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Review Article

Influence of test parameters on *in vitro* fracture resistance of post-endodontic restorations: a structured review

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SUMMARY A structured literature review aimed to elucidate test parameters for *in vitro* testing of post-endodontic restorations. The literature was digitally searched using MEDLINE, EMBASE, MedPilot and an additional hand search was performed. Two independent researchers assessed the articles in relation to the defined inclusion and exclusion criteria. The literature search revealed 125 abstracts. Sixty-nine studies were included. Fifty-seven per cent of the studies investigated maxillary incisors only. The restorative stage as complex of tooth, post, core, and crown and post-and-core restored specimens without crowns were used most frequently. Fifty-nine per cent of the studies used static loading. Only 15% of the studies performed thermocycling and mechanical loading (TCML). However, the number of thermo- and load cycles varied. The cross-head speed of linear loading after TCML ranged from 0·01 to 150 mm min^{-1}. The reviewed studies were heterogeneous in test design regarding the used test parameters. A methodological standardization of *in vitro* testing of post-endodontic restorations is recommended.

KEYWORDS: chewing simulation, dynamic loading, linear loading, one-cycle testing, post , core

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Introduction

The fracture resistance of endodontically treated teeth (ETT) is influenced by a number of parameters as age (1), plaque (1), the number of adjacent teeth (1, 2), and occlusal contacts (3, 4), tooth position in the dental arch (5, 6), crown placement (7, 8) type of abutment (5, 9), apical status (10), collagen degradation (11), intermolecular cross-linking of the root dentin (12) and by the amount of lost hard tissue (13–17). In accordance with the latest aspect, the advantage of a 1·5–2·0 mm ferrule preparation is well documented (18–21).

As ETT often suffer extensive defects, post placement is clinically necessary to create retention for the core and final restoration (12, 22). The choice of an appropriate post material is controversially discussed (23). Clinical trials are time-consuming, costly and standardization of test conditions is difficult (24). *In vitro* tests are necessary to provide scientific basic data to assess the failure risk. However, a sufficient *in vitro* test design is needed. To date, no standard test design has been introduced. Only a little methodological work was done to study the influence of specific test parameters

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on the outcome of post-endodontic restoration testing. Different devices were used to test basic mechanical properties of endodontic posts as such or as part of a restorative complex. The incomparability of individual studies was highlighted (25). At every restorative stage, the fracture resistance for each post system was significantly different. The influence of the load angulation and speed or the tooth type on the fracture resistance of ETT was also demonstrated (26–29). Furthermore, the influence of the storage medium of the samples (30, 31) was investigated. Because of the varying designs, it is not surprising that studies may deliver inconsistent or conflicting results. Thus, their clinical relevance is limited (32, 33).

It was the aim of this structured review to elucidate and discuss test parameters used in *in vitro* test of post-endodontically restored teeth in order to support researchers to carefully choose adequate test parameters for future research.

Materials and methods

The literature was digitally searched in dental journals using MEDLINE, EMBASE and MedPilot in February 2005 and updated in January 2007. An additional hand search was performed with assistance of a librarian of the central library, Charité – Universitätsmedizin Berlin. The hand search was based on the reference lists in the selected articles and on dental journals not included in the databases mentioned. The literature search was performed in subsequent steps (Table 1). In the first step 'root canal therapy', 'dental

Table 1. Literature search and selection procedure with number of included studies after each step

