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The photoelasticity method in orthodontic research: a scope review

O método da fotoelasticidade na pesquisa ortodôntica: uma revisão de escopo

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ABSTRACT

Objective: To systematically map the research carried out in the area of Orthodontics with the application of the photoelasticity method **Methods**: Studies reporting experiments that used the photoelasticity method as an instrument to assess stresses produced by any type of craniofacial orthopedic or orthodontic device

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were included. Searches were performed in the following databases: Medline, Embase, Cochrane Central Register of Controlled Trials *Literatura Latino-Americana e do Caribe em Ciências da Saúde*, ISI Web of Science, and ProQuest Dissertations & Theses Global. The date of the last search was May 2024, where reviewers independently selected and extracted data from the included studies using standardized forms, and assessed their risk of bias, with the application of the Appraisal for Cross-Sectional Studies tool. **Results**: 33 studies were included in the review. The photoelasticity method proved to be very versatile, since it was used to analyze various types of orthodontic mechanics and orthopedic appliances in different scenarios. The selected manuscripts presented insufficient or unclear reports, especially in relation to the process of producing the models and the analysis of the results. **Conclusion**: This method has been used in several areas of Dentistry, particularly as an adjuvant in orthodontics, offering a fast and effective way to assess stress distribution and orthodontic mechanics in real time. Further studies are encouraged to explore new orthodontic mechanics and document the method's processes in detail.

Indexing terms: Birefringence. Dental stress analysis. Orthodontics. Systematic review.

RESUMO

Objetivo: Mapear sistematicamente a pesquisa realizada na área de Ortodontia com a aplicação do método de fotoelasticidade. **Métodos**: Foram incluídos estudos que relataram experimentos que usaram o método de fotoelasticidade como instrumento para avaliar tensões produzidas por qualquer tipo de dispositivo ortopédico ou ortodôntico craniofacial. Pesquisas foram realizadas nas seguintes bases de dados: Medline, Embase, *Cochrane Central Register of Controlled Trials*, Literatura Latino-Americana e do Caribe em Ciências da Saúde, ISI *Web of Science* e *ProQuest Dissertations & Theses Global*. A data da última pesquisa foi maio de 2024, quando os revisores selecionaram e extraíram de forma independente dados dos estudos incluídos usando formulários padronizados e avaliaram seu risco de viés, com a aplicação da ferramenta *Appraisal for Cross-Sectional Studies*. **Resultados**: Trinta e três estudos foram incluídos na revisão. O método de fotoelasticidade provou ser muito versátil, uma vez que foi usado para analisar vários tipos de mecânica ortodôntica e aparelhos ortopédicos em diferentes cenários. Os manuscritos selecionados apresentaram relatórios insuficientes ou pouco claros, especialmente em relação ao processo de produção dos modelos e à análise dos resultados. **Conclusão**: Este método tem sido usado em várias áreas da Odontologia, particularmente como adjuvante em ortodontia, oferecendo uma maneira rápida e eficaz de avaliar a distribuição de estresses e a mecânica ortodôntica em tempo real. Outros estudos são incentivados a explorar novas mecânicas ortodônticas e documentar os processos do método em detalhes.

Termos de indexação: Birrefringência. Análise de estresse dentário. Ortodontia. Revisão sistemática.

INTRODUCTION

Photoelasticity can be defined as a method of stress analysis based on the property of mechanical birefringence, inherent to several transparent polymers, which makes use of the properties of light polarization and mechanical stress experimentally applied to the bodies of interest [1]. This experimental model is based on the identification of colored stripes, also called fringes that become visible when illuminated by polarized light, which are posteriorly analyzed by a polariscope [2].

It was introduced into dental research by Zak in 1935 [3], when he simulated the effects of various orthodontic devices on human teeth mounted in experimental models. Such method have been presented as a versatile experimental model or the analysis of several orthodontic and orthopedic therapeutic mechanics [4-6]. As well as the Finite Element Method, both techniques have been traditionally used to analyze tensions as complimentary experimental designs. However, the photoelastic method present relatively lower costs to be implemented, in addition to enable the simultaneous visualization and analysis of tensions [2,7,8].

