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Effect of splinting material type and location on resistance against deflection force of splinted periodontally compromised teeth with hypermobility

Junichiro Wada [a,b,*], Kanae Wada [a,c], Sadullah Uctasli [d], Noriyuki Wakabayashi [b], Tsutomu Iwamoto [c], Pekka K. Vallittu [a,e], Lippo Lassila [a]

[a] *Department of Biomaterials Science, Turku Clinical Biomaterials Centre - TCBC, Institute of Dentistry, University of Turku, Itäinen Pitkäkatu 4B, Turku, 20520, Finland*
[b] *Department of Advanced Prosthodontics, Tokyo Medical and Dental University - TMDU, 1-5-45, Yushima, Bunkyo-ku, Tokyo, 113-8510, Japan*
[c] *Department of Pediatric Dentistry/Special Needs Dentistry, Tokyo Medical and Dental University – TMDU, 1-5-45, Yushima, Bunkyo-ku, Tokyo, 113-8510, Japan*
[d] *Department of Prosthodontics, Faculty of Dentistry, University of Ankara, 06790, Ankara, Turkey*
[e] *Wellbeing Services County of South-West Finland, Lemminkäisenkatu 23, 20520, Turku, Finland*

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ABSTRACT

This study aimed to evaluate the effect of splinting material type and material location on the force resistance of splinted periodontally compromised teeth with hypermobility. Extracted teeth including the target tooth (maxillary second premolar) and its adjacent teeth were placed into the alveolar sockets of a dental arch model via artificial periodontal ligaments made of elastic impression material. Three different experimental models with varied target tooth mobility including Periotest® values (PTVs) of 20, 30, and 40 were fabricated (named models #20, #30, and #40, respectively). For each experimental model, the force resistance of tooth splinting was tested using the following four materials: everStick PERIO (glass fiber reinforcement: GFR), FORESTAFLEX (braided stainless steel: BSS), Ortho-FlexTech (stainless steel chain: SSC), and Super-Bond (MMA-based resin cement: MRC). The evaluated measures were the PTV after tooth splinting and the required load to cause tooth displacements of 0.05 mm and 0.10 mm in the vertical and lateral directions, respectively. The splinting material type and material location as well as the original PTV of target the tooth significantly affected all the evaluated measures ($p < 0.001$). MRC revealed the significantly highest force resistance of tooth splinting regardless of material location in each experimental model and was followed by GFR. The PTVs of splinted teeth were comparable to those of adjacent anchor teeth in models #20 and #30 when using GFR, while that was comparable in model #40 when using MRC. Meanwhile, the load causing certain tooth displacement showed a similar tendency to previous-reported data with healthy teeth in model #20 when using GFR, while that showed a similar tendency in models #30 and #40 when using MRC. Overall results concluded that splinting material type and location play a role in the resistance against the deflection force of splinted periodontally compromised hypermobile tooth. It was noted that MRC provided the highest resistance against the deflection force of splinted teeth regardless of material location whereas GFR maintained the physiologically considered tooth mobility.

1. Introduction

Tooth mobility is one of the clinically significant predictors of tooth survival. It has been indicated that teeth with hypermobility would be at higher risk of future tooth loss (Faggion et al., 2007). To maintain those hypermobile teeth after basic periodontal therapies, tooth splinting using retainer materials or prostheses is an efficient clinical strategy as well as periodontal regenerative therapy (Nyman and Ericsson, 1982; Nagayama et al., 2020). Splinting a hypermobile tooth anchored by healthy adjacent teeth has disadvantages, such as difficulty to maintain oral hygiene and the risk of overload for the adjacent teeth. Meanwhile, several clinical trials have suggested that tooth splinting would not critically affect periodontal health (Årtun et al., 1987; Heier et al., 1997; Pandis et al., 2007; Storey et al., 2018; Eroglu et al., 2019). Nevertheless,

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* Corresponding author. Department of Advanced Prosthodontics, Tokyo Medical and Dental University - TMDU, 1-5-45, Yushima, Bunkyo-ku, Tokyo, 113-8510, Japan.

E-mail address: wadajun.rpro@tmd.ac.jp (J. Wada).

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tooth splinting can be applied with lower physiological stress, lower costs, and temporal burden. Additionally, the effect of tooth splinting using retainer materials might widely differ depending on the retainer material type and the original mobility of the splinted tooth.

The most basic objective of tooth splinting is to prevent the destruction of periodontal tissue by overloads including secondary occlusal trauma (Bernal et al., 2002). On the other hand, it has been indicated that retainer materials should be passive and semirigid to maintain physiological tooth mobility in tooth splinting after orthodontic treatment (Zachrisson, 1977; Levin et al., 2008; Oshagh et al., 2014). This consideration is developed based on the maintenance of biomechanical homeostasis in periodontal tissues. The excessive rigidity of the retainer might result in undesirable situations, such as disuse atrophy of periodontal ligament and alveolar bone also in periodontally compromised teeth with hypermobility. From the viewpoint of biomechanical homeostasis, tooth splinting using removable devices showing slight splinting rigidity would be favorable (Nagayama et al., 2020; Uchida et al., 2022). However, removable devices never provide stabilization of teeth when they are removed. Therefore, fixed tooth splinting with the ideal retainer rigidity would be clinically efficient to protect periodontally compromised teeth with hypermobility.

