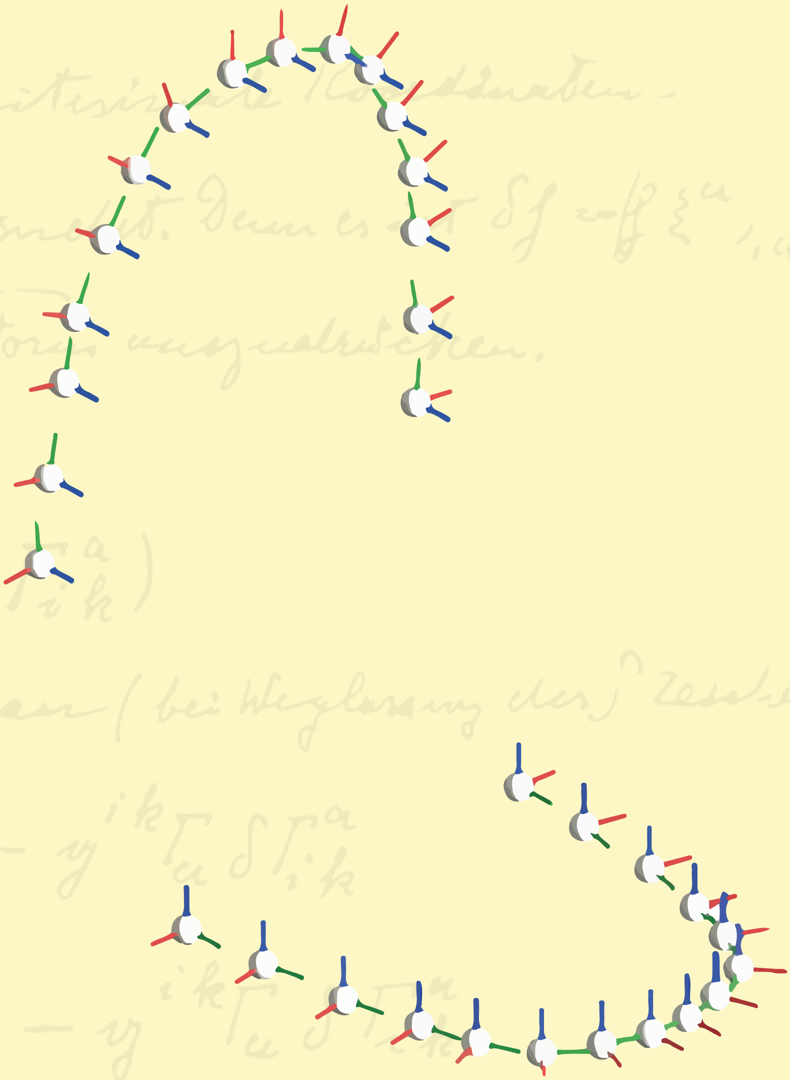
Learning about Tooth Removal with Robot Technology



Tom van Riet

Learning about Tooth Removal with Robot Technology

Tom van Riet, 2023

Financial support
Financial support for printing and distribution of this thesis was kindly provided by:
Koninklijke Nederlandse Maatschappij tot bevordering der Tandheelkunde (KNMT)
Nederlandse Vereniging voor MKA-chirurgie (NVMKA)
Academisch Centrum Tandheelkunde Amsterdam (ACTA)

The research presented in this thesis was performed at:
Department of Oral and Maxillofacial Surgery, Amsterdam University Medical Centers
Department of Cognitive Robotics, Delft University of Technology

Learning about tooth removal using robot technology
Academic thesis, University of Amsterdam, The Netherlands

ISBN:	978-90-833743-4-5
Cover design:	Tom van Riet, Willem Momma
Lay-out:	Ferdinand van Nispen, Citroenvlinder DTP & Vormgeving, *my*-thesis.nl
Printing:	Proefschriftenprinten.nl, Ede, The Netherlands

Learning about Tooth Removal with Robot Technology

ACADEMISCH PROEFSCHRIFT

ter verkrijging van de graad van doctor
aan de Universiteit van Amsterdam
op gezag van de Rector Magnificus
prof. dr. ir. P.P.C.C. Verbeek
ten overstaan van een door het College voor Promoties ingestelde commissie,
in het openbaar te verdedigen in de Aula der Universiteit
op woensdag 6 december 2023, te 14.00 uur

door Tom Cornelis Theodorus van Riet
geboren te UTRECHT

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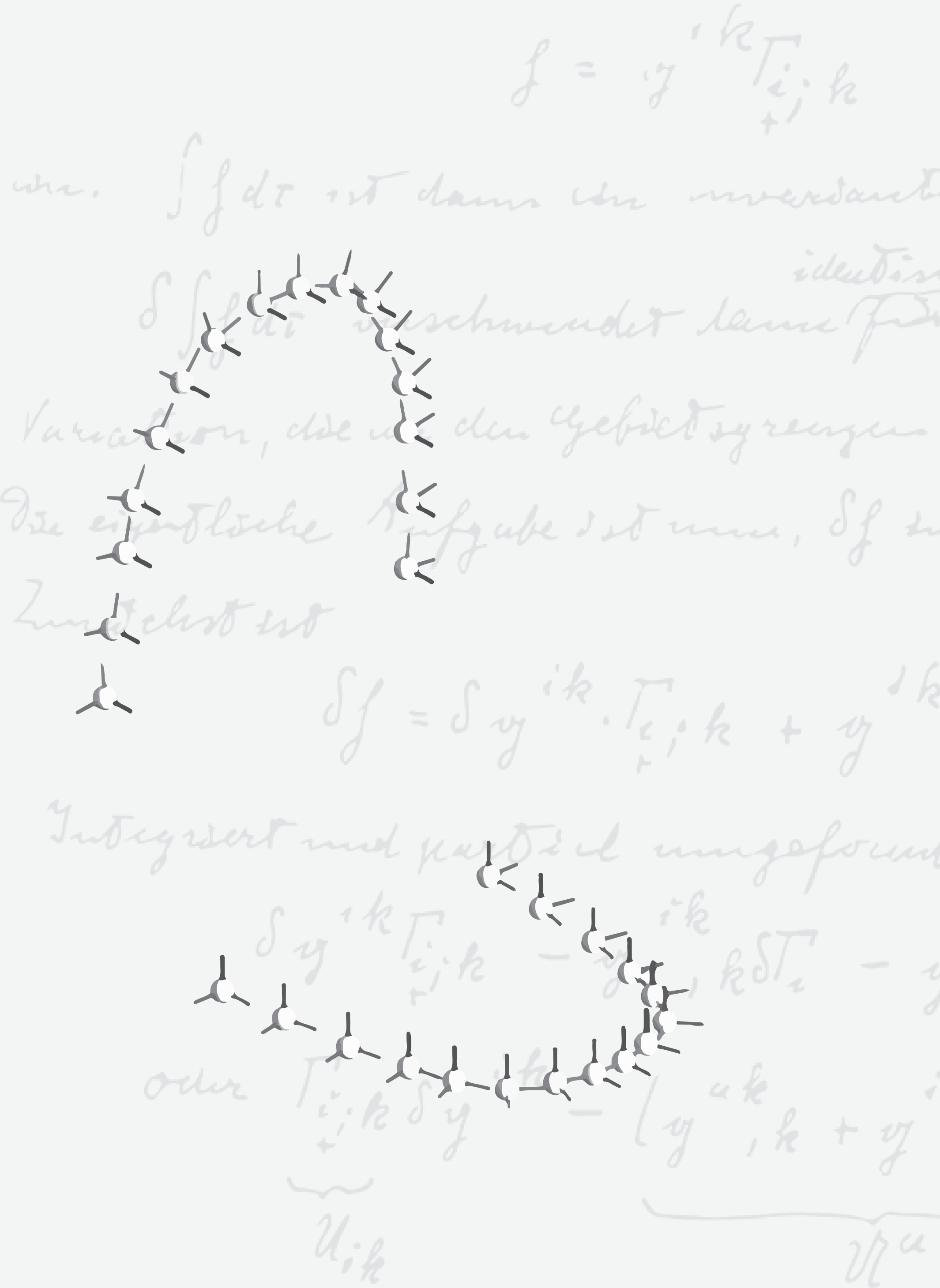


Chapter 1

General Introduction, Outline and Aims

Background

Aulus Cornelius Celsus (c. 25BC – 50AD) described a method for tooth extraction in his book *De Medicina*, in Latin. It was translated by James Grieve in 1814 to the following description: '*But if a tooth occasions pain, and it seems proper to extract it, because medicines give no relief, it ought to be scraped all round, that the gum may be loosened from it; then it is to be shook; which must be continued till it move easily*' and '*the tooth is to be taken out, if possible, by the hand, if not, by a forceps*' [1]. Science in the field of tooth removal was mostly concerned with improving the design of different surgical instruments. The modern extraction forceps was introduced at the beginning of the 19th century by Cyrus Fay (circa 1819-1826), Figure 1. Earlier forceps held teeth at their greatest diameter, instead of the neck of a tooth. Furthermore, his design was meant to allow forces to be applied perpendicular to the jawbone [2].

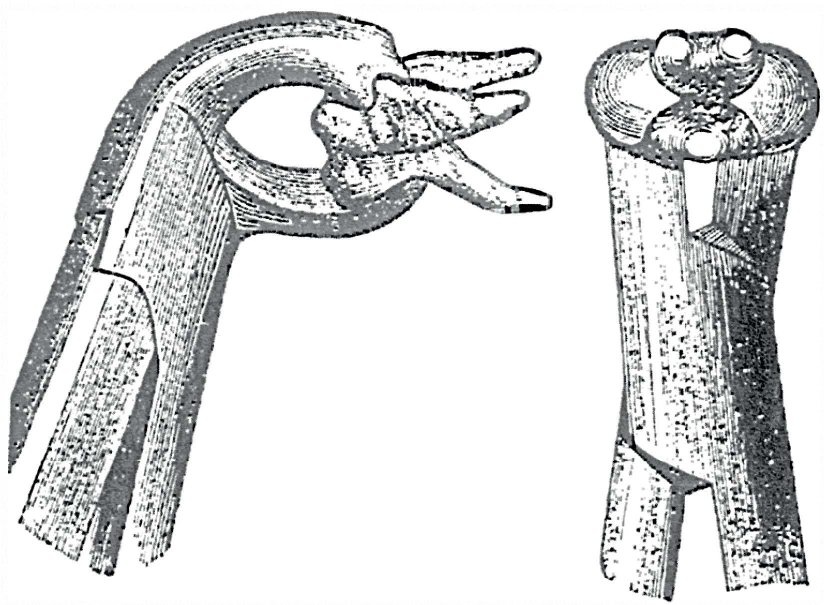


Figure 1: Design of extraction forceps by Mr. Fay with an anatomical fit around the neck of the tooth as we see in modern day extraction forceps. Reprinted from the Journal of Oral and Maxillofacial Surgery, volume 45 / edition 6, 'Cyrus Fay and the real origin of the modern day extraction forceps' by B.S. Moskow, Page no. 520, Copyright 1987, with permission from Elsevier.

In 1934, George Christiansen introduced developments in the field of tooth removal in his paper on 'Problems in Oral Surgery' as follows: 'The extraction of teeth, in spite of greatly improved technic and a multitude of new and strange instruments, remains and extremely difficult, delicate and important operation'. He reduce tooth removal procedures to a problem, which is 'to remove a calcified substance, the root, from a bony socket lined by fibrous membrane' [3]. In his paper, he described different techniques to perform standard tooth removal, mostly based on anatomic variability between the teeth.

In a recent review, it was shown that the first study that tried to objectify forces exerted in tooth removal was published in 1973 [4,5]. Since then, only a few attempts were undertake to measure a variety of metrics during these procedures ranging from gripping force, forces exerted along different axes, muscle contraction of the surgeon and rotational forces (torques). A high degree of heterogeneity was found with regard to outcome measures and methodology was often described with insufficient detail. Most studies registered force data in a limited manner by measuring forces in only one or two directions, which seems to underestimate the complexity of these procedures. The study concluded that a large knowledge gap exists in our fundamental understanding of tooth extractions [5].

Despite the successes of preventive dentistry and a concurrent decline in prevalence and incidence of tooth loss around the world, tooth removal procedures are still very common and should be considered as an essential skill for dentists [6,7]. The high frequency, in which these procedures are performed, makes the lack of scientific progress in this field remarkable [5]. The same forceps that were proposed 200 years ago are still used in everyday practice. Modern textbooks for dental students are still limited to 'rotation' or 'rocking' instructions, similar to textbooks written 2000 years ago [8].

In 2011, a questionnaire was distributed among students from 23 dental schools across Europe showing that up to 60% of students felt that their knowledge about forceps and elevators was insufficient. Moreover, preclinical training modalities were shown to be heterogeneous and not widely used, meaning that most students have to 'practice' their skill in a clinical setting. If preclinical training modalities were used, not all students considered them as useful. In Amsterdam, the mean score students gave for their satisfaction with extraction education was 2.5 $\pm$1.0 on a 5-point Liker scale ranging from 1 (absolutely not) to 5 (absolutely) [9].

A study performed at a department of Oral and Maxillofacial Surgery in Groningen, The Netherlands, compared their oldest retrievable outpatient agendas (1996) with more recent agendas (2014) to find a significant increase in referrals for simple tooth extractions. Although data is lacking, they propose that a lowered exposure to clinical training (number of teeth removed per student) might be one of the reasons that explain the increase in referrals. Furthermore, it is advocated that straightforward extractions should take place at the general dentist' office for several reasons for which rising costs in healthcare is an important one [10].

Aims and outline of this thesis

The aim of this thesis is to improve our fundamental knowledge of tooth removal. Robot technology is used to overcome previous challenges in gaining high quality data regarding forces, torques and movements. We aim to gain data in high frequency and in all relevant directions and to use modern machine learning techniques to improve our understanding of this complex data. Improved fundamental knowledge has the potential to lay a foundation for the design of new, evidence-based educational methods.

In **Chapter 2 and 3**, results of an extensive literature review are presented, regarding the use of robot technology in all fields of dentistry. The quality of the literature is evaluated as well as the Technological Readiness Levels of the proposed robot systems. In **Chapter 4**, our proposed measurement setup is presented, including the design challenges, considerations and preliminary testing results. **Chapter 5 and 6** present the results of our measurement campaign, which was performed on fresh frozen cadavers. Results on forces and torques are presented in a descriptive manner in chapter 4 and rotations in chapter 5. A classification model, to make use of the complex data as a whole, is presented in **Chapter 7**.

References

[1] Greive, J. in *Book VII* Vol. VII Ch. Chapter XII Of the Operations requisite in the mooth, 338 (Dickinson and company, 1814).

[2] Moskow, B. S. Cyrus fay and the real origin of the modern day extraction forcepts. *Journal of Oral and Maxillofacial Surgery* **45**, 516-523, doi:https://doi.org/10.1016/S0278-2391(87)80012-5 (1987).

[3] Christiansen, G. W. Problems in Oral Surgery of Interest to the General Practitioner**Read at a meeting of the Cleveland Dental Society, May 7, 1934. *The Journal of the American Dental Association (1922)* **21**, 1989-1999, doi:10.14219/jada.archive.1934.0296 (1934).

[4] Kawamoto, T. [A dynamic study of the forces exerted with tooth extraction forceps]. *Shikwa Gakuho* **73**, 59-86 (1973).