Since Glickman et al. [9] published a study using the photoelasticity method in dental research, according to which they established a positive correlation between histological findings and areas of stress concentration in photoelastic models, the use of this experimental method has been applied to several areas of research, such as Prosthesis [10,11], Implantology [12-14], Clinical Dentistry [15,16], Oral Surgery [17,18], or Occlusion [19]. In Orthodontics, most studies that used this model investigated canine retraction mechanics and tensions generated by orthopedic appliances, in addition to incisors intrusion and molar verticalization techniques, maxillary expansion, and several mechanics supported by temporary anchorage devices [20-29].

Considering the recognition of potentially deficient methodological points in the literature and the identification of knowledge gaps regarding the application of this method to the investigation of orthodontic mechanics, a scoping review was conducted in order to systematically map the research carried out in the area of Orthodontics with the application of the photoelasticity method.

METHODS

Protocol and registration

This review was reported according to the requirements in Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) [30] and was registered in the Open Science Framework (OSF) https://osf.io/search?activeFilters=%5B%5D&q=10.17605%2FOSF.IO%2FPDHE2&sort=-relevance&view_only=; https://doi.org/10.17605/OSF.IO/PDHE2).

Search and eligibility criteria

Studies reporting experiments that used the photoelasticity method as an instrument to assess, individually or comparatively, stresses produced by any type of craniofacial orthopedic or orthodontic device were included. Studies reporting duplicate results were excluded. There were no restrictions on language or publication date.

Information sources

Studies were searched from the following sources: Cochrane Central Register of Controlled Trials (CENTRAL), Medline, Ovid Embase, *Literatura Latino-Americana e do Caribe em Ciências da Saúde* (Lilacs) and ISI Web of Science from inception to June 2024. Search terms describing photoelasticity and orthodontics were combined using Boolean logical operators as shown in figure 1. The gray literature was partially covered by consulting the ProQuest Dissertations & Theses Global database and conference annals. Additionally, we analyzed the reference lists of potentially eligible studies.

(Photoelasticity OR Photoelastic cast OR Photoelastic analysis OR Photoelasticity effects OR Three-dimensional photoelasticity OR Photoelasticity method OR Photoelasticity technique OR Photoelasticity measurements OR Photoelastic model OR Photoelastic stress analysis OR Dental stress analysis PSA OR Photoelastic analysis of stress OR Digital photoelasticity) AND (Orthodontics OR Orthodontic OR Orthodontic treatment OR Orthodontic treatments OR Orthodontic therapy OR Orthodontic therapies OR Dental braces OR Orthodontiya OR Orthopedic treatments OR Orthopedic treatment OR Orthodontic mechanics OR Orthodontic appliance OR Maloclusion)

Figure 1. Search strategy.

Selection of evidence sources

After analyzing titles and abstracts resulting from the electronic search, two reviewers independently pre-selected studies, with the aid of the online Covidence software (https://www.covidence.org). This program was also used to identify and exclude duplicate research reports. Posteriorly, full-text records for potentially eligible studies were obtained. These studies were independently selected by the same reviewers, according to the same eligibility criteria. Consensus for the screening and selection phases was established by discussion with a third reviewer, as needed.

Process of extracting data and items

The characteristics of the experimental method were considered as outcomes of interest, as well as the production of the photoelastic models, materials, method of analysis of the results, and types of mechanics and malocclusions. Two reviewers collected data from the included studies independently using a standardized data extraction forms as shown by chart 1. Discrepancies at this stage were resolved after review of the original document and discussion with a third reviewer (RABS), if necessary.

Critical appraisal of individual sources of evidence

Studies were evaluated according to the modified version of the Appraisal for Cross-Sectional Studies (AXIS) tool [31] to assess their risk of bias. Two reviewers independently reviewed the included studies. Discrepancies were resolved by discussion with a third reviewer.

Summary of results

The results were summarized and presented qualitatively, as meta-analyses were not considered adequate for the synthesis of heterogeneous data.

Chart 1. Standardized data extraction form.