Fixed tooth splinting is generally classified into the following two categories: tooth splinting via a retainer bonded by adhesive resins (retainer bonding technique) and that with being directly bonded with adjacent healthy teeth using adhesive resins (direct bonding technique). One of the retainer materials used in the retainer bonding technique is metal materials, such as stainless steel (Lie Sam Foek et al., 2008; Güneş et al., 2023), while another is non-metal materials, such as glass fiber reinforcement material (Sewón et al., 2000; Kumbuloglu et al., 2008). In contrast, elastic adhesive resins, such as methyl methacrylate (MMA)--based resin cement, have been used in the direct bonding technique (Nakamura et al., 2015). The comparisons of materials used in tooth splinting have been performed with the assumption of dentition after orthodontic treatment (Scribante et al., 2011; Ohtonen et al., 2021). Ohtonen et al. reported that splinting material location would affect the resistance against the deflection force of splinted teeth after retainer placement. Those studies based on orthodontic treatment can provide the indication of splinting for periodontally healthy teeth. However, there is no previous study of retainer comparison based on dentition after periodontal therapy, and the ideal materials use to splint periodontally compromised teeth with hypermobility are still unclear. Furthermore, although the degree of original tooth mobility might affect the material selection in tooth splinting, there is no previous study of splinting material comparison considering the original mobility of the splinted tooth.

Therefore, the aim of this study was to evaluate the effect of splinting material type and material location on the resistance against deflection force of splinted hypermobile tooth with several original mobilities. The evaluated measures were the mobility after tooth splinting and the required load to cause tooth deflections of 0.05 mm and 0.10 mm in the vertical and lateral directions, respectively. The null hypotheses were as follows: (1) the splinting material type would have no impact on the evaluated measures, and (2) the material location would have no impact on the evaluated measure.

2. Materials and methods

2.1. Experimental model fabrication

The experimental model was fabricated with a dental arch model (E50-500AU, Nissin, Tokyo, Japan) and extracted teeth. Forty-eight extracted maxillary premolars (24 extracted teeth both for first and second premolars) and 24 extracted first molars without any caries lesions on buccal, lingual, and proximal surfaces were collected. The region from the canine to the second molar on the right side in the dental arch model was sectioned out, followed by the placement of three extracted teeth into the alveolar sockets of the first and second premolars and first molar. The artificial periodontal ligament was made of elastic silicone impression material (Examixfine regular type, GC, Tokyo, Japan) (Fig. 1A and B). Afterward, the mobility of extracted teeth was measured using an electronic tooth mobility measuring device (Periotest®, Gulden Medizintechnik, Bensheim, Germany) on their lingual surfaces. According to the values given by Periotest® (PTVs), tooth mobility was adjusted by shortening the height of the artificial periodontal ligament toward the apex of the root according to the previous study (Nagayama et al., 2020). The Periotest® is a device to measure the damping characteristics of periodontal ligaments by a tapping head that accelerates toward the tooth surface 16 times in 4 s and calculates tooth mobility. The PTVs range from −8 (very low mobility) to 50 (very high mobility) (Schulte et al., 1992). The PTVs of the first premolar and molar were adjusted to 5.0 (ranging from 4.5 to 5.4) for each experimental model, simulating teeth with healthy (completely healed) periodontal tissue. Meanwhile, the PTV of the second premolar was adjusted to be one of the following values: 20.0 (ranging from 19.5 to 20.4), 30.0 (ranging from 29.5 to 30.4), and 40.0 (ranging from 39.5 to 40.4). PTVs of 20.0, 30.0, and 40.0 simulated a periodontally compromised tooth with slight, moderate, and severe hypermobility, respectively (Schulte et al., 1992). The experimental models with slight hypermobility (PTV of 20), moderate hypermobility (PTV of 30), and severe hypermobility (PTV of 40) were defined as model #20, model #30, and model #40, respectively. The tapping position of Periotest® for each tooth was standardized as the mesiodistally middle and vertically 2.5 mm lower than the height of interproximal contact points on the lingual surface of the tooth. Additionally, the tapping direction was standardized as the direction perpendicular to the direction from the top of the functional cusp to the root apex (Fig. 1C). To eliminate the device variation of Periotest®, PTV measurement was performed independently by two different devices (product serial numbers were 17089H and 19263J). The arrangement of artificial periodontal ligaments was performed based on PTVs acquired using both devices. The research protocol of this study was carried out according to the Ethics Committee of the University of Turku.

2.2. Tested splinting materials

The following 4 splinting materials were tested in this study: (1) glass fiber reinforcement (everStick PERIO, GC Europe N.V., Leuven, Belgium) (GFR); (2) braided stainless steel (FORESTAFLEX, FORESTADENT Bernhard Förster GmbH, Pforzheim, Germany) (BSS); (3) stainless steel chain (Ortho-FlexTech, Reliance Orthodontic Products, Inc., Illinois, USA) (SSC); and (4) MMA-based resin cement (Super-Bond, Sun Medical Co., Ltd., Shiga, Japan) (MRC) (Table 1). Each splinting material was placed on the experimental model with two different locations as follows: the higher location (HL): the material location within 2 mm distance from the line drawn through the interproximal contact points of each tooth (the reference line); and the lower location (LL): the material location within 3–5 mm distance from the reference line (Fig. 2). For all materials other than MRC, the buccal surface of extracted teeth from the first premolar to first molar were treated with the self-etching light-cured adhesive (G-aenial bond, GC Corporation, Tokyo, Japan, Batch number 1108041). The G-aenial bond was first applied to the teeth surface and kept undisturbed for 10 s, and then dried for 5 s under air pressure, followed by the light-curing with LED curing light with a wavelength range of 430–480 nm and light intensity of 1200 mW/cm^2 (Elipar™ S10, 3M Espe, Seefeld, Germany) for 10 s. Only for GFR, the G-aenial bond was also applied to the material surface with 10 s keeping undisturbed and 5 s drying under air pressure. Afterward, each splinting material cut into 24 mm long was placed on the buccal surface of three extracted teeth according to the material location (HL or LL) and covered with the resin composite (G-Fix resin composite, GC Corporation, Tokyo, Japan, Batch number 1303011) and then light-cured for 30 s. The G-fix resin composite was applied to the mesiodistally middle area