[5] Beuling, M. G. *et al.* Forces and movements during tooth extraction: A scoping review. *Advancesin Oral and Maxillofacial Surgery* **9**, doi:10.1016/j.adoms.2023.100391 (2023).

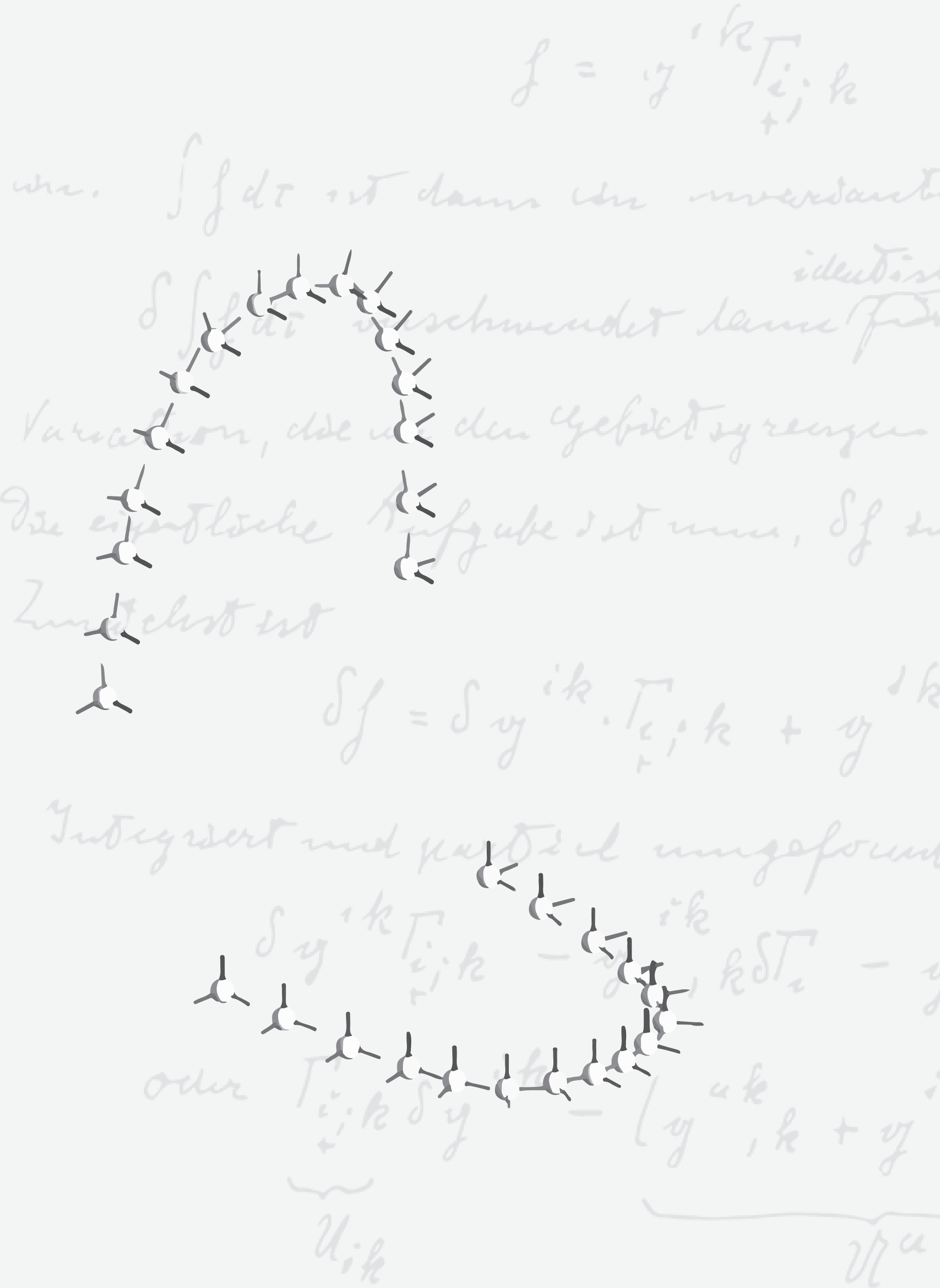
[6] Müller, F., Naharro, M. & Carlsson, G. E. What are the prevalence and incidence of tooth loss in the adult and elderly population in Europe? *Clinical oral implants research* 18 Suppl 3, 2-14, doi:10.1111/j.1600-0501.2007.01459.x (2007).

[7] Kassebaum, N. J. *et al.* Global Burden of Severe Tooth Loss: A Systematic Review and Meta-analysis. *J Dent Res* **93**, 20S-28S, doi:10.1177/0022034514537828 (2014).

[8] Stegenga, B. *MKA Chirurgie*. 2nd edn, (van Gorcum, 2013).

[9] Brand, H. S., van der Cammen, C. C. J., Roorda, S. M. E. & Baart, J. A. Tooth extraction education at dental schools across Europe. *BDJ Open* **1**, 15002-15002, doi:10.1038/bdjopen.2015.2 (2015).

[10] Onclin, P. Recent increase in simple extractions in OMF-surgeries in the Netherlands studied.*Nederlands Tijdschrift voor Tandheelkunde* **123**, 365-372, doi:10.5177/ntvt.2016.07/08.16140 (2016).



Chapter 2

Robot Technology in dentistry, literature characteristics

This chapter is based on the following publication:
Robot technology in dentistry, part one of a systematic review: literature characteristics
T.C.T. van Riet, K.T.H. Chin Jen Sem, J.T.F. Ho, R. Spijker, J. Kober and J. de Lange

Published in: Dental Materials, 2021

Abstract

Objectives:
To provide dental practitioners and researchers with a comprehensive and transparent evidence-based overview of the characteristics of literature regarding initiatives of robot technology in dentistry.

Data:
All articles in which robot technology in dentistry is described, except for non-scientific articles and articles containing secondary data (reviews). Amongst others, the following data were extracted: type of study, level of technological readiness, authors' professional background and the subject of interaction with the robot.

Sources:
Bibliographic databases PubMed, Embase, and Scopus were surveyed. A reference search was conducted. The search timeline was between January 1985 and October 2020.

Study Selection:
A total of 911 articles were screened on title and abstract of which 161 deemed eligible for inclusion. Another 71 articles were excluded mainly because of unavailability of full texts or the sole use of secondary data (reviews). Four articles were included after hand searching the reference lists. In total, 94 articles were included for analysis.

Conclusions:
Since 2013, an average of six articles per year concern robot initiatives in dentistry, mostly originating from East Asia (57%). The vast majority of research was categorized as either basic theoretical or basic applied research (80%). Technology readiness levels did not reach higher than three (proof of concept) in 55% of all articles. In 84%, the first author of the included articles had a technical background and in 36%, none of the authors had a dental or medical background. The overall quality of literature, especially in terms of clinical validation, should be considered as low.

Introduction

The first generally recognized digitally operated and programmable robot was an industrial robot called 'Unimate' (Unimation, Inc., USA) that was used in the automotive industry in 1961 [1]. The Programmable Universal Machine for Assembly 200 (PUMA 200, Westinghouse Electric, Pittsburg, PA, USA) was the first robot to be used in medicine over 25 years later (1988). Its purpose was to align a needle during neurosurgical biopsies [2].

Since then, experiments with robot technology in many fields of dentistry have been described, for example in implantology, restorative dentistry and education [3-5]. Some robotic solutions have become commercially available in recent years and are marketed for use in the general dentist practice, such as the implantology robot 'Yomi' (Neocis, Miami, Florida, USA). For the general dentist, it might be difficult to keep track of these initiatives and their level of (scientific) development. Furthermore, in 'grey literature' the capabilities of robots when it comes to their functionality and stage of development might be difficult to interpret and can be easily overestimated [6].

Most reviews on this topic have a narrow scope, i.e., describing robot technology in a specific field. A recent review by Grischke et al. (2020) explained more about the possibilities of robotics on a broader scale in dentistry, including cognitive robotics, but as with other reviews concerning robot technology in dentistry, it lacked a clear systematic approach [7-9]. To the authors best of knowledge, a strong systematic overview of available evidence in dental robotics and how this evidence is synthesized is missing.

In this first part of a systematic review, the primary aim is to provide dental practitioners and researchers with a comprehensive, transparent and evidence-based overview of the characteristics of the literature and level of development of robot initiatives in dentistry. In a second part of this systematic review, an overview of the usage of robot technology in all fields of dentistry since its very beginning is provided.

Materials and methods

Information sources and search strategy

Guidelines from both the Preferred Reporting Items for Systematic Reviews (PRISMA) as well as the Joanna Briggs Institute (JBI) were used to structure this review [10, 11]. The bibliographic databases Medline (through PubMed), Embase and Scopus were searched on 30 October 2020. In addition, the reference lists of included full texts and excluded reviews were screened and cross-referred. The search strategies were defined appropriately for each database together with an information specialist (RS). An overview of the search strategy for all three databases can be found in Tables 1-3.

Table 1. PubMed search strategy. Number of articles found = 347

	PubMed search terms
#1	Robotic Surgical Procedures[MeSH] OR robot*[tiab] OR yomi[tiab] OR suresmile[tiab]
#2	Dentistry[MeSH] OR Education, Dental[MeSH] OR Health Education, Dental[MeSH] OR Students, Dental[MeSH] OR Dental Materials[MeSH]) OR (dentistry[tiab] OR dental [tiab] OR denture[tiab] OR dentist[tiab] OR dentine[tiab] OR enamel[tiab] OR tooth[tiab] OR teeth[tiab] OR molar* [tiab] OR gingiva[tiab] OR periodontal[tiab] OR Prosthodontic[tiab] OR Periodontic[tiab] OR Endodontic [tiab] OR Implantology[tiab] OR Orthodontic[tiab] OR Dentistry/surgery[MeSH]
#3	#1 AND #2

Table 2. Scopus search strategy. Number of articles found = 634

	Scopus search terms
#1	(TITLE-ABS-KEY (robot* OR yomi OR suresmile))
#2	(TITLE-ABS-KEY (dentistry OR dental OR denture OR dentist OR dentine OR enamel OR molar* OR gingiva OR periodontal OR prosthodontic OR periodontic OR endodontic OR implantology OR orthodontic))
#3	#1 AND #2

Table 3. Embase search strategy. Number of articles found = 272

	Embase search terms
#1	((exp robot assisted surgery/) or (robot* or yomi or suresmile).ti,ab,KW)
#2	((exp "Dentistry"/ or dental education/ or dental health education/ or dental student/ or exp dental material/) OR (dentistry OR dental OR denture OR dentist OR dentine OR enamel OR tooth OR teeth OR molar* OR gingiva OR periodontal OR Prosthodontic OR Periodontic OR Endodontic OR Implantology OR Orthodontic).ti,ab,kw)
#3	#1 AND #2

Eligibility criteria

The definition of a robot differs throughout literature. For the purpose of this review, it was decided that, when an author used the term robot for the described technology, it was considered as such and was therefore eligible for inclusion. Since the first robot in medicine was described in 1988, only publications in or after 1985 were included. Articles in all languages were included. (Non-)Systematic reviews, patents, presentation slides, posters and video content were excluded from data synthesis. Robots used for research purposes only, i.e., standardized impression taking to evaluate material properties, were excluded. Literature regarding robot technology in oral and maxillofacial surgery was excluded since most of the medically used robot systems are infeasible for usage in general dentistry.

Study selection

Articles identified using the search strategy were imported into a web application for systematic reviews (Rayyan, Qatar Computing Research Institute, Doha, Qatar) [12]. Duplicates were removed before uploading to Rayyan by an in-house application, after which two independent reviewers screened all titles and abstracts for relevance (TR, KC). Results were compared afterwards and in case of any discrepancies, a discussion was held to reach an agreement. A third reviewer was consulted to act as a referee (JH), when required. After title and abstract screening, a full text screening was performed. Articles were excluded when full-text was unavailable (see Fig. 1).

Data charting process and data items

Full text of all articles meeting the inclusion criteria for further analysis were acquired. Data extraction was performed in duplicate by two authors (TR, KC) using a customized data extraction form. The following data items were collected: field of dentistry, year of publication, technological readiness levels, country of origin, authors' professional background (either clinical or technical) and the subject of interaction with the robot. The type of study was recorded according to a modified classification of study types in medical research (see Table 4) [13].

Table 4. A modified version of the classification of types of medical research described in Röhrig et al. 2009 [14].

Main classification of study design	Examples
Basic research – Theoretical	Method development (no experiments)
Basic research – Applied	Experiments on models, animals, cadavers, or humans
	Material development
Clinical research – Observational	Therapy study, case series, case reports, prognostic studies
Clinical research – Experimental	Clinical intervention studies
Epidemiological research – Observational	Case control studies
	Observational studies
	Comparative studies
Epidemiological research – Experimental	Field/group studies

The technology readiness level (TRL) of each proposed initiative was estimated on the information provided in the original research paper. The TRL scale, originating from the National Aeronautics and Space Administration (NASA), consist of 9 stages and 4 groups of development levels in which technology can be categorized (see Table 5) [15]. For data registration and analysis, Microsoft's Office Excel (version 2019, Microsoft Corporation, USA) was used.

Table 5. Technological Readiness Level (TRL) description.

Group	Technology Readiness Levels	Description
Discovery	TRL 1	Basic principles of the technology are observed.
	TRL 2	Technological concept is formulated.
	TRL 3	After laboratory tests a proof of concept is made.
Development	TRL 4	Proof of concept is validated in laboratory with prototypes.
	TRL 5	Technology is tested and validated in the relevant environment.
	TRL 6	Technology is demonstrated in relevant environment; the prototype is not yet optimized for operational environment.
Demonstration	TRL 7	Technology is integrated in operational environment.
	TRL 8	The system is completed and qualified; the technology performs properly.
Deployment	TRL 9	Actual system is proven in operational environment; technology is commercially ready.

Results

Study selection

The search in all three databases combined, excluding duplicated articles, resulted in 911 articles eligible for title and abstract screening. After title and abstract screening 161 articles were deemed valuable for inclusion of which 71 articles had to be excluded with reasons specified (Fig. 1). The most frequent reason for exclusion (26 times) was the unavailability of a full-text version of the articles. The complete texts of 90 articles were carefully reviewed and screened by hand searching to find four additional articles matching the inclusion criteria [16-19]. In total 94 articles were included in this systematic review for qualitative synthesis (Fig. 1).