Autor, year	Type of specimens (from/to)	Mold and Photoelastic model material	Was vacuum chamber used? (yes or no)	Rest tests? (yes or no) / Test rest (hours)	Work time (hours)	Characteristics of polariscope	Reference of tension produced	Movement type
Domingos et al. (2021) [47]	Lower arch a second molar at second molar with out of first premolars	Silicone / Flexible epoxy resin	NR	NR / NR	NR	Circular	**American Society for Testing and Materials. D4093-95; 2001	Retraction mechanic
Meros et al. (2019) [40]	Lower arch a second molar at second molar	Silicone / Flexible epoxy resin	Yes	Yes / 72hs	NR	Reflection	*Automatically analyzed by a software (OS CALC 2.0)	Mechanical approaches to treat anterior open bite
Abraão et al. (2018) [41]	Mandibular hemiarch with a missing first molar and mesial inclination of the second molar	Silicone / Flexible epoxy resin	NR	Yes / NR	NR	Circular	**American Society for Testing and Materials. D4093-95; 2001	Mandibular second molar uprighting
Chiang et al. (2018) [6]	Partial mandibular 3 or 5 anterior teeth	Silicone / Epoxy Photoelastic	Yes	Yes / NR	NR	Circular	NR	Orthodontic methods to subside lower anterior crowding
Schwertner et al. (2017) [42]	Model of a maxilla with first molar and incisors	Silicone / Epoxy resin	Yes	Yes / 24hs	NR	Reflection	*Automatically analyzed by a software (OS CALC 2.0)	Incisor intrusion
Claro et al. (2014) [29]	from second molar to canine, without the first premolar	Silicone / Flexible epoxy resin	Yes	Yes / NR	NR	Circular	** American Society for Testing and Materials. D4093-95; 2001	Dental and Skeletal anchorages in the canine retraction

Chart 1. Standardized data extraction form.

Autor, year	Type of specimens (from/to)	Mold and Photoelastic model material	Was vacuum chamber used? (yes or no)	Rest tests? (yes or no) / Test rest (hours)	Work time (hours)	Characteristics of polariscope	Reference of tension produced	Movement type
Sobral et al. (2014) [4]	Lower arch a second molar at second molar	NR / Photoelastic resin	NR	Yes / NR	NR	Plane	NR	Stress generated by wires when conventional and self-ligating brackets
Çehreli et al. (2013) [43]	Plexiglas block	Silicone / Photoelastic resin	NR	Yes / NR	NR	Circular	*** Data acquisition system	Torque and application of static lateral load on mirco implants
Lima et al. (2011) [37]	Model of the face	Silicone / Epoxy resin	NR	NR / NR	NR	Plane	NR	Maxillary expansion
Maia et al. (2011) [7]	Plexiglas block 2 teeth separated by a distance of 27 mm	NR / NR	NR	NR / NR	NR	Circular	NR	Compare the system of forces generated by retraction T-loop springs
D'Attilio et al. (2007) [38]	Parcial maxillary, Molar and pré-molar	NR / NR	NR	NR / NR	NR	NR	NR	Distalize appliance
Nakamura et al. (2007) [48]	Partial mandibular, Hemiarch, central incisor at second molar	Silicone / Epoxy resin urethane	NR	Yes / NR	NR	Circular	NR	Mandibular molars moved distally with the skeletal anchorage system

Chart 1. Standardized data extraction form.

3 of 5

Autor, year	Type of specimens (from/to)	Mold and Photoelastic model material	Was vacuum chamber used? (yes or no)	Rest tests? (yes or no) / Test rest (hours)	Work time (hours)	Characteristics of polariscope	Reference of tension produced	Movement type
Kusakabe et al. (2007) [49]	Model of the face	Silicone / Epoxy plastic	NR	Yes / NR	NR	Circular	NR	Rapid palatal expansion
Badran et al. (2003) [33]	Full mandibular and maxillary	Silicone / Gelatine	Yes	NR / NR	NR	Circular	Kuske and Robertson (1974)	Incisor crowding and exotic canine
Yoon-Josh et al. (2002) [44]	Upper arch a second molar in buccal crossbite	Silicone / Photoelastic resin	NR	Yes / NR	NR	Circular	****Vishay Measurements Group. Tech note (TN-702–1)	Correction of the maxillary second molar in buccal crossbite
Yoon-Josh et al. (2002) [45]	Lower arch a second molar in lingual crossbite	Silicone / Photoelastic resin	NR	Yes / NR	NR	Circular	****Vishay Measurements Group. Tech note (TN-702–1)	Correction of the mandibular second molar in lingual crossbite
Matsui et al. (2000) [50]	Model of a maxilla without the first premolar right and left	Silicone / Epoxy resin	NR	NR / NR	NR	Circular	NR	Center of resistance
Clifford et al. (1999) [34]	Lower arch simulate curve Spee	Silicone / Gelatine	NR	Yes / NR	NR	NR	NR	Lower arch simulate curve Spee
Shetty et al. (1994) [46]	Model of the face	NR / Epoxy resin	NR	Yes / NR	NR	Circular	***** Data acquisition program	Rapid palatal expansion
Stefanac et al. (1993) [5]	Model of the face	NR / Urethane	NR	Yes / NR	NR	Circular	NR	Bionator
Chaconas et al. (1989) [39]	Full maxilla with out of first premolars	NR / Photoelastic resin	NR	NR / NR	NR	Circular	NR	Retraction of the maxillary incisor when extraction of the first premolar.