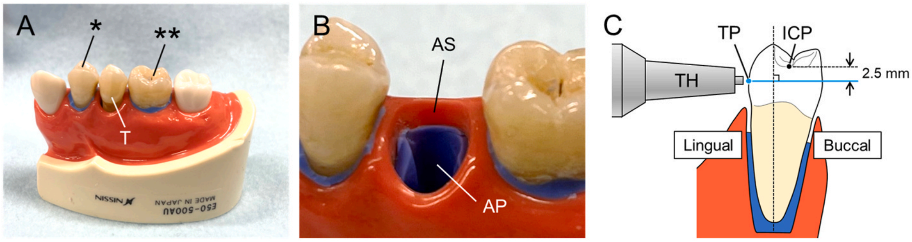

Fig. 1. A: Overall view of experimental model including natural first premolar (*) and first molar (**) with physiologically normal mobility and target tooth (second premolar) with hyper mobility (T); B: magnified image of alveolar socket (AS) and artificial periodontal ligament (AP) fabricated with elastic silicone impression material; and C: schematic illustration of the tapping position of Periotest®, where TH is the tapping head of Periotest®; TP is the tapping point; and ICP is the interproximal contact point.

Table 1
Splinting materials tested in this study.

Brand name		Manufacturer	Batch number	Material type	Chemical composition	Bonding technique	Width[a]/Thickness[b] (mm)	Abbreviation
everStick PERIO		GC Europe N.V.	2205091	Glass fiber reinforcement	Glass fiber, PMMA, Bis-GMA	Retainer bonding	1.00/1.00[c]	GFR
FORESTAFLEX		FORESTADENT Bernhard Förster GmbH	2314015810	Braided stainless steel			0.74/0.26	BSS
Ortho-FlexTech		Reliance Orthodontic Products, Inc.	114980	Stainless steel chain			0.86/0.43	SSC
Super-Bond	Monomer	Sun Medical Co., Ltd.	FF0915	Monomer	MMA, 4-META	Direct bonding	2.00/5.00[d]	MRC
	Polymer		FF0888	MMA-based resin cement	PMMA			
	Catalyst		FF0044	Initiator	TBB			

PMMA: poly(methyl methacrylate); MMA: methyl methacrylate; Bis-GMA: bisphenol A-glycidyl methacrylate; 4-META: 4-methacryloxyethyl trimellitate anhydride; and TBB: Tri-n-butylborane.

[a] The width in crown-root direction.

[b] The buccolingual thickness of material.

[c] The dimensional size before being pressed (deformed) during bonding.

[d] The dimensional size after polymerization (applied by brush-on technique).

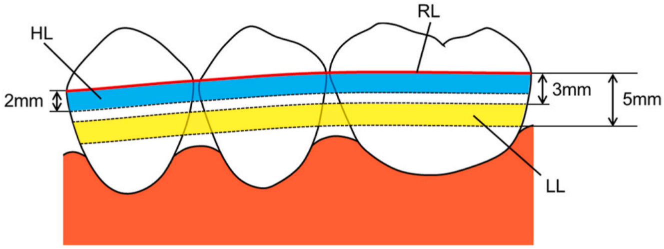

Fig. 2. Schematic illustration of the retainer locations. The line drawn through interproximal contact points of each tooth (red line) was defined as the reference line (RL). The retainer location within 2 mm distance from RL (blue area) was defined as higher location (HL), while the retainer location within 3–5 mm distance from RL (yellow area) was defined as lower location (LL).

of each tooth so that the interproximal spaces of the teeth were free from the coverage with the resin composite (Fig. 3). On the other hand, MRC was directly applied on the proximal surface of the extracted teeth by brush-on technique after the phosphoric acid treatment by the etching agent (Red Activator, Sun Medical Co., Ltd., Shiga, Japan, Batch number FF1597). After the application of MRC, it was left undisturbed for 8 min so that MRC filled the interproximal spaces, and the dimensional size was 2 mm in vertical height and 5 mm in buccolingual thickness (Fig. 3). Totally, 24 splinted experimental models based on four splinting materials, two material locations, and three categories of tooth mobility (20.0, 30.0, and 40.0 in PTV) were prepared.

2.3. Tooth mobility with splinting material placement

The mobility of the second premolar after splinting material placement was measured using two Periotest® devices in the same manner as the experimental model fabrication (Fig. 1C). Ten measurements of PTV

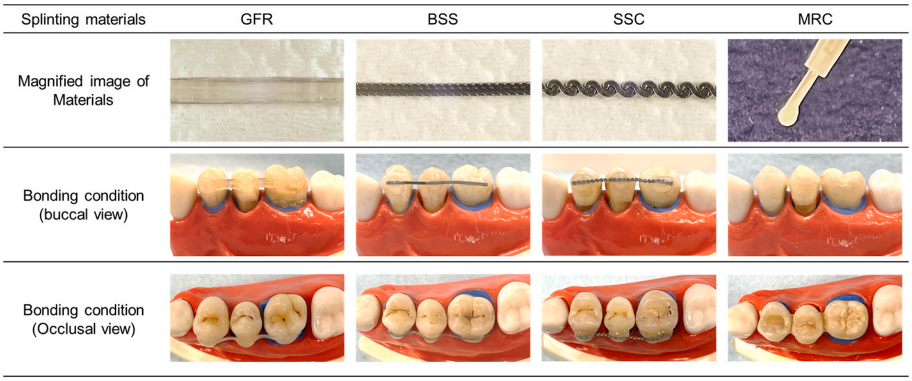

Fig. 3. Magnified images and bonding conditions of splinting materials. GFR: glass fiber reinforcement; BSS: braided stainless steel; SSC: stainless steel chain; and MRC: MMA-based resin cement.

