.
Correspondence: Avenida dos Bandeirantes, 3900, Ribeirão Preto, SP, Brazil. 14049-900. chbarbie@fmrp.usp.br

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resists to the axial compression forces through the defect site. However, there are situations in which oblique regularization of the bone ends should be preferred, in order to preserve healthy bone tissue and length, thus favouring the use of a smaller bone block. In such a case the graft must be fashioned also with oblique contact surfaces, with the hypothetical advantage of increasing the bony contact area at the same time that the graft can be securely wedged in place under pressure.[5]

Intermediate bone block grafts with oblique contact surfaces require a specific fixation technique, in order to block shearing forces, very much in the same way oblique diaphyseal fractures are fixed. It was then theorized that a bone block graft with two oblique converging contact surfaces and adequately fixed would resist shearing forces and behave just as well as the conventional rectangular profile grafts. The present study was designed to be carried out with wooden models simulating a diaphyseal bone such as the radius.

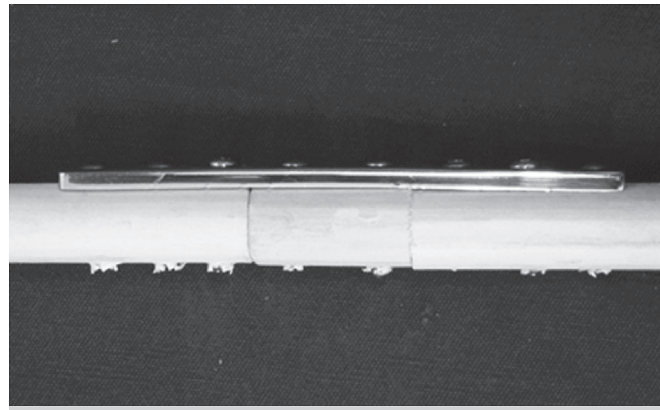

Figure 1. A model of rectangular profile graft fixed with a 3.5 mm DCP plate, under axial compression through the perpendicular contact surfaces.

MATERIAL AND METHODS

Fourteen 250 mm-long 14 mm in diameter cylinders were made from ivory wood (*Balfourodendron riedelianum*), a native tree of South America (Argentina, Brazil and Paraguay) of compact and uniform structure, high density (0.69 and 0.73 g/cm^3) and great resistance and flexibility. Its current use is in the production of fine furniture and tool handles.

The cylinders were sawed in three parts, being two 112 mm-long to represent the recipient bone stumps, and one, intermediate, 26 mm-long to represent the bone block graft. The wooden sets were distributed into two groups of seven, according to the configuration of the intermediate segment. In Group 1, the intermediate segment was sawed as a regular cylinder with a rectangular profile and two surfaces perpendicular to its long axis; in Group 2, the intermediate segment was sawed with a trapezoidal profile, with two converging oblique surfaces at 45° in relation to its long axis and the longest surface measuring 26 mm.

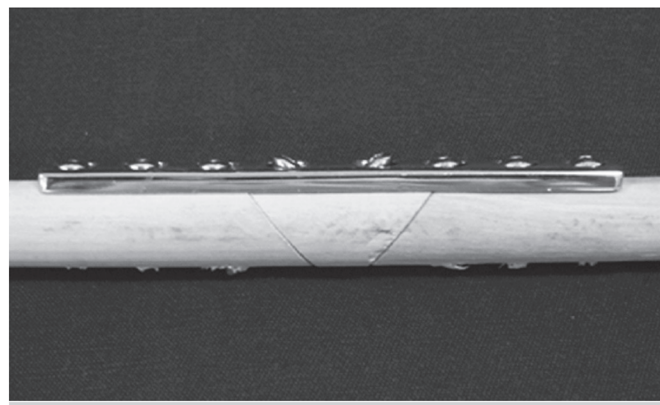

Figure 2. A model of trapezoidal profile graft fixed with a 3.5 mm DCP plate, under interfragmentary compression through the oblique contact surfaces.