Chart 1. Standardized data extraction form.

Autor, year	Type of specimens (from/to)	Mold and Photoelastic model material	Was vacuum chamber used? (yes or no)	Rest tests? (yes or no) / Test rest (hours)	Work time (hours)	Characteristics of polariscope	Reference of tension produced	Movement type
Aird et al. (1988) [32]	Polycarbonate Bracket	NR / Araldite	NR	NR / NR	NR	NR	NR	Root torqueing mechanics
Itoh et al. (1985) [28]	Model of the face	NR / Photoelastic resin	NR	NR / NR	NR	Circular	NR	Orthopedic protraction forces
Alba et al. (1982) [27]	Model of the face	NR / Photoelastic resin	NR	NR / NR	NR	Circular	NR	High-pull chin cup traction.
Perez et al. (1980) [26]	Model of the face	Silicone / Photoelastic resin	NR	Yes / NR	NR	Circular	NR	Retraction canine with J hook
Alba levy et al. (1979) [22]	Model of the face	NR / Photoelastic resin	NR	NR / NR	NR	Circular	NR	Intermaxillary class III force
Stewart et al. (1978) [35]	Upper and lower arch	NR / Birefringent urethane plastic	NR	NR / NR	NR	Circular	NR	Intermaxillary elastic traction on orthodontic tooth movement
Chaconas et al. (1976) [25]	Model of the face	Silicone / Photoelastic resin	NR	NR / NR	NR	Circular	NR	Orthopedic forces utilizing cervical and headgear appliances
Alba levy et al. (1976) [36]	Model of the face	Silicone / Epoxy birefringent plastic	NR	Yes / NR	NR	Circular	NR	

Chart 1. Standardized data extraction form.

Autor, year	Type of specimens (from/to)	Mold and Photoelastic model material	Was vacuum chamber used? (yes or no)	Rest tests? (yes or no) / Test rest (hours)	Work time (hours)	Characteristics of polariscope	Reference of tension produced	Movement type
Baeten (1975) [21]	Parcial maxillary	NR / Photoelastic resin	NR	NR / NR	NR	Circular	NR	Canine retraction
Brodsky et al. (1975) [23]	Cat partial maxillary	Silicone / Photoelastic resin	NR	NR / NR	NR	Circular	NR	Canine retraction animal's teeth.
Hayashi et al. (1975) [24]	NR	NR / Photoelastic resin	Yes	Yes / 168 hs	NR	Circular	NR	Supporting bone during tooth movement
Caputo et al. (1974) [20]	Partial mandibular	NR / Photoelastic resin	Yes	Yes / 168 hs	NR	Circular	NR	Lower canine retraction

Note: *Automatically analyzed by a software (OS CALC 2.0) which converted stress values into megapascals (MPa) (strength divided by area, being 1 MPa = 1.19 kgf/cm^2). **American Society for Testing and Materials. Standard test method for photoelastic measurements of birefringence and residual strains in transparent or translucent plastic materials. West Conshohocken: D4093-95; 2001. ***Data acquisition system (ESAM Traveller 1; Vishay Micromeasurements Group, Raleigh, North Carolina, USA) and were displayed in a computer by a special software (ESAM; ESA Messtechnik GmbH, Olching, Germany) at a sample rate of 10 KHz. ****Vishay Measurements Group. Tech note (TN-702–1): introduction to stress analysis by the photostress method. Malvern, PA: Vishay Intertechnology, Inc; 1989:1-12. *****Data acquisition program (Labtech Notebook, Laboratory Technologies Corporation, Wilmington, MA).

RESULTS

Selection of evidence sources

The electronic search yielded 385 records. After excluding duplicates and including records by manual search, 358 titles and abstracts were obtained. During the screening phase, 51 studies were retrieved for full-text reading, out of which 18 were excluded. Those eliminated during the final selection phase, and the respective justifications for their exclusion are presented in chart 2. Finally, 33 studies met the eligibility criteria and were included in this review (figure 2).