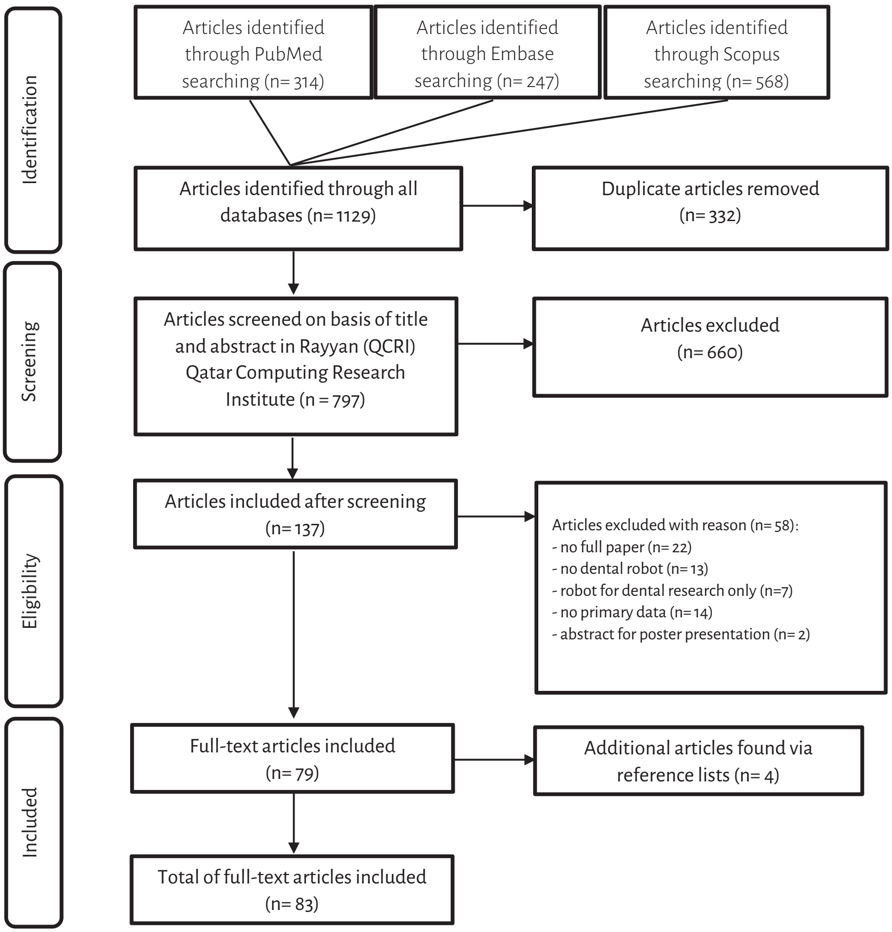


Figure. 1 Diagram of the search process and results

Study demography and professional background

Articles included from countries in East Asia (China, Japan, and Korea) formed the largest group with 54 articles in total (57%), followed by the USA with 17 articles (18%) (Fig. 2). All included articles were in English except for four Chinese articles [20-23] and one article in Turkish [24]. These five articles were translated to English before data extraction.

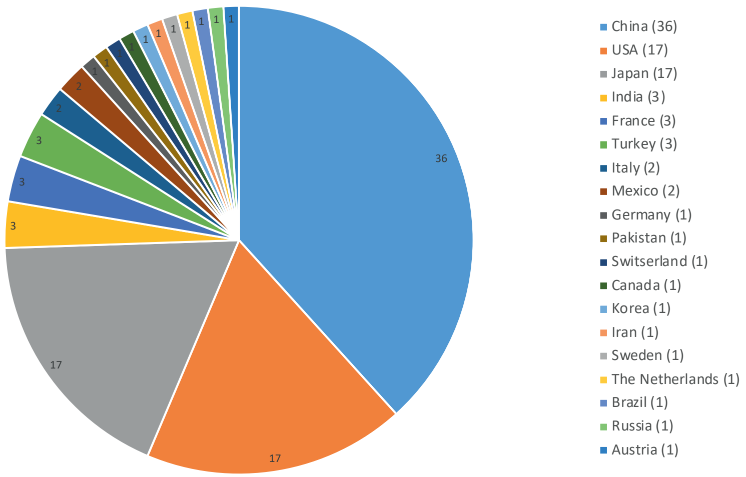


Figure 2. Country of origin of the research project

After hitting a peak number of articles around the year 2012 (nine articles), the number of published articles stabilized to around six per year, since then (Fig. 3). In 15 calendar years between 1985 and 2008, no articles were included in this study.

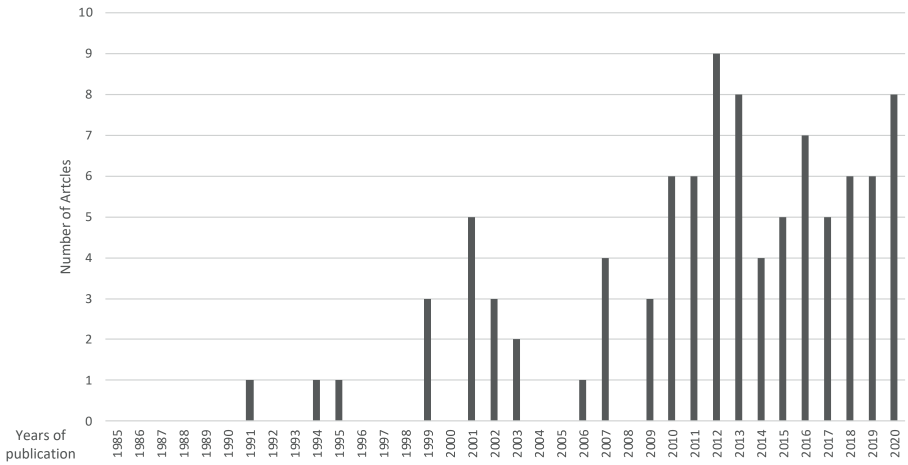


Figure 3. Number of included articles per year of publication

In total 373 authors were counted of which most (253, or 60%) had a technical background. The majority of first authors had a technical background (70 articles, 84%) and in 30 articles, no authors with a dental or medical background were involved at all (36%). In 15 articles (18%), no authors with a technical background were involved.

Fields of dentistry and study design

Orthodontics, implantology and surgery, together responsible for 43% of all included articles, formed the largest groups in this study. Dental radiology (2%) formed the smallest group with only two included articles (Fig. 4) [25, 26]. With eight articles concerning the 'Suresmile' robot, it was the most frequently mentioned robot in literature [16, 27-33]. In total, 75 articles (80%) were categorized as basic research of which 55 consisted of applied research containing some type of experiment. Outside articles describing basic research, six were categorized as observational clinical research, 12 as observational epidemiological research and one as clinical experimental research (Fig. 4). The observational clinical research category consisted of three case- reports [29, 34, 35], and three case-series [28, 30, 33]. All but one case report [35] were reported in the field of orthodontics. Observational epidemiological research consisted of five case-control [16, 27, 32, 36, 37], three observational [31, 38, 39], and four comparative studies [24, 40-42]. Other than basic research study designs, were only to be found in the field of orthodontics, implantology and in the education of both patients and students.

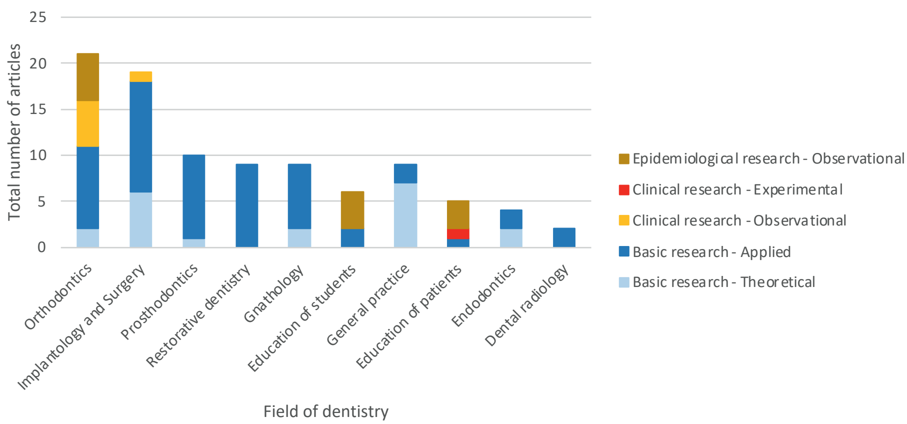


Figure 4. Total number of articles and the study design per field of dentistry.

Subject of experiments and Technological Readiness Levels (TRL)

The robots in the included articles interacted mostly with dental materials (33%) such as orthodontic wires or non-dental experimental models (29%, table 6). Interaction with humans was seen most frequently in the field of education (9 out of 11 articles) avoiding the need of physical contact of robots with their target audience. Only two articles concerning a master-slave system for the evaluation and training of the mouth opening and one case report on implantology robot Yomi had direct robot-to-patient interaction [35, 43, 44].

Table 6. Subject of interactions with the robot

Object of experiments	Number of articles (%)
Dental material ▪ orthodontic wires (18) ▪ resin teeth (6) ▪ dental impressions (6)	30 (32%)
Experimental model	27 (29%)
Humans	12 (13%)
Cadavers	11 (12%)
Other	14 (15%)

The mean level of technological readiness for all 94 studies was 4.3, median 3 (Table 7). Commercially available technology was found in the field or orthodontics (9), implantology (2), gnathology (1) and education of students (1).

Discussion

Summary of the evidence

The aim of this study was to provide dental practitioners and researchers with a comprehensive, transparent and evidence-based overview of the main characteristics of literature regarding physical robot initiatives in dentistry.

Although a rising trend following the years of robotic developments for oral and maxillofacial, craniofacial, and head and neck surgery was found by De Ceulaer et al. 2012, this trend was not seen as strongly for robots in dentistry where the number of publications has stabilized to around 6 per year [109].

Table 7. Total number of articles with their respective Technological Readiness Levels (TRL) within the different fields of dentistry.

	Discovery			Development			Demonstration		De-ployment	Number of arti-cles per field (%)
	TRL 1	TRL 2	TRL 3	TRL 4	TRL 5	TRL 6	TRL 7	TRL 8	TRL 9	
Orthodon-tics		2 [19, 43]	7 [36, 44-49]	2 [50, 51]					9 [16, 26-33]	20 (24.1%)
Implanto-logy		4 [52-55]	11 [17, 18, 22, 56-63]						1 [64]	16 (19.3%)
Prostho-dontics		1 [65]	9 [20, 66-73]							10 (12.0%)
Restorative dentistry			1 [74]	5 [75-79]	3 [4, 21, 80]					9 (10.8%)
Gnathology			5 [81-85]			2 [41, 42]				7 (8.4%)
Education of students			1 [86]			2 [37, 87]	2 [38, 39]		1 [40]	6 (7.2%)
General practice	1 [88]			4 [89-92]						5 (6.0%)
Education of patients				1 [93]		1 [23]	2 [34, 35]			4 (4.8%)
Endodon-tics		4 [94-97]								4 (4.8%)
Dental radiology			1 [24]	1 [25]						2 (2.4%)
Number of articles per TRL (%)	1 (1.2%)	11 (13.3%)	35 (42.2%)	13 (15.7%)	3 (3.6%)	5 (6.0%)	4 (4.8%)		11 (13.3%)	
Number of articles per TRL group (%)		47 (56.6%)			21 (25.3%)		4 (4.8%)		11 (13.3%)	

The present study showed 94 articles concerning a wide array of interesting robot initiatives in all fields of dentistry. The largest group of articles (80%) was classified as basic research, either purely theoretical or applied. This means that the technique has not yet been compared to any existing techniques nor tested in, for example, a series of patients. Studies categorized in the clinical or epidemiological research groups were only found in the field of orthodontics, implantology and education. Reason for this might be the relative easiness of testing on patients in most these groups, in which direct interaction of a robot with patients is unnecessary.

Where some basic research articles might describe well-designed experiments, most articles in the epidemiological and clinical research groups were, overall, very limited in their design. Only a few observational studies described the effectiveness of a workflow containing robot technology compared to the conventional workflows [16, 24, 27, 32, 36-38]. One prospective interventional study could be included [104]. No cost-effectiveness studies were found. The overall quality of literature in this review should be considered as low.

In more than half (55%) of all included studies the technology readiness of the initiatives did not exceed level three, a proof of concept. One quarter (24%) of the described technology was validated in either a laboratory setting or relevant environment and 13% of all articles described a workflow containing commercially available robot technology. It is important to realize that, especially concerning technology in the higher TRL levels, often the same robot technology is described in more than one paper of which the Suresmile system is an example as it used in eight articles. These findings are in accordance with the recent article by Grischke et al. [8] which described 49 articles, of which approximately 75% did not reach a level of technology readiness higher than level three [8].

With 76% of all first authors having a technological background and 30% of all papers lacking an author with a dental or medical background the average article has a strong technological character. The authors emphasize that, for successful development of technology in dentistry, clinicians should be more involved in the process.

According to the demographic findings (Figure 2), well over half of all included articles was from either China or Japan (East Asia). It must be noted that some included articles seem to have similar research data published either in a different journal or in another language. These studies were included in the overview nevertheless, which might cause an overestimation of results originating in East Asia. Another finding in this study was the limited number of articles (12) describing robots interacting with humans [24, 35-37, 39-44, 102, 104]. In the last 20 years, all projects avoid direct contact between a robot and human subject, except for a recent case report with implantology robot Yomi.

Limitations

This review is not free of limitations. Firstly, a relative high number (26 out of 161) of articles were excluded based on the lack of full-text articles available. This has to be taken into account when interpreting these results. Most articles were unavailable either because they concerned articles originated before 1990 or were published in local/regional or commercial journals to which the authors did not have access to. Based on the available titles and abstracts of the excluded articles, the topics and methods covered in these excluded articles were well in line with the included articles. The authors are convinced that inclusion of these articles would not have led to significant changes in the conclusions of this article.

Secondly, the determination of the level of technological readiness is made on the information supplied in the paper. In some articles information regarding the development level was limited which might lead to minor misjudgments of the TRL level.

Finally, in our search strategy an assumption was made that, if an author used the term robot technology, it was considered as such. This might lead to an underestimation since authors might describe their technology with different keywords. Despite this, the authors do not expect to have missed important articles on robot technology in dentistry by using this strategy.

Conclusion

This study provides a comprehensive overview of the characteristics of literature on robot technology in dentistry since its very beginning. While there were many interesting robot initiatives reported, the overall quality of the study design is low which was similar to the general level of technological readiness. Robots interact mostly with dental material (i.e., orthodontic wires) and interact with humans mostly when direct contact can be avoided (i.e. educational purposes). The amount of publications seems to stabilize in recent years to about six articles per year and most first authors have a technical background (84%).

References

[1] S. Chauhan, R. Coelho, S. Kalan, R. Satava, V. Patel, Evolution of Robotic Surgery: Past, Present, and Future, Robotic Urologic Surgery (2011) 3-10.

[2] J.H. Y.S. Kwoh, E.A. Jonckheere, S. Hayati, A Robot with Improved Absolute Positioning Accuracy for CT Guided Sterotactic Brain Surgery, IEEE Transactions on Biomedical Engineering 35(2) (1988) 153-160.

[3] X. Sun, Y. Yoon, J. Li, F.D. McKenzie, Automated image-guided surgery for common and complex dental implants, J Med Eng Technol 38(5) (2014) 251-9.

[4] F. Yuan, P. Lyu, A preliminary study on a tooth preparation robot, Advances in Applied Ceramics (2019) 1-6.

[5] S. Abe, N. Noguchi, Y. Matsuka, C. Shinohara, T. Kimura, K. Oka, K. Okura, O.M.M. Rodis, F. Kawano, Educational effects using a robot patient simulation system for development of clinical attitude, European Journal of Dental Education 22(3) (2018) e327-e336.

[6] Wisdom Tooth Extraction done by a Robot on a human patient in Tokyo. https://www.juniordentist.com/wisdom-tooth-extraction-done-by-a-robot-on-a-human-patient-in-tokyo.html.

[7] J.G. Jiang, Y.D. Zhang, C.G. Wei, T.H. He, Y. Liu, A Review on Robot in Prosthodontics and Orthodontics, Advances in Mechanical Engineering 7(1) (2015).