Steps	Added keywords/selection criteria	No. of studies included after the performed step	Literature search/selection
Step 1	Root canal therapy OR dental pulp devitalisation OR post and core technique	8114	Literature search
Step 2	'Step 1' AND Post OR dowel OR dentin OR failure OR brittleness OR fracture	2717	Literature search
Step 3	'Step 2' AND prefabricated post OR cast post OR Wurzelstift OR post and core restoration OR endodontically treated teeth OR post fracture OR fracture load OR fracture resistance OR fracture behaviour OR fracture strength OR Bruchfestighkeit OR survival rate OR artificial mouth OR fibre post-OR pre-fabricated fibre post OR Kausimulation OR simulated periodont OR *in vitro* OR crowns OR resin cement OR selfadhesive OR thermocycling and mechanical loading OR titanium OR dental peg OR Stiftfraktur OR load OR root pins OR pre-fabricated roto pins OR metal peg	125	Literature search
Step 4	Exclusion criteria: descriptive studies or reviews, studies in non-human teeth, the use of active screw systems, pull-out and push-out tests (retentive strength tests), studies with less than five specimens per group and load application from a facial or buccal direction respectively. Excluded studies were: Pull out design (122–130) Review design (33, 131–139) Use of non-human teeth (20, 113, 140–150) *In vivo* design (5, 151, 152) Absence of teeth (153–155) Lack of post use in a experimental group (156–164) Finite element analysis design (165–169) No loading was performed (170, 171) Incomparability of the single test groups (172) Use of less than five teeth per test group (173) One reference (174) was excluded since it was based on the same study as reference (46)	69*	Selection based on the 125 complete articles from step 3

*Because of study design one article (69) was considered as two studies total number of analyzed studies is 69.

pulp devitalisation' and 'post-and-core technique' were searched by an 'or' connection. In the second step, six keywords were added by an 'and' connection (Table 1). In the third step, 29 keywords were added by an 'and' connection. Thus, 38 keywords were used and logically connected. Two independent researchers, both graduate dentists, conducted the inclusion and exclusion step (Step 4).

Scope of review

The complete articles of the remaining abstracts were critically appraised following specific inclusion and exclusion criteria. In case of divergence between the two reviewers regarding inclusion of an article not resolved by discussion, a third researcher was asked for decision. All articles written in English and German, which described *in vitro* tests of post-endodontically restored human teeth of the secondary dentition were included. Excluded articles were descriptive studies or reviews, studies in non-human teeth, the use of active screw systems, pull- and push-out tests (retentive strength tests), studies with less than five specimens per group and a load application from a facial or buccal direction, respectively. In case of missing information authors were contacted. The test parameters were extracted and categorized.

Characteristics of articles

The structured literature search revealed 125 abstracts (Step 1–3, Table 1). After exclusion in Step 4, 68 articles (19, 25, 26, 34–98) were included in the review. One article (69) was considered as two studies as two non-comparable tooth types (molars and maxillary incisors) were used. Thus, the total number of included studies was 69 (Table 1). All test parameters are listed in Tables 2–4 and described in detail below.

Type of specimens and storage Maxillary incisors were used most frequently (n = 39; 57%) followed by both maxillary and mandibular incisors (9%) or mandibular incisors and premolars (jaw and site mostly not specified) (9%).

The number of groups per study varied between two (45) and 20 (51) with a median number of four groups per study. The minimum number of specimens per group was five (54), whereas in one study, the maximum number of 44 teeth per group was tested

Table 2. Frequency of specific test parameters within the evaluated studies

Test parameter	No. of studies	Studies in %
Embedding materials		
Not specified	2	3
Gypsum	6	9
Technovit	35	51
PMMA	6	9
Classico	2	3
Paladur	3	4
Autopolymerizing resin	3	4
Resin	2	3
Epoxy resin	2	3
Storage medium		
Not specified	3	4
Chloramine	5	7
Deionised water	8	12
Neutral buffered formaline	5	7
Water	8	12
100% humidity	2	3
Glutar-aldehyde	1	2
Zepiran chloride + water	1	2
Moist environment	1	2
Saline solution	21	30
Thymol	14	20
Definitive restoration		
Non-precious metal	18	26
Gold alloy	9	13
Ceramics	9	13
Porcelain fused to metal	1	2
Composite crown	2	3
Core like crown	5	7
Pd alloy	2	3
No restoration	19	28
FRC crown	1	2
Composite veneer	1	2
Just cast	2	3
Partial crown	1	2
Type of pre-fabricated post		
Not specified	7	10
Others	21	30
Ceramics	21	30
Glass/quartz fibre	22	32
Titanium	19	28
Carbon fibre	9	13
Tooth type used		
Upper front teeth	39	57
Upper premolars	4	6
Lower front teeth	2	3
Lower premolars	6	9
Lower molars	3	4
Upper and lower front teeth	6	9
Upper and lower premolars	6	9
Other (mixed teeth)	3	4

PMMA, polymethyl methacrylate.