(five measurements by each device) were performed for each splinted experimental model (n = 10/subgroup).

2.4. Loading test

The loads required to cause two different deflections of splinted second premolars were measured as the representative values for the stiffness of the splinting materials. One of the measured loads was the load required to cause tooth deflection of 0.05 mm in the vertical direction (Fig. 4A). Another one was the load required to cause tooth deflection of 0.10 mm in the lateral direction (Fig. 4B). The loading test was performed in the air atmosphere at room temperature by a universal testing machine (Model LRX; Lloyds Instruments Ltd., Hampshire, UK) using a load cell with a capacity of 2500 N and a crosshead speed of 1.0 mm/min. As shown in Fig. 4C, the vertical force was loaded on the top of the functional (lingual) cusp in a direction to the root apex. The lateral force was loaded on the point of 2.5 mm from the height of the interproximal contact area in the direction perpendicular to the direction of the vertical force. For each experimental model, five measurements were performed both in vertical and lateral directions (n = 5/subgroup).

2.5. Statistical analysis

Parametric testing methods were used in this study because the equality of variances and normality were detected in all the acquired data by the Levene test and Shapiro-Wilk test, respectively. Three variables including the original PTV of second premolars (20, 30, and 40), splinting material type (GFR, BSS, SSC, and MRC), and material location (HL and LL) were tested for the PTV after splinting material placement, loads required to cause vertical 0.05 mm deflection, and lateral 0.10 mm deflection using a 3-way analysis of variance (ANOVA). To assess the relationship between the PTVs before and after splinting material placement in each splinting material with each material location, linear regression analysis was performed with the original PTV as an independent variable and the PTV after splinting material placement as a dependent variable. Additionally, for each original PTVs, all the acquired data were statistically compared among the groups using a 1-way ANOVA. As *post hoc* analyses, Tukey's multiple comparisons were performed. A statistical software (IBM SPSS Statistics v28.0, IBM, Redmond, WA, USA) was used for all the statical analyses with the significance level set at 0.05.

3. Results

No tested material was debonded during each test in this study. The 3-way ANOVA showed that the original PTV, splinting material type and material location significantly affected all the evaluated measures ($p <$ 0.001 for all). *Post hoc* analyses confirmed no significant difference only in the load required to cause vertical tooth displacement of 0.05 mm between BSS and SSC ($p = 0.791$).

Table 2 shows the adjusted coefficient of determinations, partial regression coefficients, and p-values acquired by linear regression analyses. GFR at LL and MRC at HL revealed partial regression coefficients lower than 0.2, whereas SSC both at LL and HL revealed those higher than 0.8.

Table 2
Results of linear regression analyses using the original PTV as an independent variable and the PTV after splinting material placement as a dependent variable.

Splinting material	Material location	R	B	*p*-value
GFR	LL	0.887	0.110	<0.001
	HL	0.993	0.583	<0.001
BSS	LL	0.876	0.594	<0.001
	HL	0.955	0.784	<0.001
SSC	LL	0.992	0.888	<0.001
	HL	0.802	0.815	<0.001
MRC	LL	0.814	0.426	<0.001
	HL	0.684	0.180	<0.001

R: adjusted coefficient of determination; B: partial regression coefficient; GFR: glass fiber reinforcement; BSS: braided stainless steel; SSC: stainless steel chain; MRC: MMA-based resin cement; LL: lower location; and HL: higher location.

Fig. 5 shows the mean values of PTV after splinting material placement. Regardless of the material location, the lowest PTV after splinting material placement was confirmed with MRC for each original PTV followed by GFR, BSS, and SSC. In model #20, the mean values (standard deviations) of PTV after splinting material placement with the lower location were 0.90 (0.12), 9.32 (0.13), 15.32 (0.15), and 20.44 (0.22), while those with the higher location were 2.46 (0.18), 4.66 (0.11), 6.18 (0.13), and 20.38 (0.16) for MRC, GFR, BSS, and SSC, respectively. There was a significant difference between each pair selected from the data with model #20 ($p < 0.001$ for all pairs) except for the pair of SSC with lower and higher locations ($p = 1.000$). In model #30, the mean values (standard deviations) of PTV after splinting material placement with the lower location were 1.80 (0.16), 9.82 (0.13), 17.56 (0.21), and 30.60 (0.23), while those with the higher location were 2.28 (0.15), 9.72 (0.15), 11.20 (0.20), and 21.52 (0.15) for MRC, GFR, BSS, and SSC, respectively. There was a significant difference between each pair selected from the data with model #30 ($p = 0.013$ for the pair of MRC with the lower and higher location and $p < 0.001$ for all the other pairs) except for the pair of GFR with lower and higher locations ($p = 1.000$). In model #40, the mean values (standard deviations) of PTV after splinting material placement with the lower location were 9.42 (0.22), 11.52 (0.15), 27.20 (0.20), and 38.20 (0.23), while those with the higher location were 6.06 (0.19), 16.32 (0.15), 21.86 (0.19), and 36.68 (0.31) for MRC, GFR, BSS, and SSC, respectively. There was a significant difference between each pair selected from the data with model #40 ($p < 0.001$ for all pairs).