[8] J. Grischke, L. Johannsmeier, L. Eich, L. Griga, S. Haddadin, Dentronics: Towards robotics and artificial intelligence in dentistry, Dental Materials (2020) 14.

[9] Y. Wu, F. Wang, S. Fan, J.K. Chow, Robotics in Dental Implantology, Oral Maxillofac Surg Clin North Am 31(3) (2019) 513-518.

[10] G.C. Peters MDJ, McInerney P, Munn Z, Tricco AC, Khalil, H., Chapter 11: Scoping Reviews (2020 version), in: M.Z. Aromataris E (Ed.), JBI Manual for Evidence Synthesis2020.

[11] A.C. Tricco, E. Lillie, W. Zarin, K.K. O'Brien, H. Colquhoun, D. Levac, D. Moher, M.D.J. Peters, T. Horsley, L. Weeks, S. Hempel, E.A. Akl, C. Chang, J. McGowan, L. Stewart, L. Hartling, A. Aldcroft, M.G. Wilson, C. Garritty, S. Lewin, C.M. Godfrey, M.T. Macdonald, E.V. Langlois, K. Soares-Weiser, J. Moriarty, T. Clifford, O. Tuncalp, S.E. Straus, PRISMA Extension for Scoping Reviews (PRISMA-ScR): Checklist and Explanation, Ann Intern Med 169(7) (2018) 467-473.

[12] M. Ouzzani , H. Hammady, Z. Fedorowicz, A. Elmagarmid, Rayyan—a web and mobile app for systematic reviews, Systematic Reviews 5(1) (2016) 210.

[13] B. Rohrig, J.B. du Prel, D. Wachtlin, M. Blettner, Types of study in medical research: part 3 of a series on evaluation of scientific publications, Dtsch Arztebl Int 106(15) (2009) 262-8.

[14] B. Röhrig, J.-B.d. Prel, D. Wachtlin, M. Blettner, Types of Study in Medical Research. Part 3 of a Series on Evaluation of Scientific Publications, Deutsches Ärzteblatt International 106(5) (2009) 262-268.

[15] M. Héder, From NASA to EU: the evolution of the TRL scale in Public Sector Innovation, The Innovation Journal: The Public Sector Innovation Journal 22(2)(3) (2017).

[16] R.C. Sachdeva, S.L. Aranha, M.E. Egan, H.T. Gross, N.S. Sachdeva, G.F. Currier, O. Kadioglu, Treatment time: SureSmile vs conventional, Orthodontics : the art and practice of dentofacial enhancement 13(1) (2012) 72-85.

[17] A.A. Syed, A.M. Soomro, A.N. Khizar, X.-g. Duan, H. Qiang, F. Manzoor, Tele-Robotic Assisted Dental Implant Surgery with Virtual force Feedback, TELKOMNIKA Indonesian Journal of Electrical Engineering 12 (2014).

[18] K. Yu, K. Ohnishi, H. Kawana, S. Usuda, Modulated Potential Field Using 5 DoF Implant Assist Robot for Position and Angle Adjustment, IECON 2015 - 41st Annual Conference of the IEEE Industrial Electronics Society, Yokohama, , 2015, pp. 002166-002171.

[19] W. Zhang, Research of 3D Virtual Design and Automated Bending of Oral Orthodontic Archwire, International Journal of Advancements in Computing Technology(IJACT) 5(8) (2013) 741-749.

[20] P. Lu, Y. Wang, G. Li, [Development of a system for robot aided teeth alignment of complete denture], Zhonghua Kou Qiang Yi Xue Za Zhi 36(2) (2001) 139-142.

[21] F.S. Yuan, Y. Wang, Y.P. Zhang, Y.C. Sun, D.X. Wang, P.J. Lyu, [Study on the appropriate parameters of automatic full crown tooth preparation for dental tooth preparation robot], Zhonghua Kou Qiang Yi Xue Za Zhi 52(5) (2017) 270-273.

[22] F.S. Yuan, J.Q. Zheng, Y.P. Zhang, Y. Wang, Y.C. Sun, P.J. Lyu, [Preliminary study on the automatic preparation of dental implant socket controlled by micro-robot], Chin J Stomatol 53(8) (2018) 524-528.

[23] J.C. Jiang, H. Ma, X. Zhang, Y. Liu, Y., Forming Planning Method and Experimentation of Personalized Orthodontic Archwires, Zhongguo Jixie Gongcheng/China Mechanical Engineering (11) (2020) 1323-1330 and 1336.

[24] M. Yasemin, Y. Kasimoğlu, S. Kocaaydin, E. Karsli, E.B.T. Ince, G. Ince, Management of dental anxiety in children using robots, Institute of Electrical and Electronics Engineers Inc.2016.

[25] G.C. Burdea, Stanley M. Dunn, C.H. Immendorf, M. Mallik, Real-time sensing of tooth position for dental digital subtraction radiography, IEEE Transactions on Biomedical Engineering 38(4) (1991) 366-378.

[26] G.C. Burdea, S.M. Dunn, G. Levy, Evaluation of robot-based registration for subtraction radiography, Medical image analysis 3(3) (1999) 265-274.

[27] E.W. Amm, Clinical outcomes for patients finished with the SureSmile ™ method compared with conventional fixed orthodontic therapy, Angle Orthodontist 81(5) (2011) 926.

[28] B.E. Larson, C.J. Vaubel, G. T., Effectiveness of computer-assisted orthodontic treatment technology to achieve predicted outcomes, Angle Orthodontist 83(4) (2013) 557-562.

[29] R. Moles, The SureSmile system in orthodontic practice, Journal of Clinical Orthodontics 43(3) (2009) 161 - 174: quiz 184.

[30] R. Muller-Hartwich, P.G. Jost-Brinkmann, K. Schubert, Precision of implementing virtual setups for orthodontic treatment using CAD/CAM-fabricated custom archwires, Journal of Orofacial Orthopedics 77(1) (2016) 1-8.

[31] R.C. Sachdeva, SureSmile technology in a patient--centered orthodontic practice, Journal of Clinical Orthodontics 35(4) (2001) 245-253.

[32] A.K. Saxe, L.J. Louie, J. Mah, Efficiency and effectiveness of SureSmile, World journal of orthodontics 11(1) (2010) 16-22.

[33] T.L. Smith, B. Kusnoto, M.T. Galang-Boquiren, E. BeGole, A. Obrez, Mesiodistal tip and faciolingual torque outcomes in computer-driven orthodontic appliances, Journal of the World Federation of Orthodontists 4(2) (2015) 63-70.

[34] H. Kheirollahi Bisheh, S. Rahmati, F. Abesi, A novel methodology in design and fabrication of lingual orthodontic appliance based on rapid prototyping technologies, Innovative Developments in Design and Manufacturing - Advanced Research in Virtual and Rapid Prototyping (2010) 711-718.

[35] P.S. Mozer, Accuracy and Deviation Analysis of Static and Robotic Guided Implant Surgery: A Case Study, Int J Oral Maxillofac Implants 35(5) (2020) e86-e90.

[36] J.A. Rodrigues, P.A. dos Santos, P.P. Garcia, S.A. Corona, L.C. Loffredo, Evaluation of motivation methods used to obtain appropriate oral hygiene levels in schoolchildren, International journal of dental hygiene 1(4) (2003) 227-232.

[37] J.A. Rodrigues, P.A. dos Santos, W. Baseggio, S.A. Corona, R.G. Palma-Dibb, P.P. Garcia, Oral hygiene indirect instruction and periodic reinforcements: effects on index plaque in schoolchildren, Journal of Clinical Pediatric Dentistry 34(1) (2009) 31-34.

[38] A. Gilbert, An in-office wire-bending robot for lingual orthodontics, Journal of Clinical Orthodontics 45(4) (2011) 230-4;quiz 236.

[39] H. Takanobu, A. Omata, F. Takahashi, K. Yokota, K. Suzuki, H. Miura, M. Madokoro, Y. Miyazaki, K. Maki, Dental patient robot as a mechanical human simulator, Proceedings of International Conference on Mechatronics, , 2007, pp. 1-6.

[40] T. Tanzawa, K. Futaki, C. Tani, T. Hasegawa, M. Yamamoto, T. Miyazaki, K. Maki, Introduction of a robot patient into dental education, European Journal of Dental Education 16(1) (2012) e195-e199.

[41] T. Tanzawa, K. Futaki, H. Kurabayashi, K. Goto, Y. Yoshihama, T. Hasegawa, M. Yamamoto, M. Inoue, T. Miyazaki, K. Maki, Medical emergency education using a robot patient in a dental setting, European Journal of Dental Education 17(1) (2013) e114-e119.

[42] S. Abe, N. Noguchi, Y. Matsuka, C. Shinohara, T. Kimura, K. Oka, K. Okura, O. Rodis, F. Kawano, Educational effects using a robot patient simulation system for development of clinical attitude, European Journal of Dental Education 22(3) (2018) e327-e336.

[43] H. Takanobu, T. Yajima, A. Takanishi, K. Ohtsuki, M. Ohnishi, Three degrees of freedom mouth opening and closing training robot, IEEE SMC'99 Conference Proceedings. 1999 IEEE International Conference on Systems, Man, and Cybernetics (Cat. No.99CH37028) 2 (1999) 448 - 453 vol.2.

[44] H. Takanobu, M. Nakazawa, A. Takanishi, K. Ohtsuki, M. Ohnishi, Clinical training with mouth opening and closing training robot WY-3, Proceedings 1999 IEEE/RSJ International Conference on Intelligent Robots and

Systems. Human and Environment Friendly Robots with High Intelligence and Emotional Quotients (Cat. No.99CH36289) 3 (1999) 1604-1609.

[45] Y. Zhang, X. Jia, J. Jiang, Y. Liu, Y. Wang, Simulation and analysis of orthodontic archwire bending robot, International Journal of Smart Home 10(8) (2016) 263-270.

[46] F. Sassani, A. Elmajian, S. Roberts, Computer-assisted fabrication of orthodontic appliances: considering the possibilities, Journal of the American Dental Association (1939) 126(9) (1995) 1296-1300.

[47] Y. Zhang, J. Jiang, Analysis and experimentation of the robotic system for archwire bending, Applied Mechanics and Materials 121-126 (2012) 3805-3809.

[48] J.G. Jiang, Y.D. Zhang, M.L. Jin, C.G. Wei, Bending process analysis and structure design of orthodontic archwire bending robot, International Journal of Smart Home 7(5) (2013) 345-352.

[49] J.G. Jiang, P. Bo, Z. Yong De, Y. Xiao Yang, L. Yi, S. Bei Xin, Control system of orthodontic archwire bending robot based on LabVIEW and ATmega2560, International Journal of Control and Automation 9(9) (2016) 189-198.

[50] J.G. Jiang, Y.S. Han, Y.D. Zhang, Y.J. Liu, Z. Wang, Y. Liu, Springback Mechanism Analysis and Experiments on Robotic Bending of Rectangular Orthodontic Archwire, Chinese Journal of Mechanical Engineering (English Edition) 30(6) (2017) 1406-1415.

[51] J. Jiang, X. Ma, Y. Zhang, B. Huo, Y. Liu, Study on Three-Dimensional Digital Expression and Robot Bending Method of Orthodontic Archwire, Applied bionics and biomechanics 2018 (2018) 2176478.

[52] H. Deng, Z. Xia, S. Weng, Y. Gan, J. Xiong, Y. Ou, J. Zhang, Motion planning and control of a robotic system for orthodontic archwire bending, 2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) 2015 (2015).

[53] Z. Xia, H. Deng, S. Weng, Y. Gan, J. Xiong, H. Wang, Development of a robotic system for orthodontic archwire bending, 2016 IEEE International Conference on Robotics and Automation (ICRA) 2016 (2016) 730-735.

[54] R. Chaumont, E. Vasselin, D. Lefebvre, Forward kinematics and geometric control of a medical robot;Application to dental implantation, Proceedings of the Fourth International Conference on Informatics in Control, Automation and Robotics 2 (2007) 110-115.

[55] G. Kim, H. Seo, S. Im, D. Kang, S. Jeong, A study on simulator of human-robot cooperative manipulator for dental implant surgery, IEEE International Symposium on Industrial Electronics (ISIE 2009) (2009) 2159-2164.

[56] S. Yilmaz, E.I. Konukseven, H. Gurocak, Optimum design of 6R passive haptic robotic arm for implant surgery, Lecture Notes in Computer Science LNCS 6191 (2010) 105-110.

[57] Y.V.D. Rao, A.M. Parimi, D.S.P. Rahul, D. Patel, Y.V. Nitin Mythreya, Robotics in Dental Implantation, Materials Today: Proceedings 4 (2017) 9327-9332.

[58] A.M. Meleshnikov, A.A. Vorotnikov, D.D. Klimov, Y.V. Poduraev, Prototype Probe Determining Waveguide–Gum Contact for a Robot Surgical System, Russian Engineering Research 40(1) (2020) 86-88.

[59] J. Dutreuil, F. Goulette, C. Laurgeau, J.C. Zoreda, S. Lundgren, Computer assisted dental Implantology: A new method and a clinical validation, (2001) 384-391.

[60] T. Fortin, G. Champleboux, S. Bianchi, H. Buatois, J.-L. Coudert, Precision of transfer of preoperative planning for oral implants based on cone-beam CT-scan images through a robotic drilling machine: An in vitro study, Clinical oral implants research 13(6) (2001) 651–656.

[61] X. Sun, F.D. McKenzie, S. Bawab, J. Li, Y. Yoon, J.K. Huang, Automated dental implantation using image-guided robotics: registration results, International journal of computer assisted radiology and surgery 6(5) (2011) 627-634.

[62] T. Chiarelli, F. Franchini, A. Lamma, E. Lamma, T. Sansoni, From implant planning to surgical execution: An integrated approach for surgery in oral implantology, International Journal of Medical Robotics and Computer Assisted Surgery.

[63] Y. Kasahara, H. Kawana, S. Usuda, K. Ohnishi, Telerobotic-assisted bone-drilling system using bilateral control with feed operation scaling and cutting force scaling, The International Journal of Medical Robotics and Computer Assisted Surgery 8(2) (2012) 221-229.

[64] X. Sun, Y. Yoon, J. Li, F.D. McKenzie, Automated image-guided surgery for common and complex dental implants, Journal of medical engineering & technology 38(5) (2014) 251-259.

[65] K. Yu, S. Uozumi, K. Ohnishi, S. Usuda, H. Kawana, T. Nakagawa, Stereo vision based robot navigation system using modulated potential field for implant surgery, 2015 IEEE International Conference on Industrial Technology (ICIT) 2015 (2015) 493-498.

[66] S. Yeotikar, A.M. Parimi, Y.V. Daseswar Rao, Automation of end effector guidance of robotic arm for dental implantation using computer vision, 2016 IEEE Distributed Computing, VLSI, Electrical Circuits and Robotics (DISCOVER) (2016) 84-89.

[67] T.C.T.d.G. van Riet, W. M.; van Antwerpen, R.; van Frankenhuyzen, J.; de Lange, J.; Kober, J., Robot Technology in Analyzing Tooth Removal - a Proof of Concept, Annu Int Conf IEEE Eng Med Biol Soc (2020) 4721-4727.

[68] A. Eliasson, A. Ortorp, The accuracy of an implant impression technique using digitally coded healing abutments, Clinical Implant Dentistry and Related Research 14 (2012) e30-e38.