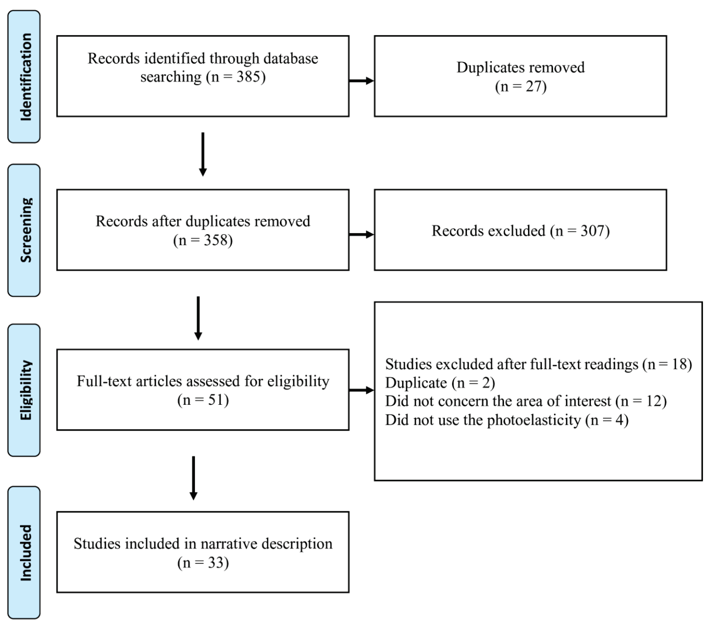

Figure 2. Flowchart of the bibliographic research and selection of articles.

Chart 2. Excluded Study Sheet.

1 of 2

Autor (year)	Reason for exclusion
Montanini et al. (2016)	Not part of the area of interest
Altemose (2016)	Did not use intervention of interest
Janovic et al., 2015	Not part of the area of interest
Sato et al. (2012)	Not part of the area of interest
Fan et al. (2011)	Not part of the area of interest
Sato et al. (2010)	Not part of the area of interest
Gracco et al. (2008)	Not part of the area of interest
Huet al. (2007)	Did not use intervention of interest
Nakamura et al. (2006)	Duplicate
N'Guyen-Gauffre et al. (1999)	Did not use intervention of interest

Chart 2. Excluded Study Sheet.

2 of 2

Autor (year)	Reason for exclusion
Lewis et al. (1997)	Not part of the area of interest
McGuinness et al. (1990)	Not part of the area of interest
Tezcan et al. (1988)	Did not use intervention of interest
Miyakawa et al. (1984)	Not part of the area of interest
Alba levy et al. (1979)	Not part of the area of interest
Stewart et al. (1977)	Duplicate
Kobayashi (1973)	Not part of the area of interest
Fujita (1972)	Not part of the area of interest

Characteristics of sources of evidence

The included studies dated from 1974 to 2021, and were characterized according to: type of specimens, mold and photoelastic model material, use of vacuum chamber, performance of rest tests, work time, characteristics of the polariscope, reference of tension produced, and tested clinical scenario. The results collected from the included studies are detailed in table 1.

Critical appraisal of individual sources of evidence

All included studies made their objective clear, and employed the appropriate design. Two studies [24,32] did not clearly define the specimens used, and few adopted species from real patients [33,34]. A relevant part of the studies did not measure outcomes or did not clearly report them [21-25,32,35-39]. In this sense, the citation of a reference table for quantitative characterization of the results is occasionally observed [29,33,40-47].

Furthermore, there were few experiments that clearly defined parameters of significance for eventual statistical analysis [29,33,40-42,47]. The smallest portion of the studies showed adequacy in the description of data [4,6,20,29,33,40-45,48-50]. More details about the quality analysis of the included studies can be found in table 3.

Summary of results

The included studies used similar materials with birefringence properties to produce the photoelastic model, namely flexible epoxy resin [29,40,41,47], photoelastic epoxy [6], epoxy resin [37,42,46,50] photoelastic resin [4,20–28,39,43-45], epoxy resin urethane [48], epoxy plastic [49], gelatine [33,34], birefringent urethane plastic [35], epoxy birefringent plastic [36]. Urethane [5], and araldite [32]. As part of the photoelastic model production, all studies cited silicone as the recommended molding material [6,22,23,25,26,29,33,34,37,40-45,48-50].