Table 3 shows the mean values and standard deviations of the loads required to cause vertical tooth deflection of 0.05 mm. Regardless of the material location, the highest load was confirmed with MRC for each experimental model ($p < 0.001$ for all). Additionally, regardless of the original PTV of experimental models, the higher location showed a significantly higher vertical load to cause the tooth deflection of 0.05

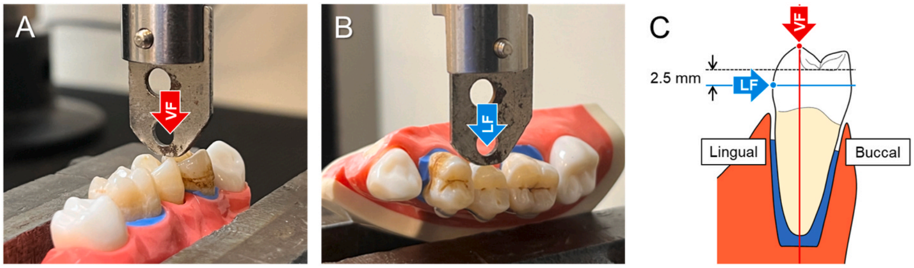

Fig. 4. The direction of force loading. A: Testing condition of vertical force (VF) loading; B: testing condition of lateral force (LF) loading; and C: schematic illustration representing the force direction. The VF was loaded on the top of functional cusp (red point) in a direction to the root apex (red line). The LF was loaded on the point (blue point) of 2.5 mm from the height of interproximal contact area (broken black line) in the direction perpendicular to the direction of VF (blue line).

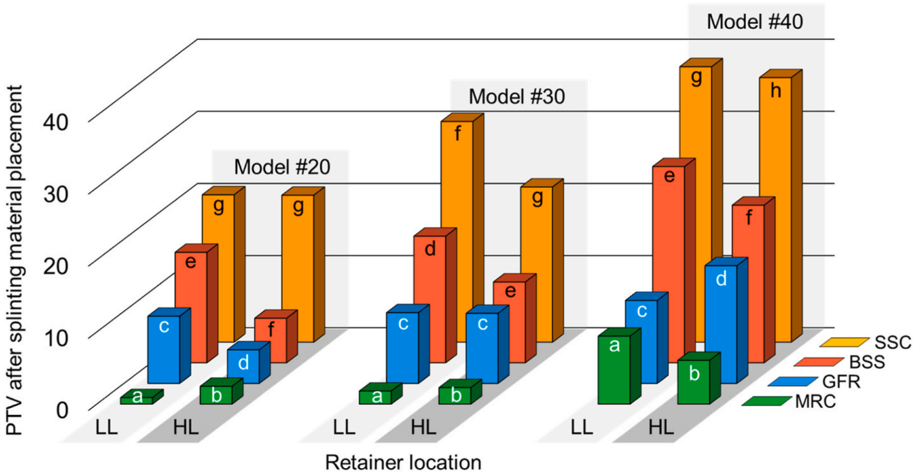

Fig. 5. Mean values of PTV after splinting material placement. PTV: Periotest value; SSC: stainless steel chain; BSS: braided stainless steel; GFR: glass fiber reinforcement; MRC: MMA-based resin cement; LL: lower location; HL: higher location. Same superscripted letters on bars indicate groups not statistically significantly different within the same original PTV when compared by Tukey multiple comparisons post hoc analysis (p ≥ 0.05).

Table 3
Mean values (standard deviations) of loads (N) required to cause 0.05 mm tooth deflection in vertical direction, and results of 1-way ANOVA statistical analysis.

Material	Material location	Experimental model					
		Model #20	#	Model #30	#	Model #40	#
GFR	LL	6.05 (0.11)	a	3.69 (0.09)	a	1.71 (0.08)	a
	HL	7.55 (0.12)	b	4.00 (0.11)	b	2.10 (0.08)	bc
BSS	LL	4.19 (0.12)	c	3.34 (0.08)	c	3.02 (0.09)	d
	HL	2.99 (0.08)	d	2.78 (0.09)	d	2.49 (0.08)	e
SSC	LL	5.11 (0.09)	e	3.76 (0.08)	a	2.27 (0.08)	be
	HL	3.30 (0.08)	f	2.49 (0.09)	e	2.02 (0.07)	c
MRC	LL	9.92 (0.13)	g	8.85 (0.10)	f	7.35 (0.11)	f
	HL	7.58 (0.12)	b	7.37 (0.10)	g	7.10 (0.09)	g

PTV: Periotest value; GFR: glass fiber reinforcement; BSS: braided stainless steel; SSC: stainless steel chain; and MRC: MMA-based resin cement; LL: lower location; and HL: higher location.
#:Same superscripted letters indicate groups not statistically significantly different when compared by Tukey multiple comparisons post hoc analysis ($p \geq 0.05$).

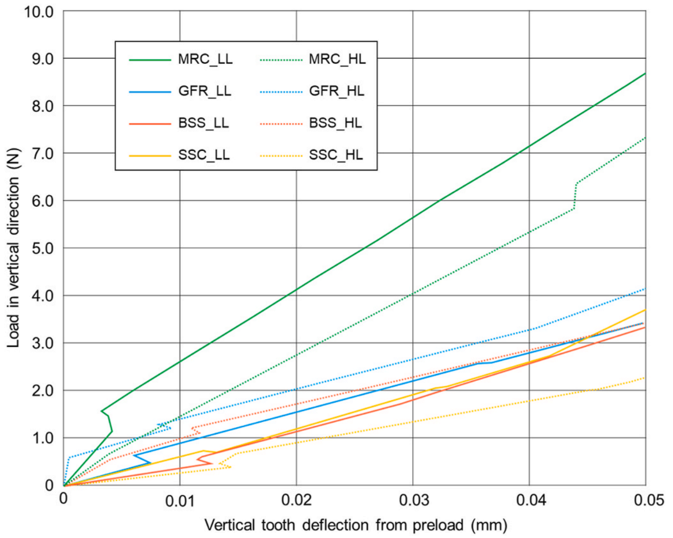

Fig. 6. Typical deflection curves with vertical loadings in experimental model #30. PTV: Periotest value; MRC: MMA-based resin cement; GFR: glass fiber reinforcement; BSS: braided stainless steel; SSC: stainless steel chain; LL: lower location; and HL: higher location.