Table 3. Specific test parameters in studies using linear compressive load application

Reference	Tooth type	Artificial periodontal ligament (yes/no)	Bone simulation by	No. of specimens per group	Restorative stage loaded			Cross-head speed (mm min^{-1})	No. of thermocycles	Primary outcome parameter
					Post	Post and core	Final restoration			
Zhi Yue and Yu Xing (34)	U1	No	Acrylic resin	12			X	0·2	0	F_{max}
Akkayan (35)	U 3	Yes	PMMA	10			X	1·0	0	F_{max}
Akkayan and Gulmez (36)	U 3	Yes	PMMA	10			X	1·0	0	F_{max}
Gluskin *et al.* (39)	L1 + 2	No	PMMA	10			X	5·0	0	F_{max}
King and Setchell (41)	U1 + 3, L 3	No	Technovit	10			X	50·0	0	MNm^2
Pilo *et al.* (43)	L P	No	Resin	10			X	2·0	0	F_{max}
Al-Wahadni and Gutteridge (44)	U/L front + P	No	Gypsum	10		X		10·0	0	F_{max}
Al-Hazaimeh Gutteridge (45)	U1	No	Gypsum	10			X	5·0	0	F_{max}
Baratieri *et al.* (48)	U1	No	Technovit	10			X	150·0	0	F_{max}
Kahn *et al.* (49)	U/L P	No	Gypsum	15			X	5·0	100	Pounds inch^{-2}
Patel and Gutteridge (50)	U/L front + P	No	Gypsum	10		X		100·0	0	F_{max}
Cohen *et al.* (51)	U/L1 + 2 + P	No	Technovit	10		X		6·35	0	F_{max}
Guzy and Nicholls (53)	U1 + U/L 3	Yes	Technovit	15		X		50·0	0	F_{max}
Hoag and Dwyer (54)	L M	No	Technovit	5			X	0·3	0	F_{max}
Brandal *et al.* (55)	U1	No	Technovit	15			X	50·0	0	F_{max}
Bex *et al.* (56)	U1	No	Not specified	12		X		1·0	0	F_{max}
Sidoli *et al.* (57)	U 1 + 3	No	Technovit	10			X	50	0	MNm^2
Sirimai *et al.* (58)	U1	Yes	Technovit	10		X		0·5	0	F_{max}
Mendoza *et al.* (59)	L 3	Yes	Technovit	10	X			0·5	360	F_{max}
Saupe *et al.* (62)	U1	Yes	Technovit	10		X		2·0	1500	F_{max}
Mezzomo *et al.* (64)	U P	No	Classico	10		X		1·0	0	F_{max}
Robbins *et al.* (66)	U/L 3	No	Technovit	10			X	0·5	0	F_{max}
Maccari *et al.* (67)	U 1 + 3	No	Technovit	10		X		0·5	0	F_{max}
Ng *et al.* (68)	U 1 + 3	No	Acrylic resin	10			X	0·5	0	F_{max}
Attin *et al.* (69)	U 1	Yes	Acrylic resin	10		X		2·5	0	F_{max}
Attin *et al.* (69)	L M	Yes	Acrylic resin	10			X	2·5	0	F_{max}
Kern *et al.* (70)	U1	No	Technovit	10			X	3·0	0	F_{max}
Raygot *et al.* (72)	U1	No	Acrylic resin	10			X	25·4	0	F_{max}
Martines insua *et al.* (74)	U/L P	No	Acrylic resin	22			X	10·0	0	F_{max}
Assif *et al.* (19)	U/L P	No	Acrylic resin	10			X	2·0	0	F_{max}
Janssen and Hulsmann (76)	U1	Yes	Technovit	20			X	1·0	10 000	F_{max}
Loney *et al.* (26)	U1	Yes	Acrylic resin	10			X	0·01	0	F_{max}
Dean *et al.* (77)	U3	No	Epoxy resin	10		X		0·5	0	F_{max}
Kern *et al.* (78)	L M	Yes	Gypsum	9			X	0·5	0	F_{max}
Katebzadeh *et al.* (79)	U1	No	Gypsum	20		X		50·8	0	F_{max}
Pene *et al.* (80)	U1	No	Acrylic resin	10		X		5·0	0	F_{max}
Newman *et al.* (81)	U1	Yes	Technovit	10	X			0·5	0	F_{max}