Few studies reported the use of a vacuum chamber during specimen preparation [6,20,24,29,33,40,42]. Amongst the ones that reported resting time after specimen preparation, a large variability was observed (24 hours [42], 72 hours [40], 168 hours [20,24]).

Table 1. Standard form for critical evaluation of studies.

1 of 2

Autor (year)	*1. Objectives of the study clear?	*2. Was the study design appropriate?	*3. Was the target specimens clearly defined?	*4. Was the specimen frame taken from a real patient?	*5. Were outcome variables measured?	*6. Were the outcome variables measured using reference?	*7. Is it clear what was used to determined statistical significance?	*8. Were the basic data adequately described?
Domingos et al. (2021) [47]	1	3	1	4	1	1	1	1
Meros et al. (2019) [40]	1	3	1	4	1	1	1	1
Abraão et al. (2018) [41]	1	3	1	4	1	1	1	1
Chiang et al. (2018) [6]	1	3	1	4	1	1	4	1
Schwertner et al. (2017) [42]	1	3	1	4	1	1	1	1
Claro et al. (2014) [29]	1	3	1	4	1	1	1	1
Sobral et al. (2014) [4]	1	3	1	4	1	4	4	1
Çehreli et al. (2013) [43]	1	3	1	4	1	1	4	1
Lima Júnior et al. (2011) [37]	1	3	3	1	3	4	4	3
Maia et al. (2011) [7]	1	3	1	4	1	4	4	3
D'Attilio et al. (2007) [38]	1	3	3	4	3	4	4	4
Nakamura et al. (2007) [48]	1	3	1	4	1	4	4	1
Kusakabe et al. (2007) [49]	1	3	1	4	1	4	4	1
Badran et al. (2003) [33]	1	3	1	4	1	1	1	1
Yoon-Josh et al. (2002) [44]	1	3	1	4	1	1	4	1
Yoon-Josh et al. (2002) [45]	1	3	1	4	1	1	4	1
Matsui et al. (2000) [50]	1	3	1	4	1	4	4	1
Clifford et al. (1999) [34]	1	3	1	4	1	4	4	3
Shetty et al. (1994) [46]	1	3	1	4	1	1	4	3
Stefanac et al. (1993) [5]	1	3	1	4	1	4	4	3
Chaconas et al. (1989) [39]	1	3	1	4	2	4	4	2

Table 1. Standard form for critical evaluation of studies.

Autor (year)	*1. Objectives of the study clear?	*2. Was the study design appropriate?	*3. Was the target specimens clearly defined?	*4. Was the specimen frame taken from a real patient?	*5. Were outcome variables measured?	*6. Were the outcome variables measured using reference?	*7. Is it clear what was used to determined statistical significance?	*8. Were the basic data adequately described?
Aird et al. (1988) [32]	1	3	1	4	3	4	4	3
Itoh et al. (1985) [28]	1	3	1	4	1	4	4	3
Alba et al. (1982) [27]	1	3	3	1	2	4	4	3
Perez et al. (1980) [26]	1	3	1	4	1	4	4	3
Alba levy et al. (1979) [22]	1	3	1	4	3	4	4	3
Stewart et al. (1978) [35]	1	3	1	4	3	4	4	3
Chaconaset al. (1976) [25]	1	3	3	4	3	4	4	4
Alba levy et al. (1976) [36]	1	3	3	4	3	4	4	4
Baeten (1975) [21]	1	3	1	4	3	4	4	3
Brodsky et al. (1975) [23]	1	3	3	4	3	4	4	3
Hayashiet al. (1975) [24]	1	3	3	4	3	4	4	3
Caputo et al. (1974) [20]	1	3	1	4	1	4	4	1

Note: *Risk of Bias. 1 = definitely yes (Low RoB), 2 = partially yes, 3 = unclear, 4 = definitely no (High RoB).

A great versatility was observed in relation to the types of photoelastic models. Some of the included studies [7,43] described rectangular models, so that only the teeth of interest were fixed. Others [5,22,25-28,36,46,49] described full-face photoelastic models. There were also studies that reported the elaboration of integral [33,35,39,42,45,50] or partial maxillary models [21,38]. The development of mandibular models was also described, whether integral [4,33-35,40,44,47] or partial [6,20,29,41,48]. Still, a single study described the construction of a model after the molding of a cat's mandible [23].