The wooden sets were then fixed with an 8-hole 3.5 mm DCP plate (Synthes Brasil®, Rio Claro SP, Brazil) and 14 mm-long (2.6 mm-long for the lag screw technique in Group 2) 3.5 mm in diameter cortical screws, according to AO technique. All plates were bent at 5° at its middle portion in order to provide pre-tensioning. For the constructs in Group 1, the first step was to fix the intermediate segment ("graft") below the pre-tensioned plate with two screws inserted in the neutral position (Figure 1). The two longer segments were then assembled below the plate in as close contact as possible between them and the intermediate segment and so maintained with the help of a vise, until the fixation was complete with three screws on each end. Axial compression was provided with two screws, one on each end of the construct, through the hole just next to the contact surfaces. The construct was released from the vise before definitively tightening the compression screws and the remaining screws were introduced in the neutral position (Figure 2). In Group 2, the constructs with the trapezoidal intermediate segment were mounted directly onto the vise with its longest surface looking up. Reduction was carefully checked by direct vision and maintained by hand until the vise was tightened. The pre-tensioned plate was then positioned and held in site by hand, while two inter-fragmentary 26 mm-long lag screws were inserted through the plate towards the contact surfaces of the greater segments. Likewise in Group 1, the construct was released from the vise before definitively tightening the two lag screws, after which the remaining screws were inserted in the neutral position.

Once ready, the constructs were identified by numbers according to group (11, 12, 13 and so on in Group 1; 21, 21, 23 and so on in Group 2) and then submitted to two non-destructive bending tests, ccording to the direction of load application in relation to the fixation plate (upper and lower bending) and a non-destructive torsion test.

Bending tests: A universal testing machine (EMIC® model DL2000, Instron Brasil Equipamentos Científicos Ltda., São José dos Pinhais PR Brazil; www.emic.com.br), linked to a computer fed with specific software (TESC® Emic, v. 3.04) programmed for controlling and measuring the applied loads and for storing and interpreting the obtained data. The constructs were fixed onto the machine's vise by one end, comprising a 30 mm-long segment of its total length, so that a 220 mm-long portion of its length remained free. For the upper bending tests the constructs were fixed onto the universal testing machine with the fixation plate looking upwards while the load was applied on the opposite direction (downwards); for the lower bending tests, the construct was turned 180° and fixed onto the machine with the fixation plate looking downwards, while the load was applied in the same direction. The load was applied vertically from above below on the opposite free end, at a point 180 mm distant from the vise, by means of a rounded wedge-shaped accessory (Figure 3). Identical steps were followed for both upper and lower bending tests.

The non-destructive test consisted of load application up to a pre-determined limit (50 N in the present case) before any system failure occurred. The test began by applying a 5 N pre-load for 60 seconds for system accommodation. The actual load was then continuously applied at the rate of 5 mm/min, to the maximum predetermined load of 50 N. At this point, the resulting deformation (displacement) was automatically measured (mm) and the system rigidity (N/mm) was automatically calculated, as well as graphs of both displacement and rigidity were supplied for each construct. All constructs were tested three times, not in a row but in separate sequences of the seven constructs of each group, according to numbering. After each test, the screws were tightened again and the construct was removed from the vise and reserved for the next sequence. The average of the three values obtained was used for the comparisons between groups. The rigidity data concerning both upper and lower bending tests were submitted to statistical analysis according to a mixed effect linear regression model using the *ProcMixed* procedure of the SAS v.9.0 software, at the 5% level of significance ($p \leq 0.05$).[6]

Torsion tests: An Instron 55MT (Instrom Industrial Products, 900 Liberty Street, Grove City, PA 16127, USA) universal testing machine linked to a computer fed with specific software (PARTNER®) was used for the torsion tests. The constructs were fixed onto the machine by both ends, leaving a free 180 mm-long segment (lever arm), with the intermediate segment ("graft") exactly in the middle (Figure 4). Torsion load was then applied at the rate of 5°/minute, up to a 5° deformation, when the torque (N.m) was then automatically measured. Similarly to the bending tests, all constructs were tested three times, not in a row but in separate sequences of the seven constructs of each group and the screws were equally re-tightened before removing the construct from the machine, until the next sequence according to numbering. The average of the three values obtained was used for the comparisons between groups. The data concerning torque were recorded and submitted to statistical analysis by Student's t test, using the PROC T TEST procedure of the SAS v.9.0 software, at the 5% level of significance ($p \leq 0.05$).[6]

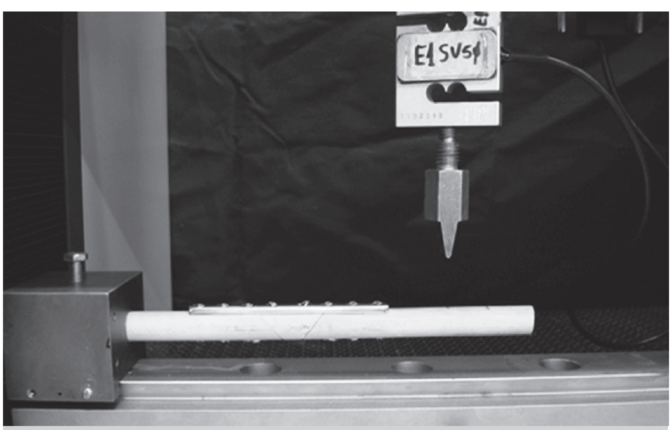

Figure 3. A model of trapezoidal profile graft immediately before being submitted to a upper flexion test.