Table 3. Continued

Reference	Tooth type	Artificial periodontal ligament (yes/no)	Bone simulation by	No. of specimens per group	Restorative stage loaded: Post	Restorative stage loaded: Post and core	Restorative stage loaded: Final restoration	Cross-head speed (mm min^{-1})	No. of thermocycles	Primary outcome parameter
Hu *et al.* (83)	U1	No	Technovit	10			X	2·5	0	F_{max}
Volwiler *et al.* (84)	U1	No	Technovit	10			X	5·0	0	F_{max}
Martinez Gonzales *et al.* (86)	U3	No	Technovit	10			X	0·5	0	F_{max}
Cormier *et al.* (25)	L P	No	Acrylic resin	10			X	1·27	0	F_{max}
Schmitter *et al.* (89)	U/L 1	No	PMMA	8			X	0·5	10 000	F_{max}
Ng *et al.* (90)	U front	No	Acrylic resin	10			X	5·0	0	F_{max}
Tan *et al.* (91)	U1	No	Acrylic resin	10			X	2·5	0	F_{max}
Fokkinga *et al.* (94)	U P	Yes	Acrylic resin	11			X	5·0	6000	F_{max}
Mezzomo *et al.* (95)	U P	No	Classico	10			X	1·0	0	F_{max}
Grieznis *et al.* (98)	U/L P	No	PMMA	20		X		0·5	0	F_{max}

U, upper; L, lower; 1, central incisor; 3, canine; P, premolar; M, molar; PMMA, polymethyl methacrylate.

(99). The median number was 10 teeth per experimental group. In three studies (4%) (94, 96, 97), no randomization of specimens was reported. The specimens were most commonly stored in saline solution (n = 21; 30%) and thymol (n = 14; 20%).

Specimen preparation If root canal treatment was performed, root canals were enlarged varying from International Organization for Standardization (ISO) 30 to ISO 70. The predominant way of obturating the root canal was lateral condensation (n = 42, 61%). Twenty-one studies (30%) provided no details about root canal obturation. Six studies (9%) were based on single cone, injection or alternative techniques.

The materials used to embed the specimen teeth are listed in Table 2. Thirteen studies (19%) involved covering the root surface with silicone aimed at simulating the natural mobility of a tooth in the alveolar bone. Two studies (3%) involved the application of polyether (47, 75), whereas another study involved the application of rubberdam (69). Polyvinyl siloxan and rubberized film were used in three studies (4%), respectively. One study (1%) (63) ensured tooth-like mobility of the specimens by an alternative artificial periodontal ligament, whereas 45 studies (65%) did not specify if or what type of artificial periodontal ligament was used.

Restoratives In all included studies, a total number of 325 groups were tested. The evaluation is group-based as in some studies partly different test designs were used. Almost half of the included groups (n = 151; 46%) tested the completely post-endodontically restored complex of tooth, post, core build-up and final crown restoration; 81 groups (25%) investigated specimens without crown restoration. In 26 groups (8%), the teeth were decoronated, i.e. tooth cut at or close to the level of the cemento-enamel junction, and in eight groups (2%), no decoronation was performed. A large diversity of final restorations as, e.g. veneer restorations or amalgam crown–cores and countersink cores were used (5%). In 14% of the groups, ETT with or without crowns represented control groups.