The vast majority of studies used the circular polariscope, with the exception of two [40,42] which used the reflection polariscope, and two others [4,37], which used the plane polariscope. Most of the studies reported baseline checking of the model [4-6,20,24,26,29,34,36,40-46,48,49].

As for the method of tension analysis, few studies have described the results using reference tables [6,29,33,40-46], and the results were mostly described only with the qualitative characterization of the fringe colors [4,5,7,20-28,32,34-39,48-50].

Interestingly several scenarios and orthodontic mechanics were reproduced for photoelastic analysis. For instance, open-bite correction methods were investigated [40], as well as various methods for lower molars uprighting [41]. The correction of models with lower incisor crowding using different wires, such as NiTi round and rectangular wires, ISW (improved superelastic NiTi alloy wire), and stainless steel [6,33] were investigated.

There were also experiments that verified tensions caused by incisor intrusion mechanics [42]. Studies have also evaluated different types of wires associated with conventional and self-ligating brackets [4]. Forces applied to orthodontic mini-implants at different angles [43] and maxillary expansion appliances were also the subject of experiments [37,46,49].

Part of the studies included here also proposed the comparative analysis of retraction mechanics [7,39] and Class II correction using the Friction Free Distalize Appliance [38]. In addition, tensions caused by lower molar distalization using cortical anchorage and an open spring [48], as well as crossbite correction using an elastic chain and fixed appliance [44,45] were evaluated. One of the experiments reported the analysis of the center of resistance in cases of maxillary incisor retraction [50], while another one was dedicated to the analysis of torque in polycarbonate brackets [32].

A relevant proportion of the studies investigated canine retraction methods [20,21,23,26,47] and also the anchorage conjugating adjacent teeth in comparison to mini-implants in canine retraction [29].

The action of several orthopedic appliances, such as: Bionator, Nance holding arch, lingual arch, acrylic fixed appliance with a buccal arch wire, chin-cup, cervical and headgear appliances [5,24-28,36], was investigated. Mechanics of leveling the curve of Spee [34], as well as Class III correction using intermaxillary elastic [22,35] were also analyzed.

DISCUSSION

The photoelasticity method has proved to be extremely versatile for the analysis of various orthodontic and orthopedic mechanics, and it has been used for analyzing scenarios ranging from tooth alignment [4,6,33] to more complex mechanics with the use of mini-implants [29,48] and rapid maxillary expansion [37,46,49].

Photoelasticity and the finite element methods have been both considered as important and complementary experimental techniques for stress analysis [8], since whenever possible, they could be applied for the same experimental purposes, enabling the validation of the results. However, the photoelasticity method refers to a relatively lower cost evaluation tool, which enables simultaneous visualization of tensions, which can be measured and photographed instantly. As for the finite element method, however, software, graphs and force distribution schemes built from numerical data are required. Even though the finite element model can simulate, in a more detailed fashion, complex shapes, such as dental and periodontal structures, it has been documented a correspondence between the tensions observable in photoelastic models with real-life scenarios [2,7,9,23,51-53]. Nevertheless, one of the limitations of the photoelasticity method refers to the dependence on the simulation of physical models similar to the original scenario, as well as the restriction of maximum force that can be applied to the model, which must not exceed the limit of the photoelastic material.

There are reports of several types of photoelastic materials, such as: flexible epoxy resin [29,40,41,47], photoelastic epoxy [6], epoxy resin [37,42,46,50], photoelastic resin [4,20-28,39,43-45], epoxy resin urethane [48], epoxy plastic [49], gelatine [33,34], birefringent urethane plastic [35], epoxy birefringent plastic [36], urethane [5], and araldite [32], where all respected the properties of birefringent materials. There were also some studies that did not mention the type of material used [7,38].

The polariscope refers to a system consisting of a set of optical elements whose objective is to transmit polarized light, in order to produce fringes in birefringent materials, when it undergoes some tension [2,8,54]. Essentially, two models can be used, namely the plane and the circular polariscope. The plane polariscope is composed of two polarizing filters, where the first – called polarizer, has the function of absorbing light waves, and the second (analyzer) is placed behind the photoelastic model to be analyzed. The circular one presents quarter-wave plates between the polarizing and analyzer filters with the function of eliminating the isoclinic fringes, since they are dark and have the potential to interfere in the visualization of the isochromatic fringes, where the voltage magnitude is observed [2,33,54,55]. Considering this advantage, most of the selected studies [5-7,20-24,26-29,33,35,36,39,41,43-46,48-50] used the second model.