mm than the lower location with GFR ($p < 0.001$ for all), while the lower location showed a significantly higher vertical load than the higher location with BSS, SSC, and MRC ($p < 0.001$ for all except for $p = 0.013$ for SSC and $p = 0.022$ for MRC in model #40). In model #20, GFR and MRC showed significantly higher vertical loads than BSS and SSC ($p < 0.001$ for all). Meanwhile, although there were significant differences among GFR, BSS, and SSC ($p < 0.001$ for all except for $p = 0.027$ for GFR at the higher location and SSC at the lower location, $p = 0.002$ for BSS at the higher location and SSC at the higher location), the vertical loads confirmed with those three splinting materials were comparable when compared to that with MRC in models #30 and #40. Fig. 6 shows the typical deflection curves with vertical loading testing in experimental model #30. It was noted that MRC at the higher location showed notably high resistance against tooth deflection at the beginning (around 0–0.004 mm of tooth deflection), while the other splinting materials including MRC at the lower location showed almost linear deflection curves.

Table 4 shows the mean values and standard deviations of the loads required to cause lateral tooth deflection of 0.10 mm. Regardless of the material location, the highest load was confirmed with MRC for each experimental model ($p < 0.001$ for all except for model #20 on which MRC showed notably high resistance so that the lateral load reached 10 N before causing 0.10 mm tooth deflection). Additionally, regardless of the original PTV of experimental models, the higher location showed a significantly higher lateral load to cause the tooth deflection of 0.10 mm than the lower location with SSC ($p < 0.001$ for all), while the lower location showed a significantly higher lateral load than the higher location with GFR and MRC ($p < 0.001$ for all). Regarding BSS, the lower location showed a significantly higher load than the higher location in model #20 ($p < 0.001$), while the higher location showed a significantly higher load than the lower location in models #30 and #40 ($p < 0.001$ for all). In model #20, GFR showed significantly higher vertical loads than BSS and SSC ($p < 0.001$ for all). In models #30 and #40, although there were significant differences between GFR and BSS ($p < 0.001$ for

Table 4
Mean values (standard deviations) of loads (N) required to cause 0.10 mm tooth deflection in lateral direction, and results of 1-way ANOVA statistical analysis.

Material	Material location	Experimental model					
		Model #20		Model #30		Model #40	
			#		#		#
GFR	LL	7.42 (0.06)	a	3.64 (0.06)	a	2.30 (0.06)	a
	HL	8.29 (0.06)	b	4.50 (0.06)	b	3.07 (0.05)	b
BSS	LL	4.53 (0.05)	c	3.27 (0.05)	c	2.51 (0.05)	c
	HL	3.33 (0.06)	d	3.92 (0.06)	d	3.37 (0.05)	d
SSC	LL	5.83 (0.07)	e	1.97 (0.07)	e	1.17 (0.06)	e
	HL	4.78 (0.06)	f	1.68 (0.07)	f	1.04 (0.04)	e
MRC	LL	NA		6.97 (0.06)	g	5.71 (0.05)	f
	HL	NA		9.42 (0.06)	h	6.78 (0.04)	g

PTV: Periotest value; GFR: glass fiber reinforcement; BSS: braided stainless steel; SSC: stainless steel chain; and MRC: MMA-based resin cement; LL: lower location; HL: higher location; and NA: not applicable because load reached 10 N before 0.10 mm deflection.
#: Same superscripted letters indicate groups not statistically significantly different when compared by Tukey multiple comparisons post hoc analysis ($p \geq 0.05$).

all), the lateral loads confirmed with those splinting materials were comparable when compared to that with MRC. BSS showed the lowest load in model #20, while SSC showed the lowest load in models #30 and #40. Fig. 7 shows the typical deflection curves with vertical loading testing in experimental model #30. It was noted that all the splinting materials showed almost linear deflection curves regardless of the material location.

4. Discussion

This study demonstrated the effect of the splinting material type and material location on the resistance against the deflection force of a splinted hypermobile tooth. The tooth mobility after the splinting material placement and vertical and lateral loads required to cause certain tooth deflections were evaluated in the experimental models with the slight, moderate, and severe hypermobility of the upper second premolar. The overall results rejected the two null hypotheses and revealed that the splinting materials and material location affected the evaluated measures.

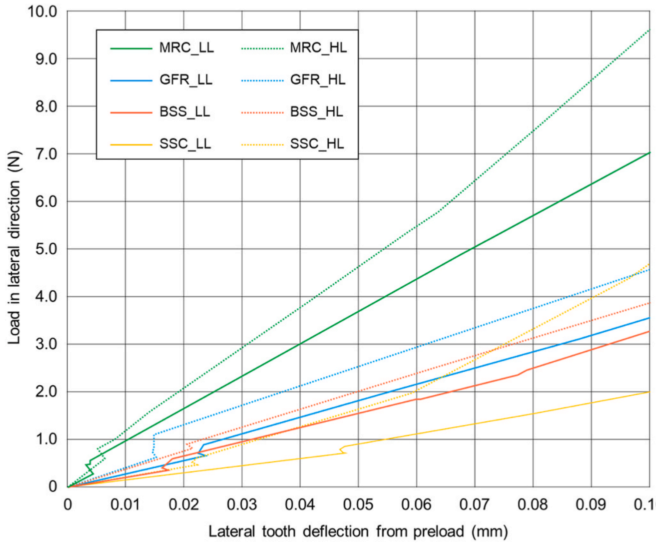

Fig. 7. Typical deflection curves with lateral loadings in experimental model #30. PTV: Periotest value; MRC: MMA-based resin cement; GFR: glass fiber reinforcement; BSS: braided stainless steel; SSC: stainless steel chain; LL: lower location; and HL: higher location.