Post types were cast as well as pre-fabricated posts (Table 2). Frequently, the post system itself was a variable, thus more than one type of post was used within one study. Sixteen studies (23%) investigated cast gold alloy posts, 11 (16%) cast non-precious metal posts and five used other cast posts with no specification of the alloy.

Table 4. Specific test parameters in studies using dynamic load application

Reference	Tooth type(s) used	Periodontal membrane simulated (yes/no)	Bone simulation with	No. of specimens per group	Restorative stage loaded			Number of thermocycles	Number of cyclic loads applied	Amplitude and frequency (N; Hz)	Primary outcome parameter	Additional linear load application (yes; no)
					Post	Post and core	Final restoration					
Heydecke *et al.* (37)	U1	Yes	Technovit	16			X	Simultaneous	$1{\cdot}2 \times 10^6$	(30; 1·3)	F_{max}	Yes
Krejci *et al.* (38)	U/L P	No	Not specified	7			X	3000	$1{\cdot}2 \times 10^6$	(49; 1·7)	Marginal integrity	Yes
Freeman *et al.* (40)	U1	No	Technovit	10			X	0		(35; 1·2)	Cycles to failure	No
Pontius and Hutter (42)	U1	No	Technovit	10			X	0	$1{\cdot}2 \times 10^6$	Not specified	Survival rate	Yes
Heydecke *et al.* (46)	U1	Yes	Technovit	16			X	Simultaneous	$1{\cdot}2 \times 10^6$	(30; 1·3)	F_{max}	Yes
Rosentritt *et al.* (47)	U1	Yes	Technovit	7			X	6000	$1{\cdot}2 \times 10^6$	(50; 1·6)	F_{max}	Yes
Rosentritt *et al.* (52)	U1	No	PMMA	8			X	6000	$1{\cdot}2 \times 10^6$	Not specified	F_{max}	Yes
Huysmans *et al.* (99)	U P	No	Technovit	44		X		0	1×10^6	(5; 5)	Survival rate	No
Krejci *et al.* (61)	U/L P	No	Technovit	6		X		0	$1{\cdot}2 \times 10^6$	(49; 1·5)	Marginal integrity	Yes
Reagan *et al.* (63)	L P	Yes	Technovit	10		X		0		(45·4; 4·7)	Cycles to failure	No
Cohen *et al.* (65)	U/L 3	No	Technovit	5	X			0	2×10^6	(22·3; 3)	Pounds inch^{-2}	Yes
Dietschi *et al.* (71)	U 1 + 3	No	Technovit	8		X		5000	250 000	(70; 1·5)	Marginal integrity	No
Butz *et al.* (73)	U1	Yes	Technovit	16			X	10 000	$1{\cdot}2 \times 10^6$	(30; 1·3)	F_{max}	Yes
Rosentritt *et al.* (75)	U1	Yes	PMMA	8			X	6000	$1{\cdot}2 \times 10^6$	(50; 1·6)	F_{max}	Yes
Goto *et al.* (82)	U1	No	Technovit	5			X	0		(58·9; 4·3)	Cycles to failure	No
Strub *et al.* (85)	U1	No	Technovit	10			X	0	$1{\cdot}2 \times 10^6$	(49; 1·3)	Survival rate	Yes
Mannocci *et al.* (87)	L P	Yes	Technovit	10			X	0	400 000	(250; 2)	Survival rate	No
Naumann *et al.* (88)	U1	Yes	Technovit	10			X	6000	$1{\cdot}2 \times 10^6$	(50; 1·6)	Fmax	Yes
Sahafi *et al.* (92)	U1 + U/L3	Yes	Acrylic resin	10			X	0		(600; 2)	Cycles to failure	No
Stricker and Gohring (93)	L 3 + P	No	Epoxy resin	8			X	3000	$1{\cdot}2 \times 10^6$	(49; 1·7)	F_{max}	Yes
Friedel and Kern (96)	U1	Yes	Technovit	8			X	6500	$1{\cdot}2 \times 10^6$	(30; 1·3)	F_{max}	Yes
Salam *et al.* (97)	L P	Yes	Acrylic resin	20		X		0	40 000	(40;1·6)	Survival rate	No