In accordance with some studies [2,8,54-56], which have been emphasizing the limitations of photoelasticity, and in view of the unclear or insufficient reports generally observed in most of the studies selected here, it is recommended that future researches should engage efforts to further detailing each experimental method step. In this sense, it seems essential that there is certification and report of the absence of fringes prior to the application of the tension test, ruling out hypotheses of potential interference in the results that could compromise the reliability of the method. Although most studies have carried out an appropriate report in this regard [4-6,20,24,26,29,34,36,40-46,48,49], it is emphasized that in cases of the presence of fringe – indicating the presence of previous tension, it is necessary to insert the model in a stove, in order to carry out a thermal treatment to eliminate residual tension.

Another point that has not been clarified in most of the studies included here refers to the use of a vacuum chamber during the process of models' production, which has the important function of eliminating potential air bubbles resulting from the initial reaction between the components of the photoelastic resin. The use of this resource was cited in only few of the selected studies [6,20,24,29,33,40,42]. Regarding the rest specification of the model for the complete polymerization of the photoelastic resin, just over half of the selected studies reported having completed this step [6,20,24,29,33,40,42], among which only four specified the rest time [20,24,40,42]. Since this is an important factor in the production of the photoelastic model, it is recommended that the curing time of the material should be respected, according to the manufacturer. Across the studies included in this review, curing time ranged from 24 hours [42], 72 hours [40] to 168 hours [20,24].

The report of the use of a reference table for the analysis of results is a relevant factor in this type of study, which allows the results to be quantitatively compared, not only between scenarios in the same study, but also with those of other studies. The American Society for Testing and Materials has classified photoelastic fringe standards into ordinal numbers, so that each fringe has an identity or so-called fringe order (ASTM D4093-95, 2001). Therefore, the use of a reference table is recommended, as reported by few of the selected studies [6,29,33,40-46].

Most of the studies clearly defined the specimens used, describing their individual characteristics [4-7,20-22,26,28,29,32-35,37,39-46,48-50]. On the other hand, only a minority of studies cited the type of mechanics that were evaluated, not clearly describing the characteristics of the specimens [23-25,27,36,38]. Relevant part of the studies [22-25,32,35-38] also did not pre-define the areas of teeth and/or specimens to be analyzed, being restricted to the description of the results in general. The absence of detailed reports about the specimens and the analyzed areas might hamper comparative analyses, as well as the comprehensive interpretation of the results. Finally, few studies [29,33,40-42] used significance parameters for eventual statistical analysis, which is another important information to be regarded during the interpretation of results.

In view of its versatility, the authors of this review consider that further studies can still be carried out in order to evaluate new orthodontic techniques and mechanics, such as extra-alveolar mini-implants, esthetic aligners, distalization systems, as well as mechanics with self-ligating brackets. In order to seek results resulting from new orthodontic mechanics, the application of the photoelasticity method can enable the production of new parameters that are useful to orthodontists in their clinical practice, provided that further studies pay attention to the conduct and report of each step necessary for the correct execution of this method.

LIMITATIONS

The limitations identified by this study refer, above all, to the frequent incompleteness of information about methods or the lack of clarity in their reports. In addition, there was a lack of standardization in the production of the photoelastic model and in the analysis of the results.

CONCLUSION

It is concluded that the photoelasticity method proved to be very versatile, analyzing various types of orthodontic and orthopedic appliances and mechanics in different scenarios. The selected manuscripts presented generally insufficient or unclear reports, especially in relation to the process of producing the models and the analysis of the results. Further studies are suggested to investigate new orthodontic mechanics and toclearly follow and report all the processes of this method.

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Data availability: The research data are available from the corresponding author upon reasonable request

Collaborators

MP Dessimoni, conceptualization, data curation, formal analysis, investigation, methodology, resources, software, writing-original draft, writing-review & editing. VL Paschoini-Costa, investigation, methodology, writing-review & editing. RAB Segato, LAB Silva, and P Nelson Filho, conceptualization, project administration, writing-review & editing. MFN Feres, conceptualization, data curation, formal analysis, methodology, project administration, software, supervision, validation, visualization, writing-original draft, writing-review & editing.

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