A previous study indicated that the stainless steel retainers would maintain physiological tooth mobility and be recommended for tooth splinting after orthodontic treatment, while GFR would be too rigid as a fixed orthodontic retainer (Ohtonen et al., 2021). Nevertheless, the result of the tooth mobility (PTV) after splinting material placement showed revealed that BSS and SSC provided insufficient stability of the splinted tooth when compared to GFR and MRC. It was suggested that BSS and SSC would not be suitable to splint periodontally compromised tooth with hypermobility. Additionally, linear regression analysis revealed that GFR placed at LL showed the lowest partial regression coefficient indicating that splinting rigidity would hardly vary regardless of the original PTV, followed by MRC placed at HL.

Schulte et al. reported that PTV would correlate with clinical tooth mobility based on Miller's classification (Schulte et al., 1992). According to Schulte's indication, a PTV of 40 is comparable to class III of Miller's classification, while PTVs of 20 and 30 are comparable to the border between class I and II and the border between class II and class III, respectively. The PTVs after splinting with MRC in models #20 and #30 were lower than the PTVs of the adjacent anchor teeth (PTV of 5). This finding suggested that tooth splinting using MRC would be too rigid for the periodontally compromised teeth with slight or moderate hypermobility (class I or II of Miller's classification). On the other hand, the PTVs after splinting with MRC in model #40 and with GFR in models #20 and #30 were comparable to or slightly higher than those of the adjacent teeth. From the viewpoint of PTVs, it could be concluded that GFR would be the ideal splinting material for periodontally compromised teeth with slight or moderate hypermobility, while MRC would be recommended for those with severe hypermobility (class III of Miller's classification).

Several studies have focused on tooth deflections with certain loads in teeth with healthy periodontal tissues (Yoshida et al., 2001; Amarsaikhan et al., 2002; Goellner et al., 2010). Physiological lateral deflection of healthy teeth has been reported to be equal to or less than 0.10 mm (Yoshida et al., 2001; Amarsaikhan et al., 2002; Boldt et al., 2012). Based on those studies, 0.10 mm was set to the maximum tooth deflection in a lateral direction in this study. Because there was no data referable for setting the maximum deflection in a vertical direction, the preliminary experiment was performed to set the vertical maximum deflection prior to this study. The preliminary experiment showed that the load to cause the lateral deflection of 0.10 mm would cause the vertical deflection of around 0.05 mm in each splinting material. Based on the results of the preliminary experiment, the maximum tooth deflection in a vertical direction was set to 0.05 mm. In accordance with the results of PTV after splinting, the loads to make the maximum tooth deflections in vertical and lateral directions reveal the highest values when using MRC for tooth splinting. However, three materials used with the retainer bonding technique (GFR, BSS, and SSC) showed similar deflection curves. This finding with those three materials was poorly correlated with the trend found in PTVs after splinting. Yoshida et al. indicated that the lateral force of 2 N would cause a deflection of 0.01 mm in healthy teeth (Yoshida et al., 2001). In this study, MRC revealed a load of around 2 N to cause the deflection of 0.01 mm in models #30 and #40, while GFR revealed a similar load in model #20. Therefore, from the viewpoint of the relationship between tooth deflection and the deflection force, MRC would be suitable for the splinting of the periodontally compromised tooth with moderate or severe hypermobility, while GFR would be suitable for tooth splinting with slight hypermobility.

Deflection curves in natural teeth have been reported to consist of the following two phases: the first phase is based on the distortion of the periodontal ligament and the second phase is based on the distortion of the alveolar bone (Amarsaikhan et al., 2002). On the other hand, all deflection curves except one with MRC at the lower location under the lateral loading were almost linear, indicating that the deflection curves in this study would reflect only the distortion of the artificial periodontal ligament. It was suggested that functional loading would provide physiological stimulation only on the periodontal ligament but not on the alveolar bone of periodontally compromised hypermobile teeth showing the expansion of periodontal ligament space.

According to the previous study, the brittleness of splinting material can disturb the physiological tooth movement and brittle materials would not be recommended for tooth splinting (Ohtonen et al., 2021). Even MRC (Super-bond) had flexibility because of the lack of fillers (Irie et al., 2023). Therefore, we selected no brittle material as the splinting material in this study. BBS and SSC revealed higher flexibility due to the structure (braided- and chain types) in addition to the ductility of the stainless steel itself. Focusing on GFR and MRC, the flexural modulus of GFR was reported to be 5.2–5.3 GPa (Narva et al., 2005), while that of MRC was reported to be less than 3.0 GPa (Irie et al., 2023). Although the flexural modulus of MRC is lower than that of GFR, MRC showed a higher force resistance than GFR in this study. This finding suggested that difference in splinting effect between GFR and MRC would be derived from the difference in bonding techniques but not their mechanical properties. In this study, the measurement of the mobility of splinted tooth and loading test were performed immediately after the completion of bonding material curing. It was reported that the flexural modulus of MRC would get higher after thermal cycles (Irie et al., 2023), indicating that the splinting effect with MRC would get more rigid over time. Due to the lack of data relevant to long-term changes in the mechanical properties of GFR, a discussion comparing these two materials based on long-term usage could not be available. Additionally, although the bonding strength of MRC has been previously investigated (Nogawa et al., 2015), comparisons of bonding strength between MRC and composite resins based on long-term observations are lacking. Because this study focused on the splinting rigidity immediately after the splinting material placement, no material debonding was confirmed.