U, upper, L, lower; 1, central incisor; 3, canine; P, premolar; PMMA, polymethyl methacrylate.

Loading protocol Most of all included studies (59%) used a linear load application (i.e. static loading) in a universal material testing machine (Table 3). Ten studies combined thermocycling (TC) and mechanical dynamic loading (ML) (dynamic loading; synonymously used: thermomechanical loading, thermocycling and mechanical loading (TCML), chewing simulation) with subsequent linear load application until fracture or other types of failure. Six studies loaded the specimens linearly after TC and three studies loaded the specimens linearly after ML (without TC). Eight studies performed only ML, and one combined ML and TC without additional linear loading. For detailed information, see Table 4.

The cross-head speed during linear load application varied between a minimum value of 0·01 mm min^{-1} (26) and a maximum speed of 150 mm min^{-1} (48) with a median speed value of 1·5 mm min^{-1}. The minimum load value applied during cyclic loading was 1 N (68) and the maximum was 600 N (92). The maximum force amplitude during ML ranged from 29 to 49 N. The frequency of load application varied between 1·2 and 5·0 Hz. In most cases, 1·6 Hz was used. Tables 3 and 4 show the protocols used for static and dynamic load tests.

Critical analysis of reviewed articles

A structured literature review was performed to systematically survey *in vitro* tests of post-endodontically restored human teeth of the second dentition. The results show that there is significant heterogeneity of study designs. However, in *in vitro* studies test variables and confounding test parameters may be better controlled than in clinical studies. A certain research hypothesis can be pre-tested, risks can be assessed, and bench marking (best-case or worse-case scenarios to define indications and/or contraindications) of restorative approaches is possible. Thus, besides ethical aspects, costs, and the time of observation needed clinically, *in vitro* tests do have obvious advantages when compared with clinical studies. However, this review indicates the difficulties in comparing results of different *in vitro* studies because of their heterogeneous test designs. In some studies, in terms of clinical application, questionable designs were used.

Type of specimens, storage and number per group As front teeth are described as a high-risk area regarding mechanical failures because of a high amount of shear forces (100), it is important to study their behaviour under load application. Best and worst-case scenarios are recommended (101). However, because of their structurally anatomic differences and different functional loading, it appears to be meaningful to distinguish between front teeth, premolars and molars (102–104).

Another basic question is how to store specimen teeth to avoid structural changes of the hard tissue, in particular dentin until the time of specimen preparation and testing (105). The storage medium used most often was saline solution in about 30% of the cases followed by thymol (20%). Saline solution is the only storage medium affecting the bond strength negatively (30). Thus, saline solution might be unsuitable for the purpose of storing specimens. The use of thymol solutions leads to significantly lower shear bond strengths (106). The ISO recommended in their ISO/TS 11405 the use of distilled water or 0·5% chloramine-trihydrate solution with periodically replacement. However, the teeth should not be stored longer than 6 months.

The procedure of assigning specimens to the experimental groups may also influence the study results. One study (63) took both the largest teeth and the smallest teeth for one group to acquire an equal mean length for each group. Cutting each specimen 15 mm from the apex resulted in different heights from the cemento-enamel junction (CEJ). It is recommended to distribute the specimens by a sort of tooth size assessment. For example, the product of the mesial-distal and buccal-palatal extension at the level of the CEJ can be calculated. Teeth of extreme size should be excluded. The remaining teeth can be randomly allocated according to a randomization plan (e.g. 10-digit number table).