[69] Y. Zhang, Z. Zhao, J. Lu, K. Tso Shiu, Robotic manufacturing of complete dentures, Proceedings 2001 ICRA. IEEE International Conference on Robotics and Automation (Cat. No.01CH37164) 3 (2001) 2261-2266.

[70] Y. Zhang, Z. Zhao, R. Song, J. Lu, P. Lu, Y. Wang, Tooth arrangement for the manufacture of a complete denture using a robot, Industrial Robot: An International Journal 28(5) (2001) 420-425.

[71] Y. Zhang, Z. Zhao, P. Lu, Y. Wang, R. Song, J. Lu, Robotic system approach for complete denture manufacturing, IEEE/ASME Transactions on Mechatronics 7(3) (2002) 392-396.

[72] Y. Zhang, J. Jiang, P. Lv, Y. Wang, Coordinated control and experimentation of the dental arch generator of the tooth-arrangement robot, The International Journal of Medical Robotics and Computer Assisted Surgery 6(4) (2010) 473-482.

[73] Y. Zhang, J. Jiang, T. Liang, W. Hu, Kinematics modeling and experimentation of the multi-manipulator tooth-arrangement robot for full denture manufacturing, Journal of Medical Systems 35(6) (2011) 1421-1429.

[74] Y. Zhang, J. Jiang, P. Lv, Y. Wang, Study on the multi-manipulator tooth-arrangement robot for complete denture manufacturing, Industrial Robot 38(1) (2011) 20-26.

[75] J. Jiang, Y. Zhang, W. Zhang, Collaborative simulation and experimentation on the dental arch generator of a multi-manipulator tooth-arrangement robot, International Journal of Advanced Robotic Systems 9 (2012).

[76] J. Jiang, Y. Zhang, Motion planning and synchronized control of the dental arch generator of the tooth-arrangement robot, The International Journal of Medical Robotics and Computer Assisted Surgery 9(1) (2013) 94-102.

[77] L. Ren, J. Yang, Y. Tan, J. Hu, D. Liu, J. Zhu, An intelligent dental robot, Advanced Robotics 32(12) (2018) 659-669.

[78] L. Wang, D. Wang, L. Ma, Y. Zhang, F. Yuan, Y. Sun, P. Lv, Preliminary experiments of a miniature robotic system for tooth ablation using ultra-short pulsed lasers, 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (2013) 2566-2571.

[79] L. Ma, Y. Zhang, D. Wang, P. Lv, Y. Sun, H. Wang, Trajectory tracking control of a miniature laser manipulation robotic end-effector for dental preparation, 2013 IEEE International Conference on Robotics and Biomimetics (ROBIO) (2013) 468-473.

[80] L. Wang, D. Wang, Y. Zhang, L. Ma, Y. Sun, P. Lv, An automatic robotic system for three-dimensional tooth crown preparation using a picosecond laser, Lasers in surgery and medicine 46(7) (2014) 573-581.

[81] D. Wang, L. Wang, Y. Zhang, P. Lv, Y. Sun, J. Xiao, Preliminary study on a miniature laser manipulation robotic device for tooth crown preparation, The International Journal of Medical Roboitcs and Computer Assisted Surgery 10(4) (2014) 482-494.

[82] T. Otani, A.J. Raigrodski, L. Mancl, I. Kanuma, J. Rosen, In vitro evaluation of accuracy and precision of automated robotic tooth preparation system for porcelain laminate veneers, Journal of Prosthetic Dentistry 114(2) (2015) 229-235.

[83] F. Yuan, J. Zheng, Y. Sun, Y. Wang, P. Lyu, Regulation and Measurement of the Heat Generated by Automatic Tooth Preparation in a Confined Space, Photomed Laser Surg 35(6) (2017) 332-337.

[84] F. Yuan, Y. Wang, Y. Zhang, Y. Sun, D. Wang, P. Lyu, An automatic tooth preparation technique: A preliminary study, Scientific Reports 6 (2016) 25281.

[85] H. Takanobu, A. Takanishi, D. Ozawa, K. Ohtsuki, M. Ohnishi, A. Okino, Integrated dental robot system for mouth opening and closing training, Proceedings 2002 IEEE International Conference on Robotics and Automation (Cat. No.02CH37292) 2 (2002) 1428-1433.

[86] H.U. Takanobu, A. Takanishi, Dental robotics and human model, First International IEEE EMBS Conference on Neural Engineering, 2003. Conference Proceedings. (2003) 671-674.

[87] K. Nishigawa, T. Satsuma, S. Shigemoto, E. Bando, M. Nakano, O. Ishida, Development of a novel articulator that reproduced jaw movement with six-degree-of-freedom, Medical engineering & physics 29(5) (2007) 615-619.

[88] T. Araie, T. Ikeda, U. Nishizawa, A. Kakimoto, S. Toyama, M. Ragulskis, Study of the chewing assistance mechanism in powered robotic dentures, Vibroengineering PROCEDIA 19 (2018) 163-168.

[89] D.A. Kizghin, C.A. Nelson, Optimal design of a parallel robot for dental articulation, 2019 Design of Medical Devices Conference, 2019.

[90] H.T. Takanobu, Takashi; Takanishi, Atsuo; Kato, Ichiro;, Adaptive masticatory jaw motion using jaw position and biting force information, Proceedings of the 1994 IEEE International Conference on Multisensor Fusion and Integration for Intelligent Systems (1994) 360-365.

[91] M. Carossa, D. Cavagnetto, P. Ceruti, F. Mussano, S. Carossa, Individual mandibular movement registration and reproduction using an optoeletronic jaw movement analyzer and a dedicated robot: a dental technique, BMC Oral Health 20(1) (2020) 271.

[92] L. Chen, The application of robots and eye tracking devices in a general dentist's clinic, 2013 IEEE Third International Conference on Consumer Electronics - Berlin (ICCE-Berlin) (2013) 5-7.

[93] I.H. Bula, E. Stapleton, L. Kopacek, P. Topalov, A., Cost oriented autonomous mobile service robot, IFAC PapersOnLine (2019) 91-94.

[94] J.L. Ortiz Simon, A.M. Martinez, D.L. Espinoza, J.G. Romero Velazquez, Mechatronic assistant system for dental drill handling, International Journal of Medical Robotics and Computer Assisted Surgery 7(1) (2011) 22-26.

[95] J. Li, Z. Shen, W.Y.T. Xu, W.Y.H. Lam, R.T.C. Hsung, E.H.N. Pow, K. Kosuge, Z. Wang, A Compact Dental Robotic System Using Soft Bracing Technique, IEEE Robotics and Automation Letters 4(2) (2019) 1271-1278.

[96] J. Li, W.Y.H. Lam, R.T. Chiu Hsung, E.H.N. Pow, Z. Wang, A Customizable, Compact Robotic Manipulator for Assisting Multiple Dental Procedures, 2018 3rd International Conference on Advanced Robotics and Mechatronics (ICARM) (2018) 720-725.

[97] J. Li, W.Y.H. Lam, R.T.C. Hsung, E.H.N. Pow, C. Wu, Z. Wang, Control and motion scaling of a compact cable-driven dental robotic manipulator, 2019 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM) (2019) 1002-1007.

[98] T.M. Iijima, T. Shimono, T. Ohnishi, K. Usuda, S. Kawana, H., Development of a Multi DOF Haptic Robot for Dentistry and Oral Surgery, Proceedings of the 2020 IEEE/SICE (2020) 52-57.

[99] J. Li, J. Lam, M. Liu, Z. Wang, Compliant Control and Compensation for A Compact Cable-Driven Robotic Manipulator, IEEE Robotics and Automation Letters 5(4) (2020) 5417-5424.

[100] Y.Z. Tao, T. Xu, W. Tsang, H. Y. Li, J. Wang, Z., A Compact Asymmetrical Manipulator for Robotic Dentistry, Proceedings of the 9th IEEE International conference on CYBER technology in automation, Control and Intelligent Systems (2019) 164-168.

[101] K. Yu, T. Matsunaga, H. Kawana, S. Usuda, K. Ohnishi, Frequency-based analysis of the relationship between cutting force and CT number for an implant-surgery-teaching robot, IEEJ Journal of Industry Applications 6(1) (2017) 66-72.

[102] H. Takanobu, A. Takanishi, A. Okino, M. Madokoro, Y. Miyazaki, K. Maki, Dental Patient Robot, Proceedings of the 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems (2006) 1273-1278.

[103] M. Ahire, N. Dani, R. Muttha, Dental health education through the brushing ROBOTUTOR: A new learning experience, Journal of Indian Society of Periodontology 16(3) (2012) 417-420.

[104] Y. Kasimoglu, S. Kocaaydin, E. Karsli, M. Esen, I. Bektas, G. Ince, E.B. Tuna, Robotic approach to the reduction of dental anxiety in children, Acta Odontol Scand 78(6) (2020) 474-480.

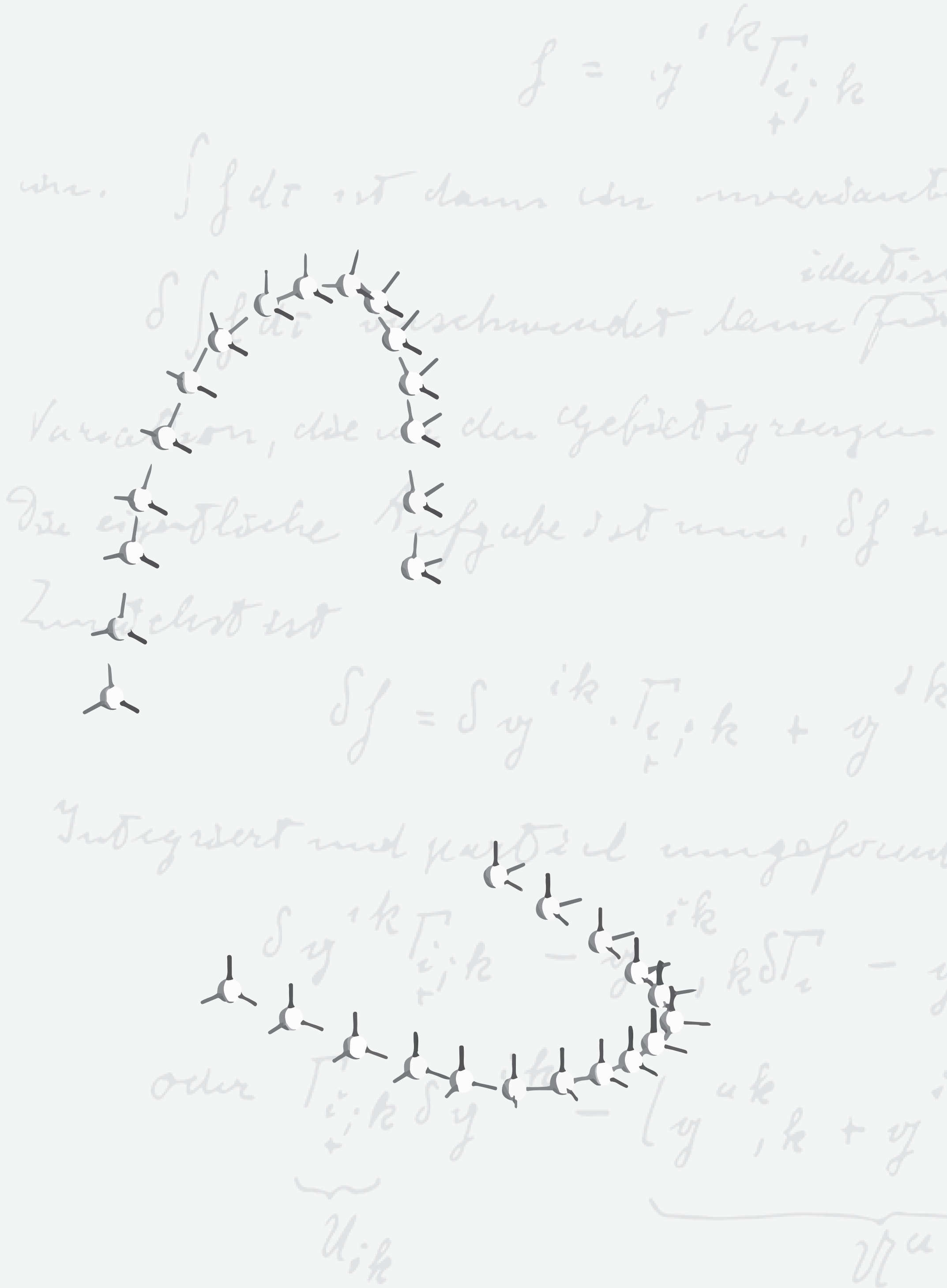
[105] J. Dong, H. Everett, The development of endodontic micro robot, 2007 ASME International Mechanical Engineering Congress and Exposition 2 (2007) 201-204.

[106] J. Dong, S.Y. Hong, Design of Z axis actuator & quick tool change assembly for an endodontic micro robot, ASME 2010 International Mechanical Engineering Congress and Exposition 10 (2010) 507-511.

[107] T. Gulrez, A.K. Shahid, U. Sana, N.G. Chaudhary, Visual guided robotic endodontic therapeutic system, International Conference on Information and Emerging Technologies, IEEE, 2010, pp. 1-6.

[108] C.A. Nelson, S.G. Hossain, A. Al-Okaily, J. Ong, A novel vending machine for supplying root canal tools during surgery, Journal of medical engineering & technology 36(2) (2012) 102-116.

[109] J. De Ceulaer, C. De Clercq, G.R. Swennen, Robotic surgery in oral and maxillofacial, craniofacial and head and neck surgery: a systematic review of the literature, Int J Oral Maxillofac Surg 41(11) (2012) 1311-24.



Chapter 3

Robot Technology in dentistry, an overview of initiatives

This chapter is based on the following publication:
Robot technology in dentistry, part two of a systematic review: an overview of initiatives
T.C.T. van Riet, K.T.H. Chin Jen Sem, J.T.F. Ho, R. Spijker, J. Kober and J. de Lange

Published in: Dental Materials, 2021

Abstract

Objectives:
To provide dental practitioners and researchers with a comprehensive and transparent evidence-based overview of physical robot initiatives in all fields of dentistry.

Data:
Articles published since 1985 concerning primary data on physical robot technology in dentistry were selected. Characteristics of the papers were extracted such as the respective field of dentistry, year of publication as well as a description of its usage.

Sources:
Bibliographic databases PubMed, Embase, and Scopus were searched. A hand search through reference lists of all included articles was performed.

Study selection:
The search timeline was between January 1985 and October 2020. All types of scientific literature in all languages were included concerning fields of dentistry ranging from student training to implantology. Robot technology solely for the purpose of research and maxillofacial surgery were excluded. In total, 94 articles were included in this systematic review.

Conclusions:
This study provides a systematic overview of initiatives using robot technology in dentistry since its very beginning. While there were many interesting robot initiatives reported, the overall quality of the literature, in terms of clinical validation, is low. Scientific evidence regarding the benefits, results and cost-efficiency of commercially available robotic solutions in dentistry is lacking. The rise in availability of open source control systems, compliant robot systems and the design of dentistry-specific robot technology might facilitate the process of technological development in the near future. The authors are confident that robotics will provide useful solutions in the future but, strongly, encourage an evidence-based approach when adapting to new (robot) technology.