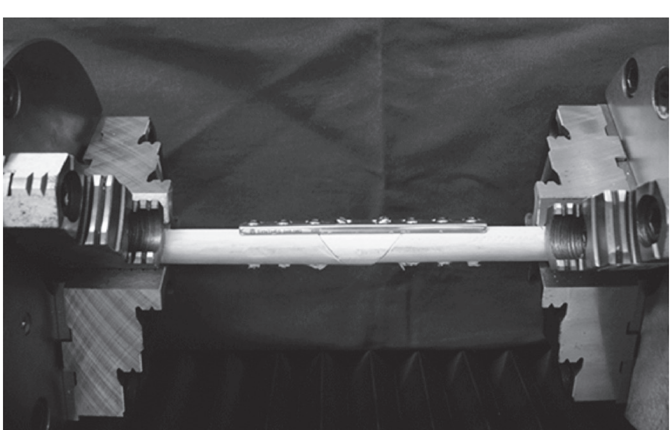

Figure 4. A model of trapezoidal profile graft being submitted to the torsion test.

RESULTS

Bending tests: The average displacement as measured on the free end of the construct was significantly ($p=0.01$) lower for the upper (3.99 mm) than for the lower (5.6 mm) plate position in Group 1 (rectangular profile "grafts"), while no significant difference ($p=0.06$) existed between upper (3.56 mm) and lower (4.67 mm) position in Group 2 (trapezoidal profile "graft") (Table 1). Displacement was greater for Group 1 than Group 2 constructs, regardless of the plate position, but the differences between groups were non-significant for both positions ($p=0.45$ for the upper position; $p=0.12$ for the lower position) (Table 2, Figure 5).

The average rigidity was significantly ($p=0.04$) higher for the upper (13.75 N/mm) than for the lower (10.26 N/mm) plate position in Group 1. Likewise, the average rigidity was significantly ($p=0.03$) higher for the upper (15.27 N/mm) than for the lower (11.59 N/mm) in Group 2 (Table 3). However, for both the upper and lower plate position,

Table 1. Displacement (mm) on the bending tests according to plate position.

Group	Plate position	n	Average	CI (95%)		SD	Minimum	Median	Maximum
				LL	UL				
1	lower	7	5.6	4.24	6.95	1.46	3.99	4.95	7.76
	upper	7	3.99	2.88	5.1	1.2	2.73	3.9	6.05
2	lower	7	4.67	3.86	5.48	0.87	3.51	4.36	5.77
	upper	7	3.56	2.75	4.38	0.88	2.28	3.61	5.03

CI, confidence interval; LL, lower limit; UL, upper limit; SD, standard deviation.

Table 2. Statistics of the bending displacement according to plate position.

Effect	Estimate	LV	UV	p
Lower position (G1 - G2)	-0.9229	-21.027	0.2570	0.12
Upper position (G1 - G2)	-0.4300	-16.099	0.7499	0.45
G2 (lower - upper)	11.114	-0.06846	22.913	0.06
G1 (lower - upper)	16.043	0.4244	27.842	0.01

LV, lower value; UV, upper value.

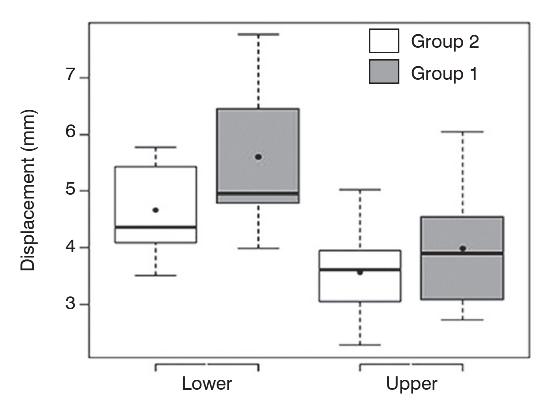

Figure 5. Box plot graph of the displacement during the flexion tests, according to group and plate position.

the average rigidity was higher in Group 2 than Group 1, although with non-significant difference between groups for both positions (p=0.42 for Group 2; p=0.36 for Group 1) (Table 4, Figure 6).
Torsion tests: The average torque at 5° deformation was 2.38 N.m in Group 1 and 2.18 N.m in Group 2, with non-significant differences between groups (p=0.0537) (Table 5 and 6; Figure 7).