The number of specimens per group reported in the studies reviewed varied from five (54) to 44 teeth (99). The median specimen number per group was 10. It seems to be the actual compromise between the feasibility and the minimum statistical requirements to use between eight and 12 specimens per group. However, in contrast to clinical studies, the need of a proper power analysis for *in vitro* tests was not addressed.

A statistical problem arises when cyclic loading is performed before linear loading in fracture tests. Some specimens do not survive the chewing simulation and

some authors comprise these specimens (37, 46, 73, 85) with a load to fracture of 0 N while some do not (42, 88). Thus, mean and standard deviations are affected by the decision if specimens are considered failures. The inclusion of all specimens was suggested (107). The opposite problem occurs when specimens resisted the maximum load application (68). In these cases, the maximum applied load was considered for further analysis (69, 94). Pilot studies or pre-testing ahead of the main experiment might help to avoid such problems.

Specimen preparation To improve the simulation of a clinical situation, the physiological tooth mobility should be simulated. Some studies used an artificial periodontal ligament. However, only one approach has been attempted to be validated (108).

An aspect to date also not addressed properly is the choice of the embedding material. When failure of the embedding material was reported, the specimens were embedded in gypsum or acrylic resin (39, 44, 45, 78). The results show that the embedding material Technovit* as an autopolymerizing acrylic resin was used in half of all included studies. However, further investigations on the impact of the type of the embedding material on the test results of *in vitro* load-to-fracture tests are urgently needed. To our knowledge, a validated standard material is not introduced to simulate mandibular and maxillary bone characteristics.

Of questionable value are studies where the post does not have the same geometry as the prepared root canal. For example, in one study parallel-sided posts were inserted in tapered root canals (55). Another study used a cylindro-conical post system upside down to use the parallel part in the canal not reporting the geometry of the part connected with the core (92). Anusavice *et al.* (101) suggest a test design as close as possible to clinical reality (e.g. geometry, loading) with structurally representative specimens. As it is impossible to simulate all possible test conditions in one test, a worst-case/best-case scenario should be designed. The absence of sealer or gutta-percha might improve the bond to dentin of luting cements (94). Post placement in root canals that are not obturated does not totally represent the clinical situation introducing possible effects on the test results.

Restoratives No final restoration was used in approximately 28% of the studies. However, as discussed elsewhere (25), the final restoration introduces the well-known ferrule effect (18). As described before (109), the combination of a post and ferrule revealed the optimum load capability. Varying post systems probably have only little impact on the load capability when inserted in crown-restored teeth in *in vitro*. In about two-third of the reviewed studies full-metal crowns were placed, and even more teeth (approximately 70%) were from the anterior region. However, obviously it is not very common clinically to use full-metal restoration is the aesthetic zone, and failure characteristics might be different when porcelain fused-to-metal, composite or all-ceramic crowns are placed.

Another aspect of importance is the restorative stage, e.g. when only the endodontic post is loaded. One study (65) used a complex calculation model to compensate for study flaws as different post lengths, force vectors, and surface sizes that could probably have been solved by small changes in the study design.

Loading protocol In general, one can distinguish between destructive and non-destructive loading protocols. Destructive test arrangements predominantly use static loading to test the maximum load capability F_{max} (equivalent used terms are load-to-fracture, fracture strength or resistance, load bearing capacity) as primary outcome parameter in combination with or without dynamic loading. The crosshead speed is a crucial parameter of static loading (28, 29). The fracture resistance increases as crosshead speeds decreases (77), and speeds up to 150 mm min^{-1} (48) are an approximation on traumatic effects. Crosshead speeds of less than 1 mm min^{-1} affect the load-to-fracture of ceramic restorations alter their normal crack development (110). Therefore, a crosshead speed of 1 mm min^{-1} was recommended (111).