Several studies have assessed the risk of debonding of splinting retainer based on long-term observation. Sfondrini et al. compared the survival probability of several bonding systems for fixed retainer bonding and indicated that the risk of debonding of splinting retainer would be partially based on the bonding system used to fix the retainer with the tooth surface (Sfondrini et al., 2021). Accordingly, not only the material type but also the bonding system would affect the long-term survival probability of tooth splinting. Additionally, Scribante et al. revealed that polyethylene fiber reinforcement would be at a lower risk of debonding than multistrand stainless steel wire (Scribante et al., 2011). In this study, only one fiber reinforcement based on glass fiber was tested as a non-metal retainer for tooth splinting. Therefore, further study is necessary to assess the effect of long-term changes in the mechanical properties of splinting material and/or debonding with the combination of several types of fiber reinforcement and bonding systems.

For three materials applied by the retainer bonding technique (GFR, BSS, and SSC), there was a difference in the area covered by composite resin to adhere the splinting materials to the tooth surface. Because the material width in GFR was originally wider than BSS and SSC, the coverage area in GFR was larger than those in BSS and SSC. Ohtonen et al. indicated that the larger coverage area would provide higher rigidity of tooth splinting (Ohtonen et al., 2021). Based on Ohtonen's indication, it was suggested that the larger coverage area in GFR would partially result in higher resistance characteristics of GFR when compared to those of BSS and SSC. On the other hand, the larger coverage area generally requires a larger amount of composite resin. Additionally, it might disturb the biologically harmonious environment to maintain the hygiene of splinted teeth. Nevertheless, several studies have revealed no critical evidence concerning any undesirable status of periodontal tissues after tooth splinting (Årtun et al., 1987; Pandis et al., 2007). Compared to the splinting materials for the retainer bonding technique, MRC (especially located at HL) would have the advantage that it hardly disturbs the biological environment, while it would be associated with the difficulty in material removal because MRC fills interproximal spaces to connect the splinted tooth with adjacent teeth. The above-mentioned advantages and disadvantages based on the bonding techniques may not provide any superiority of specific splinting material, and they should be minded as operating precautions regardless of splinting material type. In addition to the splinting material type, the location of material placement has been reported to affect the rigidity of tooth splinting (Ohtonen et al., 2021). Therefore, two different locations were tested in this study. Our findings revealed that the material location affected the resistance against the deflection force of splinted hypermobile tooth. However, the effect of material locations varied by material type and loading direction. The total findings suggested that tooth splinting using GFR would be enhanced with the higher location, while the other splinting materials would show the opposite tendency.

There were several limitations in this study. The thickness of the artificial periodontal ligament was not standardized. The extracted teeth were used in this study so that sufficient bonding strength between the adhesive resin and the tested tooth surface would be obtained. This might be why no tested material was debonded in this study. Meanwhile, using standardized artificial teeth might be efficient to standardize the thickness of artificial periodontal ligaments (Rosentritt et al., 2011), while they would be at risk of insufficient bonding strength of adhesive resins. Especially for the measurement of loads causing tooth deflections, it should be noted that the variety in the thickness of the artificial periodontal ligament might have a certain impact on the results. Additionally, the acquired PTVs partially depended on the tapping position of Periotest®. In this study, the tapping position was standardized to faithfully measure PTVs, suggesting that the comparisons of PTVs were reliably performed. However, it is unclear whether the PTVs shown in this study would be comparable to the data shown in previous studies.

5. Conclusions

Within the limitations of this study focusing on the resistance against deflection force immediately after the splinting material placement, it can be concluded as follows: (1) the splinting material type and location would have an impact on the resistance against deflection force of splinted periodontally compromised tooth with hypermobility; (2) using MMA-based resin cement as the splinting material for the periodontally compromised hypermobile tooth can provide the highest resistance against tooth deflection after splinting regardless of material location; (3) tooth splinting using MMA-based resin cement was so rigid that it constricted physiologically considered tooth mobility when the hypermobility of splinted tooth was slight, while tooth splinting using glass fiber reinforcement can maintain the physiologically considered tooth mobility; and (4) MMA-based resin cement would be recommended for splinting periodontally compromised teeth with severely increased mobility, while glass fiber reinforcement would be recommended for splinting those with slightly increased mobility.

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CRediT authorship contribution statement

Junichiro Wada: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Kanae Wada:** Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Sadullah Uctasli:** Validation, Methodology. **Noriyuki Wakabayashi:** Validation. **Tsutomu Iwamoto:** Validation. **Pekka K. Vallittu:** Writing – review & editing, Supervision, Project administration, Conceptualization. **Lippo Lassila:** Writing – review & editing, Supervision, Software, Resources, Project administration, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Junichiro Wada reports financial support was provided by Japan Society for the Promotion of Science. Lippo Lassila reports a relationship with Helsinki-Uusimaa Regional Council that includes: funding grants. Noriyuki Wakabayashi reports a relationship with Japan Society for the Promotion of Science that includes: funding grants. Tsutomu Iwamoto reports a relationship with Japan Society for the Promotion of Science that includes: funding grants. Kanae Wada reports a relationship with Japan Society for the Promotion of Science that includes: funding grants. Author Pekka K. Vallittu consults Stick Tech-GC in RD and training and serves in an editorial capacity for the Journal of the Mechanical Behavior of Biomedical Materials as an associate editor.

Data availability

Data will be made available on request.

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