DISCUSSION

The treatment of diaphyseal critical-sized cortical bone defects often requires the use of some form of bone grafting associated with a very stable fixation. Specific surgical techniques for the treatment of such defects of the forearm bones were introduced as early as the decade of the years 40 of the last century, involving different types of graft and resulting in variable outcome rates.[7-9] The TCC bone block graft from the iliac crest was introduced shortly thereafter with very good results in 12 very complicated cases; in all of them, an intramedullary pin was used for fixation.[10] A modification of the technique was later introduced, consisting of harvesting the graft already devoid of the upper and medial or lateral cortices, or both, and fixing it with plate and screws,[1] but with similar outcomes; for both techniques, the graft profile was rectangular from the very beginning. The TCC graft as described by Spira is the one we regularly use in our clinical practice, particularly for not too extensive but critical-seized defects,[4] with regularly good results, as characterized by full integration and cortical transformation of the graft.

Table 3. Rigidity (N/mm) on the bending tests according to plate position.

Group	Plate position	n	Average	CI (95%) LL	CI (95%) UL	SD	Minimum	Median	Maximum
1	lower	7	10.26	7.91	12.62	2.54	6.73	10.78	13.72
	upper	7	13.75	10.35	17.15	3.67	8.75	12.89	18.61
2	lower	7	11.59	9.20	13.98	2.58	8.89	12.00	15.83
	upper	7	15.27	11.52	19.02	4.05	9.86	14.76	22.77

CI, confidence interval; LL, lower limit; LS, upper limit; SD, standard deviation.

Table 4. Statistics of bending rigidity according to plate position.

Effect (G1 - G2)	Estimate	LV	UV	p
Lower position	13.214	-20.806	47.234	0.42
Upper position	15.200	-18.820	49.220	0.36
G2 (lower - upper)	-36.814	-70.834	-0.2794	0.03
G1 (lower - upper)	-34.829	-68.848	-0.08087	0.04

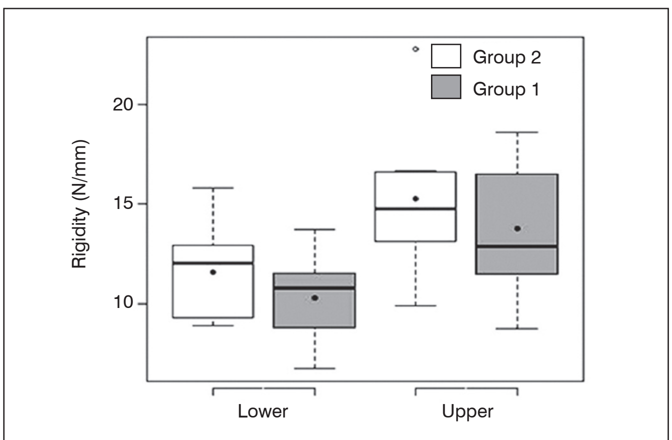

Figure 6. Box plot graph of rigidity (N/mm) according to group and plate position.

Table 5. Torque (N.m) at 5° torsion deformation, according to group.

Group	N	Average	CI (95%) LL	CI (95%) UL	SD	Minimum	Average	Maximum
1	7	2.38	2.20	2.56	0.19	2.08	2.38	2.65
2	7	2.18	2.03	2.33	0.16	1.91	2.14	2.39

CI, confidence interval; LL, lower limit; UL, upper limit; SD, standard deviation.

Table 6. Statistics of the results of torque on the torsion tests.

Effect	Estimate	LV	UV	p
G1 - G2	-0.41	-0.203	0.0038	0.0537

LV, lower value; UV, upper value.

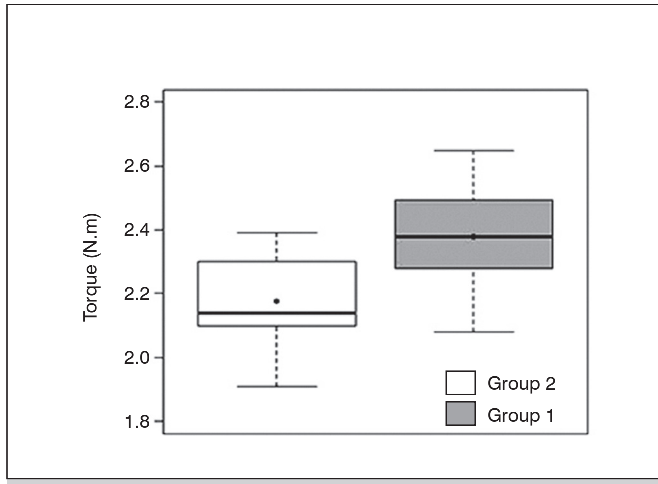

Figure 7. Box plot graph of torque (N.m) according to group (graph profile).