Non-destructive test designs include measurement of gap formations before, during or/and after subcritical dynamic loading (61, 71). Dynamic subcritical loading of specimens until failure may also be meaningful and a correlation to a clinical situation is likely (112). The statistical analysis can use mechanical load cycles until failure as the dependent variable (113). Log rank statistics compare the number of cycles until failure of the individual groups, and constructed Kaplan–Meier survival plots describe at a glance study results. In fact, it would be arbitrary to stop dynamic loading after a

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certain number of load cycles, to destroy specimens and to derive clinical recommendations.

Dynamic (cyclic) load application with or without TC provokes the fatigue phenomenon. At least 10^5–10^6 cycles are necessary (114, 115). The most popular dynamic load test is the chewing simulation in a computer-controlled mastication simulation (112). For wear testing, 240 000 load cycles of 49 N (50 N) were combined with 600 thermocycles. As this protocol is assumed to correspond with 1 year of clinical service 1 200 000 cycles simulate a 5-year service time (116). However, to date this correlation is still discussed and appears to be dependent from the tested type of restoration (115). As modification, an applied load of 30 N with 10 000 thermocycles was specified (46, 73). An intermittent loading of ETT was described, in which a load of 250 N is applied at a frequency of 2 s^{-1} (87, 113). This protocol was also modified to load peaks of 70 N at a 1·5-Hz frequency with additional TC (71) or a 4-kg load at 72 cycles per minute (117). A disadvantage of the intermittent loading type is that if no failure occurs during the cycling procedure (in most studies, intermittent loading did stop after 400 000 cycles), a comparison to studies using a load-to-failure testing is not possible.

In a specific test method introduced by Strand *et al.* (118), a gradual cycling dynamic force is used with a frequency of 2Hz, initially varying between 50 and 100 N for 500 cycles. The force increases in increments of 50 N and 500 cycles until failure occurs. Another approach uses gradual cycling loading with incrementally increasing peak force levels. Each force level is applied for 100 cycles and increases in steps of 50 N starting from cycles between 0 and 50 N. Prior to loading, the specimens are exposed to 2000 cycles of TC between 5 and 55 °C (119). Comparable to static loading, it is possible to perform the gradual cycling approach in a common material-testing machine, which is less expensive. However, it is possible to test only one specimen at a time.

In most studies static loading was used, although it is known that TC and in particular TCML affect the results of load-to-fracture tests significantly (73, 96). In particular, when load values exceed the maximum biting force observed clinically, the orientation of today's *in vitro* tests to achieve a certain maximum fracture load value is questionable. A cyclic load application of up to 600 N (92) shows that this parameter was also for dynamic tests not properly addressed. It may be misleading when the material with the highest load-to-fracture is judged best, as interactions of the material and the type of testing was shown (119). There is a lot of scientific work ahead to validate laboratory tests. To date, one failed to show the clinical significance of *in vitro* tests as the overall aim in order to predict clinical performance of restorative materials or restorations (120, 121).

Conclusion

The studies included in this structured literature review are heterogeneous. It is likely, that this has an impact on the results observed. A standardization of test procedures should deliver reliable, meaningful, and comparable results. Therefore, further investigations have to focus on the influence of the specimen type, storage, and preparation, the restorative stage loaded (i.e. post and/or core and/or crown), the embedding material as bone simulation, simulation of tooth mobility (artificial periodontal ligament), and loading protocol. Based on the evidence presented, it appears advisable to use human teeth of the second dentition. One should distinguish between front teeth, premolars, and molars depending on the working hypothesis or restorative aspect investigated. There is evidence that a simulation of the fatigue phenomenon is necessary; the dynamic test approach appears to be appropriate. Subsequent static loading until failure (destructive test design) with the maximum load-to-fracture is an easy to handle and comparable outcome parameter without clinical parallel. Non-destructive dynamic test arrangements may be more meaningful. The relevance of *in vitro* test to predict the clinical performance of restorative materials lies in its ability to validate by respective controlled clinical trials and is the aim of future scientific work.

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