Introduction

In the field of medical surgery, different types of robotic systems are already widely in use. The "Da Vinci" robot (Intuitive Surgery, Inc., Sunnyvale, CA, USA) is one of the most well-known examples. According to data provided by Intuitive in 2019, over 5500 systems are in clinical use worldwide and over 7 million surgical cases have been performed [1]. The robot is a master-slave system, in which hand movements of a surgeon are transmitted to the robot and reproduced on a smaller scale, usually in difficult to reach locations. Whilst the Da Vinci robot is most commonly used in the field of Urology and Gynecology, it is also used by Head and Neck surgeons in, for example, transoral robotic surgery and neck dissections [2, 3].

In dentistry one of the most well-known robots is the archwire bending robot of the Suresmile orthodontic system (OraMetrix, Inc., Richardson, TX, USA), first described in 2001 [4]. Since then, robot technology has been described in many other fields of dentistry such as in restorative dentistry and education [5-7]. Some of these systems have become commercially available for use in the general dentist practice, such as the implantology robot 'Yomi' (Neocis, Miami, Florida, USA).

In part one of this systematic review, it was shown that over 80% of the first authors of articles concerning robot technology in dentistry have a technological background. Therefore, it might be difficult for the general dentist to keep track of these technological developments and their scientific standing. Robot technology itself is a rapidly developing scientific field. With a recent shift towards the development of more compliant robots, which facilitates human-robot interaction, it might be expected that new initiatives of robot technology in dentistry will be introduced.

For robot technology in oral and maxillofacial surgery an extensive systematic review of literature exists [3] but a systematic overview of initiatives in dentistry is, to the authors best of knowledge, missing.

After discussing the characteristics of literature and technological readiness in part one of this systematic review, the primary aim of this second part was to construct a comprehensive overview of the usage of different robot technology initiatives in all fields of dentistry.

Materials and methods

Information sources and search strategy

This review followed both Preferred Reporting Items for Systematic Reviews and Meta-Analyses and Joanna Briggs Institute guidelines to structure the report [8, 9]. A systematic search of the electronic databases Medline (through PubMed), Embase and Scopus was performed on 30 October 2020. In addition, the reference lists of included full text and excluded reviews were hand searched for additional articles. Search strategies were defined together with a medical librarian (RS). The search strategy for all three databases can be found in Tables 1-3.

Table 1. PubMed search strategy. Number of articles found = 314

	PubMed search terms
#1	Robotic Surgical Procedures[MeSH] OR robot*[tiab] OR yomi[tiab] OR suresmile[tiab]
#2	Dentistry[MeSH] OR Education, Dental[MeSH] OR Health Education, Dental[MeSH] OR Students, Dental[MeSH] OR Dental Materials[MeSH]) OR (dentistry[tiab] OR dental [tiab] OR denture[tiab] OR dentist[tiab] OR dentine[tiab] OR enamel[tiab] OR tooth[tiab] OR teeth[tiab] OR molar* [tiab] OR gingiva[tiab] OR periodontal[tiab] OR Prosthodontic[tiab] OR Periodontic[tiab] OR Endodontic [tiab] OR Implantology[tiab] OR Orthodontic[tiab] OR Dentistry/surgery[MeSH]
#3	#1 AND #2

Table 2. Scopus search strategy. Number of articles found = 568

	Scopus search terms
#1	(TITLE-ABS-KEY (robot* OR yomi OR suresmile))
#2	(TITLE-ABS-KEY (dentistry OR dental OR denture OR dentist OR dentine OR enamel OR molar* OR gingiva OR periodontal OR prosthodontic OR periodontic OR endodontic OR implantology OR orthodontic))
#3	#1 AND #2

Table 3. Embase search strategy. Number of articles found = 247

	Embase search terms
#1	((exp robot assisted surgery/) or (robot* or yomi or suresmile).ti,ab,KW)
#2	((exp "Dentistry"/ or dental education/ or dental health education/ or dental student/ or exp dental material/) OR (dentistry OR dental OR denture OR dentist OR dentine OR enamel OR tooth OR teeth OR molar* OR gingiva OR periodontal OR Prosthodontic OR Periodontic OR Endodontic OR Implantology OR Orthodontic).ti,ab,kw)
#3	#1 AND #2

Eligibility criteria

To cope with the difficult definition of a robot, when authors used the term robot for the described technology, it was considered as such. The search timeline started in 1985 and no language restrictions were applied. Articles not containing any primary data such as reviews were excluded as well as patents, presentation slides, posters and video content. Robots used for research purposes only or articles concerning oral and maxillofacial surgery were excluded.

Study selection

For title and abstract screening, articles were imported into a web application for systematic reviews (Rayyan, Qatar Computing Research Institute, Doha, Qatar) [10]. Duplicates were removed using an in-house application before uploading to Rayyan in which two independent reviewers screened titles and abstracts for relevance (TR, KC). Results were compared afterwards and in case of any discrepancies, a discussion was held to reach an agreement. A third reviewer was consulted to act as a referee (JH), when required.

Data charting process and data items

Full texts of all included articles were collected and a customized data extraction form was used for data extraction in duplicate by two authors (TR, KC). Relevant data items collected were the corresponding field of dentistry as well as a summary of the performed study, the robot usage and its technological readiness level (TRL). For data registration and analysis, Microsoft's Office Excel (version 2019, Microsoft Corporation, USA) was used.

Results

Study selection

The search in all three databases combined resulted in 1253 articles of which 363 duplicates were excluded. During screening of title and abstracts another 751 articles were excluded because they did not match the inclusion criteria for this review. In total 137 articles were deemed eligible for inclusion but 71 articles had to be removed with reasons as summarized in figure 1. In total 94 articles were included in this systematic review for qualitative synthesis (Fig. 1).

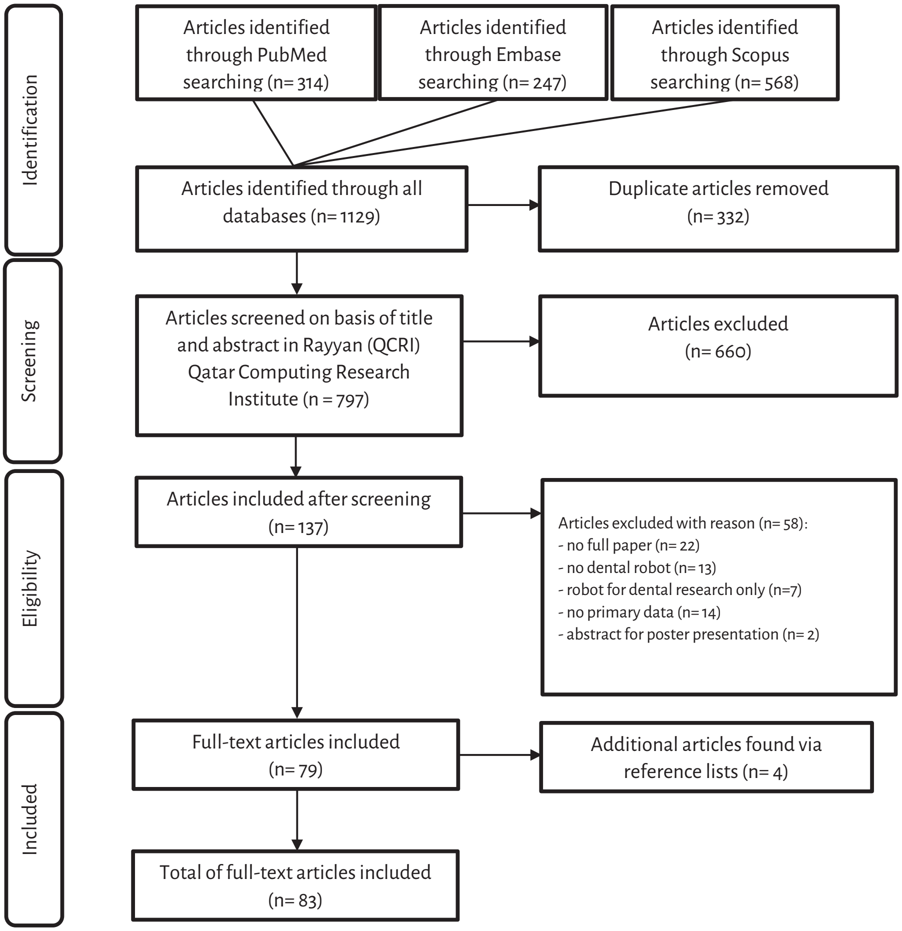


Figure 1 Diagram of the search process and results

Results per field of dentistry

Orthodontics

With 21 included articles, orthodontics has a higher number of articles concerning robot technology compared to any other fields in this study. It also contained most articles describing commercially available technology (Fig. 2). The oldest included study in this field is the only one not concerning the bending process of orthodontic wires. It described the automatic deposit and cure of the acrylic part of a maxillary orthodontic appliance [11]. With eight articles 'Suresmile' (OraMetrix, Richardson, Tex) was the most frequently described robot in this review. Suresmile is a computer-aided design and computer-aided manufacturing system for customized archwire bending. Treatment outcomes and treatment time have been compared to the conventional method (manual bending) in observational epidemiological studies [12-14]. Other articles evaluated the accuracy and effectiveness of tooth positioning [15-17]. In two articles, 'Suresmile' users described their opinions of its use in their practices [18, 19]. No prospective interventional studies were found. Other bending robot initiatives outside Suresmile were mostly originating from Eastern Asia and focused on (improving) the design of archwire bending robots. Clinical studies have, to the authors best of knowledge, not yet been performed [20-29]. One group of researchers developed an orthodontic archwire bending robot based on Robot Operating System (ROS), an open-source control system [20, 28]. Next to the more traditional buccal orthodontic appliances, also the technique of automated manufacturing of lingual appliances has been described in detail together with clinical results of five cases [30]. Another initiative on lingual archwire bending was described called Lingual Archwire Manufacturing and Design Aid (LAMDA). A limited experiment was conducted to compare manually bent wires with this technique [31].

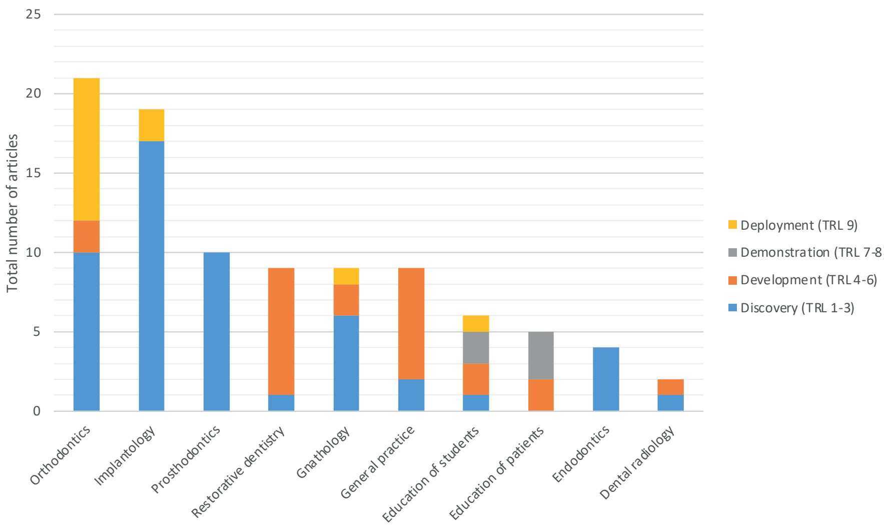


Figure 2. Included articles per field of dentistry including the respective technological readiness levels (TRL) ranging from lowest (Discovery, TRL 1-3) to commercially available systems (Deployment, TRL 9).

Implantology and surgery

Seventeen articles addressed the field of implantology and two the field of dental surgery, making it the second largest group of articles concerning robot technology in dentistry. Except for two articles, describing a commercially available robot, all included articles were categorized into the basic research group [32, 33]. In contrast to other fields, the application of robot technology in implantology is heterogeneous. A few studies were categorized as being theoretical research only and proposed designs for different parts of an implantology robot [34-37]. Some papers propose different methods of how robot technology can be used for transferring a treatment plan to the patient. One method is an indirect technique where the robot assists in creating drill guides for a surgeon to use during implant treatment [32, 38-40], whereas other initiatives let the robot guide the drill directly towards the proposed location. The latter has been performed by using a separate coordinate measuring machine attached to both robot and jaw [41, 42] or directly with the aid of computer vision [43-45]. Two articles focused on tele-robotic systems where haptic feedback was studied during implant drilling [46, 47]. The development of an ultra-short pulse laser robot-controlled system for preparation of implant sites [48] was described by the same research group involved in using the robot and laser combination for restorative dentistry purposes [6]. Despite being commercially available, only one case report was included describing the use of Yomi [33]. Other reviews often mention the system, but refer to other reviews or grey literature when discussing its capabilities [49-51].

Most articles concerning implantology and dental surgery are aimed towards hard tissue surgery. A recent paper by a Russian research group developed a prototype of a probe determining soft tissue contact, necessary for (diode) laser surgery to the soft tissue [52]. Another study described a robot as part of a measurement setup to enable an in depth analysis of movements during tooth removal procedures. Data is used to model the procedure for both scientific as well as educational purposes [53].

Prosthodontics

All ten articles concerning prosthodontics originated in China. No article had a technology readiness level exceeding the level of proof of concept (level 3) and all were categorized into basic research. Nine articles described the developmental process of an automatic tooth arrangement robot for dentures by researchers from the same research institutes in Eastern China. Four of these originated between 2000 and 2002 [54-57], five between 2010 and 2013 (Fig. 3) [58-62]. Its goal was to automatically place artificial teeth into a dental arch to manufacture complete dentures based upon the patient's arch size. Limited experiments in a laboratory setting were performed. To the authors best of knowledge no clinical studies to evaluate the functional or esthetic outcomes were undertaken. Another research group more recently reported the design and test results of an 'intelligent dental robot' for the purpose of testing full dentures [63]. Its goal was to replicate human's masticatory movements and perform stress and wear test on artificial dentures. Experiments were performed in a laboratory setting.

Restorative dentistry

Robotics in the field of restorative dentistry is relatively new with all included articles published after 2013 (Fig. 3). All articles were categorized into basic applied research, and experiments were mostly conducted on cadavers. Eight out of the nine articles originated from China. In a series of eight articles, a research group from Beijing reported the development of an automatic full-crown tooth preparation robot using ultrashort pulse lasers. [6, 64-70] The most recent version of the robot consisted of computer-aided design and manufacturing system (CAD/CAM), a tooth positioning system and a 6-DoF robotic arm controlling the position of a laser system [6]. Preparation of a full-crown was done with layer-by-layer laser ablation of the tooth and experiments took place on extracted human teeth inside a phantom model to show its clinical potential. Another group also evaluated an automated tooth preparation system but used a high-speed handpiece attached to the robot instead of a laser [71]. The reduction for porcelain laminate veneers with a robot were compared to conventional freehand preparation. Experiments took place in a laboratory setting.