Despite the early description of fixation with intramedullary pins or conventional plate and screws, fixation with a compression plate became the most convenient model, particularly after the demonstration that absolute stability ("pressure-proof blocks") facilitates and accelerates graft integration[4,11,12]. However, good results are also obtained with intramedullary pins, perhaps over a slightly longer period.[2,3]
The main advantage of the TCC bone block graft from the iliac crest is the availability and relative easiness to do, at the reach of any well trained orthopaedic surgeon. Among other requirements (no infection, adequate recipient bed preparation), the shape and dimensions of the graft seem to play a major role for good results. The rectangular profile seems to be the most used since Nicoll's and Spira's description;[1,10] it provides two contact surfaces perpendicular to the long axis of the recipient bone and, therefore, the ability to withstand axial compression and shearing forces imposed by motion. However, the trapezoidal profile ("keystone") more recently suggested provides two oblique wider contact surfaces, with the alleged advantage that healing would be quicker,[5] but possibly with the disadvantage that the operative act would be considerably more difficult and time-consuming, not to mention that fixation with an intramedullary pin would be virtually impossible.
However, from a theoretical standpoint, the trapezoidal graft profile would favour a more economic bone resection in the preparation of the recipient bed and help reduce the defect length. Actually, a limiting factor for the use of the TCC bone block graft is the defect length, since wide defects require wide grafts, with an inevitable reflex over time of integration. Although this seems to vary among authors, it is our own experience that up to 5 cm long defects can

be corrected with the TCC graft. In the present study we limited the defect length to 26 mm, which roughly corresponds to 10% of the bone length (25 cm), thus characterizing a critical-sized defect, meaning that in a clinical situation it would not heal on its own or without the assistance of a surgical grafting procedure.

From a biological standpoint, the graft with oblique contact surfaces could even be superior to that with perpendicular surfaces, since the contact area is wider in the first case, thus contributing to speed up healing and integration. Assuming that both profile grafts would take up in approximately the same time, it was the mechanical behaviour of the trapezoidal profile graft that intrigued us. In the present investigation we decided to compare solely the biomechanical behaviour of both rectangular and the trapezoidal profile types of graft because the first is undoubtedly the most used, while the second has not yet been thoroughly addressed since its original description and the capability of which in solving clinical situations is not entirely known.[5]

For both profile "grafts", fixation of the experimental construct was done with a 3.5 DCP plate according to the AO technique in order to assure absolute stability against bending and rotational stresses. In order to make it work properly the plate installation must be adequately balanced, meaning that equal plate lengths are maintained above and below the defect.[13,14] Also, the graft must be compressed against both recipient bone stumps, by means of axial (Group 1) or interfragmentary (Group 2) dynamic compression. Interfragmentary dynamic compression associated with a neutralizing plate is the most sensible indication for fixation of up to 45° oblique diaphyseal fractures of the forearm bones. In fact, the compression by the lag screw through the oblique surfaces is at least equivalent to the dynamic axial compression through the surfaces of perpendicular or not more than 30° oblique fractures. From this standpoint, the idea of using TCC bone block grafts with oblique contact surfaces is also very attractive and was the reason why its mechanical behavior was compared with that of the perpendicular contact surfaces.

The present study was designed to be carried out with wooden models, according to a protocol of regular use in our department, for investigation on the fixation of several different bones, including spinal vertebrae.[15] The wood used to make the models is of the kind recommended by engineers for mechanical studies. Obviously, it does not present the same biomechanical properties as the bones, but its compact and uniform structure, great density (~0.71 g/cm^3, on average) and anisotropy account for uniform and reliable results, which theoretically can be translated to a real situation in living bones.

According to our results, the mechanical behavior of both profile "grafts" was very similar. Constructs in Group 1 (rectangular profile "grafts") were more flexible than those in Group 2, but not significantly so, meaning that both present identical mechanical resistance against bending stress. As expected, resistance against bending stress was significantly higher for the load applied on the same surface of the plate position, as confirmed by the rigidity figures. Rigidity was significantly higher for Group 2 constructs, probably indicating that the combination of a wedge shaped "graft" fixed by means of interfragmentary screws with a neutralizing plate should be preferred in a clinical situation whenever possible. Resistance against torsion was virtually the same for both Group 1 and 2 constructs.

CONCLUSION

The results presented above permit the authors to conclude that, from a biomechanical standpoint, both graft profile would behave similarly in a clinical situation. Therefore, the choice between one another would only depend on the surgeons' preference and on the defect geometry.

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