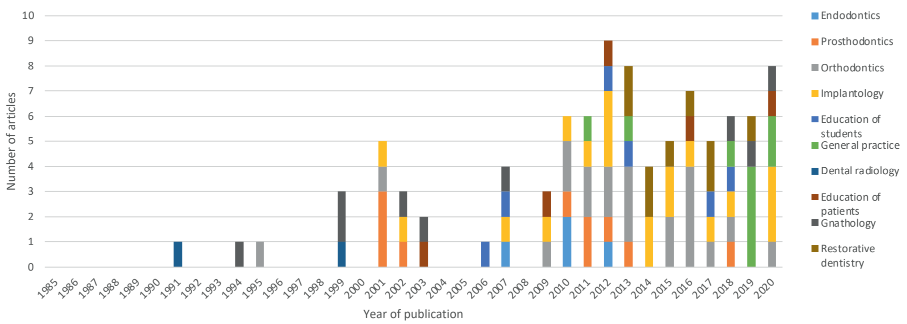


Figure 3. Included articles per field of dentistry and their respective year of publication

Gnathology

Seven out of nine included articles concerning gnathology originated from Japan. All articles were categorized into basic research, except for one recent article describing commercially available technology [72]. Four articles published between 1999 and 2003 looked at a mouth opening-and-closing rehabilitation robot [73-76]. A master-slave system was developed, called Waseda Yamanashi (WY). The goal of this robot was to facilitate mouth opening training. Limited experiments were performed. Four articles looked at robotic articulators to reproduce jaw movements either with or without the use of jaw movement tracking devices [72, 77-79]. An experiment on a single patient's working cast was performed for the fabrication of a full veneer crown using a robotic articulator [77]. The most recent paper in this group describes a case study of a commercially available robot, called the 'Bionic Jaw Motion' (Bionic Technology, Vercelli, Italy) to reproduce mandibular kinematics with a combination of a movement analyzer (high-speed camera) and a robot articulator [72]. A validation of the technique is, to the authors best of knowledge, not reported. Finally, a Japanese article published in 2018 described the development of a motorized robotic denture for healthy elderly people to assist with chewing and swallowing [80]. Experiments were performed in a laboratory setting.

Education of students

All six articles concerning the education of students originate from Japan and were published between 2006 and 2018. Technological readiness levels in this category were relatively high and subjects for these performed studies were mostly human. Although most papers fell into the observational epidemiological research category, study design was mostly limited to unvalidated questionnaires with dental students or their trainers regarding their subjective perception of usefulness as results. In two articles, a humanoid (human-like) robot was developed for dental training purposes [81, 82]. It came with different 'effects' such as performing hand movement, tongue movements, saliva production, effusion of bleeding, pain-sensors for drilling with too much force, and voice recognition. The robot was used to practice dental restorations. A questionnaire was completed by trainers and trainees showing their satisfaction with the system. Recent research showed a more extensive version of a humanoid training robot which was developed by members of the same group together with a commercial robot manufacturer (Tmusk Co., Ltd. Fukuoka, Japan) [83]. This robot is capable of moving its head, to have a conversation with students, perform unexpected (but intended) movements, create vomiting reflexes and produce saliva. The same robot, after adjustments, was later used for the practice of medical emergencies [84]. In both studies a questionnaire was used to evaluate the student's opinion about education using a robot patient. In another article of a parallel group, a robot (Simroid, Morita Group, Japan) with similar functions was compared to a mannequin phantom model with jaw movement reproducibility [85]. Dental students performed preparations for restorative treatments and were given questionnaires to evaluate the use of robot patients for educational purposes. One article looked at a haptic robotic drilling system for training of implant surgery [86]. The goal was to simulate realistic cutting-force responses during implant procedures for dental students. An experiment was conducted on pinewood to test the force response in relation to the actual forces.

General practice

Five recent articles by the same research group from Hong Kong describe the development a compact robotic manipulator specially designed for dentistry [87-91]. By using a tendon-driven mechanism, the dimension of the manipulator was kept within limits. Motion scaling is an additional feature of the system. Experiments in a laboratory setting and under different circumstances where performed to validate the system. Two other groups designed systems supporting the dentist in its movements. One group designed a system in which a handpiece is both guided by dentist and robot to actively support its movements. Limited experiments were performed showing results in terms of accuracy and tremor reduction [92]. Another group designed a master-slave system in which the robot copies movement made by the dentists and haptic feedback is given to the dentist. Laboratory experiments were performed to validate the setup [93]. Other projects include a system to identify and position dental instruments automatically [94] and a basic 'service robot' to be used for delivering messages between patients in a waiting room and their dentist [95]. Limited experiments were performed.

Education of patients

Four out of the five included articles concerning the education of patients described technology tested in its relevant environment, leading to technology readiness levels higher than five [96-98]. Robots in this field could interact with humans whilst avoiding necessity for physical contact. Two articles derived from the same research group described the effect of 'The Smiling Robot' in a Brazilian population of schoolchildren. [96, 97]. 'The Smiling Robot' is a humanoid android, whose movements and sound are remotely controlled by an operator. It emits previously recorded messages with a metallic voice with instructions on oral hygiene. Epidemiological observational research conducted on children exposed to different learning methods evaluated their effect on a plaque index after 30 days compared to a group of children who did not receive any education at all. A comparable initiative is the 'Robotutor' brushing robot designed for educating the 'Bass brushing method'. [99] It consisted of a toothbrush, which is moved by a robot arm alongside dental plaster models and an audio tape with instructions. A questionnaire was used to evaluate its effectiveness. Another initiative in this field was described in a Turkish paper on the effect of a humanoid robot as a distraction method during dental treatment [98]. The same group published the only prospective interventional study found in this review comparing dental anxiety in children with and without distraction by a customized commercially available robot (iRobiQ, Yujin Robot Co., Ltd. Incheon, Korea) [100].

Endodontics

Four articles were included concerning endodontology, published in the years between 2007 and 2012. None of these articles exceeded level two when it comes to technological readiness. Two articles derived from the same research group looked at an endodontic microrobot, with a tool changer to hold or switch instruments [101, 102]. A theoretical model was proposed for the design of a part of a (micro)robot, called an actuator, to enable reliable drilling in the axis of the tooth. To the authors best of knowledge no prototype has been build. In another study, a preliminary visual-guided robot to reduce procedural errors during endodontic treatments was described. Based on image data a robotic-file was controlled in two axes and a single experiment in a laboratory setting was performed showing preliminary results of the system [103]. In the most recent study of this group a design is proposed for an automatic 'tool vending machine' to increase work efficiency and to reduce the amount of space needed during treatment [104]. Its goal was to provide dentists automatically with the correct endodontic tools and had the capability of cleaning the tools as well. No working prototype has been described.

Dental radiology

Only two articles were included concerning dental radiology, published in 1991 and 1999 [105, 106]. Both articles derived from the same research group and looked at the possibility of automatic alignment of a robot containing the x-ray source to the patient for the purpose of digital radiographic subtraction. The goal was to replace free-hand alignment with non-contact positioning of the x-ray source. Experiments were performed with an industrial robot to compare alignment errors between mechanical and robotic alignment.

Discussion

Summary of the evidence

The primary aim of this systematic review was to construct a comprehensive overview of the different robot technology initiatives in all fields of dentistry.
A recent review of literature was published by Grischke et al. including 49 articles on a broader field of dental robotics. The review included robot technology in the field of oral and maxillofacial surgery as well as cognitive robotics technology such as machine learning [107]. In contrast to their work, this study has provided a more systematic approach in addition to a narrower search field in order to provide a more thorough overview of all literature concerning physical robotic technology specifically relevant to the general dentist. A broad timeframe (starting in 1985) was used and, besides Medline and Embase, the Scopus database was included in the search. Despite the narrower scope of this review, the number of included articles were almost twice as compared to Grischke et al., emphasizing the thoroughness of this review.

Robot technology in dentistry is, compared to general medicine, in its relative infancy. Although articles on this topic started to appear around 20 years ago and initiatives can be found in every field dentistry, the initiatives that made it into practice are scarce. This is interesting since robots can be particularly useful in difficult to reach areas and are known for their accurate performances in a reliable and reproducible manner. This review showed that most research in this field has been limited to those situations where physical contact with a human can be avoided, i.e., education or manipulation of dental materials such as orthodontic wires. As discussed in a recent review by Grischke et al. this might be caused by the limited availability and accessibility of robot systems for dental researchers. Where in earliest experiments industrial robots where used for experiments [105] in recent literature a shift towards widely available, human-compliant robots or even robots specifically designed for dentistry has occurred [87]. Next to that, the use of open-source control software (ROS) for robot control has been described in this review [20, 28, 53]. Together with robot technology improving on a wider scale and generally becoming less expensive, these developments might help to facilitate the progression of initiatives to higher levels of technology readiness more easily.

Despite the important limitations found in literature, as also described in part one of this review, there are commercialized systems using robot technology available on the market, mainly in orthodontics and to a lesser extend in implantology and education of students. The implantology robot 'Yomi' (Neocis, Miami, Florida, USA) is marketed as being the first and only Food and Drug Administration approved robot device for dental surgery, including implantology. Its capabilities have been described in other reviews, referring to either grey literature or non-scientific papers [49, 50, 107]. The present search resulted in one article matching the inclusion criteria and concerned a case report on its usage. Strong scientific data supporting the functionality of commercially available robotic systems in dentistry seems limited in clinical terms but also in terms of cost-effectiveness. Therefore, the authors would strongly encourage the publication of well-designed research supporting the use of these innovative and state of the art examples of robot technology in dentistry.

Limitations

This study was designed to give an overview of scientific literature on robot technology in dentistry. This approach led to the exclusion of, amongst others, grey literature and patents. Following this decision, some initiatives that could be relevant were not included in this review and might have led to an underestimation of the hereby-presented results. The authors nevertheless believe to have established a transparent and thorough review of relevant literature, which is meaningful for the general dentists.

Conclusion

This extensive literature review gives an overview of robot initiatives in all fields of dentistry. The overall quality of the literature, especially in terms of clinical validation, should be considered as low. In cases where technology reaches the level of commercial availability, articles supporting their value in clinical or economical terms is largely absent or very limited. The rise in availability of open source control systems, compliant robot systems that enable human-robot interaction and the design of dentistry-specific robot technology might facilitate the process of technological development in the near future. The authors are confident that robotics will provide useful solutions in the future but, strongly, encourage an evidence-based approach when adapting to new (robot) technology in dentistry.

References

[1] Intuitive Surgical, Intuitive Announces Fourth Quarter Earnings, 2020. https://www.intuitive.com/en-us/about-us/company.

[2] S. Kang, S. Lee, H. Ryu, K. Lee, J. Jeong, K. Nam, W. Chung, C. Park, Initial Experience with Robot-Assisted Modified Radical Neck Dissection for the Management of Thyroid Carcinoma with Lateral Neck Node Metastasis, Surgery 148(6) (2010) 1214-1221.

[3] J. De Ceulaer, C. De Clercq, G.R. Swennen, Robotic surgery in oral and maxillofacial, craniofacial and head and neck surgery: a systematic review of the literature, International journal of oral and maxillofacial surgery 41(11) (2012) 1311-24.

[4] J. Mah, R. Sachdeva, Computer-assisted orthodontic treatment: the SureSmile process, Am J Orthod Dentofacial Orthop 120(1) (2001) 85-7.

[5] X. Sun, Y. Yoon, J. Li, F.D. McKenzie, Automated image-guided surgery for common and complex dental implants, J Med Eng Technol 38(5) (2014) 251-9.

[6] F. Yuan, P. Lyu, A preliminary study on a tooth preparation robot, Advances in Applied Ceramics (2019) 1-6.

[7] S. Abe, N. Noguchi, Y. Matsuka, C. Shinohara, T. Kimura, K. Oka, K. Okura, O.M.M. Rodis, F. Kawano, Educational effects using a robot patient simulation system for development of clinical attitude, European Journal of Dental Education 22(3) (2018) e327-e336.

[8] G.C. Peters MDJ, McInerney P, Munn Z, Tricco AC, Khalil, H., Chapter 11: Scoping Reviews (2020 version), in: M.Z. Aromataris E (Ed.), JBI Manual for Evidence Synthesis2020.

[9] A.C. Tricco, E. Lillie, W. Zarin, K.K. O'Brien, H. Colquhoun, D. Levac, D. Moher, M.D.J. Peters, T. Horsley, L. Weeks, S. Hempel, E.A. Akl, C. Chang, J. McGowan, L. Stewart, L. Hartling, A. Aldcroft, M.G. Wilson, C. Garritty, S. Lewin, C.M. Godfrey, M.T. Macdonald, E.V. Langlois, K. Soares-Weiser, J. Moriarty, T. Clifford, O. Tuncalp, S.E. Straus, PRISMA Extension for Scoping Reviews (PRISMA-ScR): Checklist and Explanation, Ann Intern Med 169(7) (2018) 467-473.

[10] M. Ouzzani , H. Hammady, Z. Fedorowicz, A. Elmagarmid, Rayyan—a web and mobile app for systematic reviews, Systematic Reviews 5(1) (2016) 210.

[11] F. Sassani, A. Elmajian, S. Roberts, Computer-assisted fabrication of orthodontic appliances: considering the possibilities, Journal of the American Dental Association (1939) 126(9) (1995) 1296-1300.

[12] E.W. Amm, Clinical outcomes for patients finished with the SureSmile ™ method compared with conventional fixed orthodontic therapy, Angle Orthodontist 81(5) (2011) 926.

[13] R.C. Sachdeva, S.L. Aranha, M.E. Egan, H.T. Gross, N.S. Sachdeva, G.F. Currier, O. Kadioglu, Treatment time: SureSmile vs conventional, Orthodontics : the art and practice of dentofacial enhancement 13(1) (2012) 72-85.

[14] A.K. Saxe, L.J. Louie, J. Mah, Efficiency and effectiveness of SureSmile, World journal of orthodontics 11(1) (2010) 16-22.

[15] B.E. Larson, C.J. Vaubel, G. T., Effectiveness of computer-assisted orthodontic treatment technology to achieve predicted outcomes, Angle Orthodontist 83(4) (2013) 557-562.

[16] T.L. Smith, B. Kusnoto, M.T. Galang-Boquiren, E. BeGole, A. Obrez, Mesiodistal tip and faciolingual torque outcomes in computer-driven orthodontic appliances, Journal of the World Federation of Orthodontists 4(2) (2015) 63-70.

[17] R. Muller-Hartwich, P.G. Jost-Brinkmann, K. Schubert, Precision of implementing virtual setups for orthodontic treatment using CAD/CAM-fabricated custom archwires, Journal of Orofacial Orthopedics 77(1) (2016) 1-8.

[18] R.C. Sachdeva, SureSmile technology in a patient--centered orthodontic practice, Journal of Clinical Orthodontics 35(4) (2001) 245-253.

[19] R. Moles, The SureSmile system in orthodontic practice, Journal of Clinical Orthodontics 43(3) (2009) 161 - 174: quiz 184.

[20] H. Deng, Z. Xia, S. Weng, Y. Gan, J. Xiong, Y. Ou, J. Zhang, Motion planning and control of a robotic system for orthodontic archwire bending, 2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) 2015 (2015).

[21] J. Jiang, X. Ma, Y. Zhang, B. Huo, Y. Liu, Study on Three-Dimensional Digital Expression and Robot Bending Method of Orthodontic Archwire, Applied bionics and biomechanics 2018 (2018) 2176478.

[22] J.G. Jiang, P. Bo, Z. Yong De, Y. Xiao Yang, L. Yi, S. Bei Xin, Control system of orthodontic archwire bending robot based on LabVIEW and ATmega2560, International Journal of Control and Automation 9(9) (2016) 189-198.

[23] J.G. Jiang, Y.S. Han, Y.D. Zhang, Y.J. Liu, Z. Wang, Y. Liu, Springback Mechanism Analysis and Experiments on Robotic Bending of Rectangular Orthodontic Archwire, Chinese Journal of Mechanical Engineering (English Edition) 30(6) (2017) 1406-1415.

[24] J.G. Jiang, Y.D. Zhang, M.L. Jin, C.G. Wei, Bending process analysis and structure design of orthodontic archwire bending robot, International Journal of Smart Home 7(5) (2013) 345-352.

[25] W. Zhang, Research of 3D Virtual Design and Automated Bending of Oral Orthodontic Archwire, International Journal of Advancements in Computing Technology(IJACT) 5(8) (2013) 741-749.

[26] Y. Zhang, X. Jia, J. Jiang, Y. Liu, Y. Wang, Simulation and analysis of orthodontic archwire bending robot, International Journal of Smart Home 10(8) (2016) 263-270.

[27] Y. Zhang, J. Jiang, Analysis and experimentation of the robotic system for archwire bending, Applied Mechanics and Materials 121-126 (2012) 3805-3809.

[28] Z. Xia, H. Deng, S. Weng, Y. Gan, J. Xiong, H. Wang, Development of a robotic system for orthodontic archwire bending, 2016 IEEE International Conference on Robotics and Automation (ICRA) 2016 (2016) 730-735.

[29] J.C. Jiang, H. Ma, X. Zhang, Y. Liu, Y., Forming Planning Method and Experimentation of Personalized Orthodontic Archwires, Zhongguo Jixie Gongcheng/China Mechanical Engineering (11) (2020) 1323-1330 and 1336.

[30] H. Kheirollahi Bisheh, S. Rahmati, F. Abesi, A novel methodology in design and fabrication of lingual orthodontic appliance based on rapid prototyping technologies, Innovative Developments in Design and Manufacturing - Advanced Research in Virtual and Rapid Prototyping (2010) 711-718.

[31] A. Gilbert, An in-office wire-bending robot for lingual orthodontics, Journal of Clinical Orthodontics 45(4) (2011) 230-4;quiz 236.

[32] A. Eliasson, A. Ortorp, The accuracy of an implant impression technique using digitally coded healing abutments, Clinical Implant Dentistry and Related Research 14 (2012) e30-e38.

[33] P.S. Mozer, Accuracy and Deviation Analysis of Static and Robotic Guided Implant Surgery: A Case Study, Int J Oral Maxillofac Implants 35(5) (2020) e86-e90.

[34] R. Chaumont, E. Vasselin, D. Lefebvre, Forward kinematics and geometric control of a medical robot;Application to dental implantation, Proceedings of the Fourth International Conference on Informatics in Control, Automation and Robotics 2 (2007) 110-115.

[35] G. Kim, H. Seo, S. Im, D. Kang, S. Jeong, A study on simulator of human-robot cooperative manipulator for dental implant surgery, IEEE International Symposium on Industrial Electronics (ISIE 2009) (2009) 2159-2164.

[36] S. Yilmaz, E.I. Konukseven, H. Gurocak, Optimum design of 6R passive haptic robotic arm for implant surgery, Lecture Notes in Computer Science LNCS 6191 (2010) 105-110.

[37] Y.V.D. Rao, A.M. Parimi, D.S.P. Rahul, D. Patel, Y.V. Nitin Mythreya, Robotics in Dental Implantation, Materials Today: Proceedings 4 (2017) 9327-9332.

[38] J. Dutreuil, F. Goulette, C. Laurgeau, J.C. Zoreda, S. Lundgren, Computer assisted dental Implantology: A new method and a clinical validation, (2001) 384-391.

[39] T. Fortin, G. Champleboux, S. Bianchi, H. Buatois, J.-L. Coudert, Precision of transfer of preoperative planning for oral implants based on cone-beam CT-scan images through a robotic drilling machine: An in vitro study, Clinical oral implants research 13(6) (2001) 651–656.

[40] T. Chiarelli, F. Franchini, A. Lamma, E. Lamma, T. Sansoni, From implant planning to surgical execution: An integrated approach for surgery in oral implantology, International Journal of Medical Robotics and Computer Assisted Surgery.

[41] X. Sun, F.D. McKenzie, S. Bawab, J. Li, Y. Yoon, J.K. Huang, Automated dental implantation using image-guided robotics: registration results, International journal of computer assisted radiology and surgery 6(5) (2011) 627-634.

[42] X. Sun, Y. Yoon, J. Li, F.D. McKenzie, Automated image-guided surgery for common and complex dental implants, Journal of medical engineering & technology 38(5) (2014) 251-259.

[43] S. Yeotikar, A.M. Parimi, Y.V. Daseswar Rao, Automation of end effector guidance of robotic arm for dental implantation using computer vision, 2016 IEEE Distributed Computing, VLSI, Electrical Circuits and Robotics (DISCOVER) (2016) 84-89.

[44] K. Yu, S. Uozumi, K. Ohnishi, S. Usuda, H. Kawana, T. Nakagawa, Stereo vision based robot navigation system using modulated potential field for implant surgery, 2015 IEEE International Conference on Industrial Technology (ICIT) 2015 (2015) 493-498.

[45] K. Yu, K. Ohnishi, H. Kawana, S. Usuda, Modulated Potential Field Using 5 DoF Implant Assist Robot for Position and Angle Adjustment, IECON 2015 - 41st Annual Conference of the IEEE Industrial Electronics Society, Yokohama, , 2015, pp. 002166-002171.

[46] Y. Kasahara, H. Kawana, S. Usuda, K. Ohnishi, Telerobotic-assisted bone-drilling system using bilateral control with feed operation scaling and cutting force scaling, The International Journal of Medical Robotics and Computer Assisted Surgery 8(2) (2012) 221-229.

[47] A.A. Syed, A.M. Soomro, A.N. Khizar, X.-g. Duan, H. Qiang, F. Manzoor, Tele-Robotic Assisted Dental Implant Surgery with Virtual force Feedback, TELKOMNIKA Indonesian Journal of Electrical Engineering 12 (2014).

[48] F.S. Yuan, J.Q. Zheng, Y.P. Zhang, Y. Wang, Y.C. Sun, P.J. Lyu, [Preliminary study on the automatic preparation of dental implant socket controlled by micro-robot], Chin J Stomatol 53(8) (2018) 524-528.

[49] Z.S. Haidar, Autonomous robotics: A fresh era of implant dentistry… is a reality!, Journal of Oral Research 6(9) (2017) 230-231.

[50] Y. Wu, F. Wang, S. Fan, J.K. Chow, Robotics in Dental Implantology, Oral and maxillofacial surgery clinics of North America 31(3) (2019) 513-518.

[51] P.J. Lyu, [Condition and future of robotics in stomatology], Zhonghua Kou Qiang Yi Xue Za Zhi 53(8) (2018) 513-518.

[52] A.M. Meleshnikov, A.A. Vorotnikov, D.D. Klimov, Y.V. Poduraev, Prototype Probe Determining Waveguide–Gum Contact for a Robot Surgical System, Russian Engineering Research 40(1) (2020) 86-88.

[53] T.C.T.d.G. van Riet, W. M.; van Antwerpen, R.; van Frankenhuyzen, J.; de Lange, J.; Kober, J., Robot Technology in Analyzing Tooth Removal - a Proof of Concept, Annu Int Conf IEEE Eng Med Biol Soc (2020) 4721-4727.

[54] Y. Zhang, Z. Zhao, J. Lu, K. Tso Shiu, Robotic manufacturing of complete dentures, Proceedings 2001 ICRA. IEEE International Conference on Robotics and Automation (Cat. No.01CH37164) 3 (2001) 2261-2266.

[55] P. Lu, Y. Wang, G. Li, [Development of a system for robot aided teeth alignment of complete denture], Zhonghua Kou Qiang Yi Xue Za Zhi 36(2) (2001) 139-142.

[56] Y. Zhang, Z. Zhao, R. Song, J. Lu, P. Lu, Y. Wang, Tooth arrangement for the manufacture of a complete denture using a robot, Industrial Robot: An International Journal 28(5) (2001) 420-425.

[57] Y. Zhang, Z. Zhao, P. Lu, Y. Wang, R. Song, J. Lu, Robotic system approach for complete denture manufacturing, IEEE/ASME Transactions on Mechatronics 7(3) (2002) 392-396.

[58] Y. Zhang, J. Jiang, P. Lv, Y. Wang, Coordinated control and experimentation of the dental arch generator of the tooth-arrangement robot, The International Journal of Medical Robotics and Computer Assisted Surgery 6(4) (2010) 473-482.

[59] Y. Zhang, J. Jiang, T. Liang, W. Hu, Kinematics modeling and experimentation of the multi-manipulator tooth-arrangement robot for full denture manufacturing, Journal of Medical Systems 35(6) (2011) 1421-1429.

[60] Y. Zhang, J. Jiang, P. Lv, Y. Wang, Study on the multi-manipulator tooth-arrangement robot for complete denture manufacturing, Industrial Robot 38(1) (2011) 20-26.

[61] J. Jiang, Y. Zhang, W. Zhang, Collaborative simulation and experimentation on the dental arch generator of a multi-manipulator tooth-arrangement robot, International Journal of Advanced Robotic Systems 9 (2012).

[62] J. Jiang, Y. Zhang, Motion planning and synchronized control of the dental arch generator of the tooth-arrangement robot, The International Journal of Medical Robotics and Computer Assisted Surgery 9(1) (2013) 94-102.

[63] L. Ren, J. Yang, Y. Tan, J. Hu, D. Liu, J. Zhu, An intelligent dental robot, Advanced Robotics 32(12) (2018) 659-669.

[64] L. Wang, D. Wang, L. Ma, Y. Zhang, F. Yuan, Y. Sun, P. Lv, Preliminary experiments of a miniature robotic system for tooth ablation using ultra-short pulsed lasers, 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (2013) 2566-2571.

[65] L. Ma, Y. Zhang, D. Wang, P. Lv, Y. Sun, H. Wang, Trajectory tracking control of a miniature laser manipulation robotic end-effector for dental preparation, 2013 IEEE International Conference on Robotics and Biomimetics (ROBIO) (2013) 468-473.

[66] D. Wang, L. Wang, Y. Zhang, P. Lv, Y. Sun, J. Xiao, Preliminary study on a miniature laser manipulation robotic device for tooth crown preparation, The International Journal of Medical Roboitcs and Computer Assisted Surgery 10(4) (2014) 482-494.

[67] L. Wang, D. Wang, Y. Zhang, L. Ma, Y. Sun, P. Lv, An automatic robotic system for three-dimensional tooth crown preparation using a picosecond laser, Lasers in surgery and medicine 46(7) (2014) 573-581.

[68] F. Yuan, J. Zheng, Y. Sun, Y. Wang, P. Lyu, Regulation and Measurement of the Heat Generated by Automatic Tooth Preparation in a Confined Space, Photomedicine Laser Surgery 35(6) (2017) 332-337.

[69] F. Yuan, Y. Wang, Y. Zhang, Y. Sun, D. Wang, P. Lyu, An automatic tooth preparation technique: A preliminary study, Scientific Reports 6 (2016) 25281.

[70] F.S. Yuan, Y. Wang, Y.P. Zhang, Y.C. Sun, D.X. Wang, P.J. Lyu, [Study on the appropriate parameters of automatic full crown tooth preparation for dental tooth preparation robot], Zhonghua Kou Qiang Yi Xue Za Zhi 52(5) (2017) 270-273.

[71] T. Otani, A.J. Raigrodski, L. Mancl, I. Kanuma, J. Rosen, In vitro evaluation of accuracy and precision of automated robotic tooth preparation system for porcelain laminate veneers, Journal of Prosthetic Dentistry 114(2) (2015) 229-235.

[72] M. Carossa, D. Cavagnetto, P. Ceruti, F. Mussano, S. Carossa, Individual mandibular movement registration and reproduction using an optoeletronic jaw movement analyzer and a dedicated robot: a dental technique, BMC Oral Health 20(1) (2020) 271.

[73] H. Takanobu, M. Nakazawa, A. Takanishi, K. Ohtsuki, M. Ohnishi, Clinical training with mouth opening and closing training robot WY-3, Proceedings 1999 IEEE/RSJ International Conference on Intelligent Robots and Systems. Human and Environment Friendly Robots with High Intelligence and Emotional Quotients (Cat. No.99CH36289) 3 (1999) 1604-1609.

[74] H. Takanobu, T. Yajima, A. Takanishi, K. Ohtsuki, M. Ohnishi, Three degrees of freedom mouth opening and closing training robot, IEEE SMC'99 Conference Proceedings. 1999 IEEE International Conference on Systems, Man, and Cybernetics (Cat. No.99CH37028) 2 (1999) 448 - 453 vol.2.

[75] H. Takanobu, A. Takanishi, D. Ozawa, K. Ohtsuki, M. Ohnishi, A. Okino, Integrated dental robot system for mouth opening and closing training, Proceedings 2002 IEEE International Conference on Robotics and Automation (Cat. No.02CH37292) 2 (2002) 1428-1433.

[76] H.U. Takanobu, A. Takanishi, Dental robotics and human model, First International IEEE EMBS Conference on Neural Engineering, 2003. Conference Proceedings. (2003) 671-674.

[77] K. Nishigawa, T. Satsuma, S. Shigemoto, E. Bando, M. Nakano, O. Ishida, Development of a novel articulator that reproduced jaw movement with six-degree-of-freedom, Medical engineering & physics 29(5) (2007) 615-619.

[78] D.A. Kizghin, C.A. Nelson, Optimal design of a parallel robot for dental articulation, 2019 Design of Medical Devices Conference, 2019.

[79] H.T. Takanobu, Takashi; Takanishi, Atsuo; Kato, Ichiro;, Adaptive masticatory jaw motion using jaw position and biting force information, Proceedings of the 1994 IEEE International Conference on Multisensor Fusion and Integration for Intelligent Systems (1994) 360-365.

[80] T. Araie, T. Ikeda, U. Nishizawa, A. Kakimoto, S. Toyama, M. Ragulskis, Study of the chewing assistance mechanism in powered robotic dentures, Vibroengineering PROCEDIA 19 (2018) 163-168.

[81] H. Takanobu, A. Takanishi, A. Okino, M. Madokoro, Y. Miyazaki, K. Maki, Dental Patient Robot, Proceedings of the 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems (2006) 1273-1278.

[82] H. Takanobu, A. Omata, F. Takahashi, K. Yokota, K. Suzuki, H. Miura, M. Madokoro, Y. Miyazaki, K. Maki, Dental patient robot as a mechanical human simulator, Proceedings of International Conference on Mechatronics, , 2007, pp. 1-6.

[83] T. Tanzawa, K. Futaki, C. Tani, T. Hasegawa, M. Yamamoto, T. Miyazaki, K. Maki, Introduction of a robot patient into dental education, European Journal of Dental Education 16(1) (2012) e195-e199.

[84] T. Tanzawa, K. Futaki, H. Kurabayashi, K. Goto, Y. Yoshihama, T. Hasegawa, M. Yamamoto, M. Inoue, T. Miyazaki, K. Maki, Medical emergency education using a robot patient in a dental setting, European Journal of Dental Education 17(1) (2013) e114-e119.

[85] S. Abe, N. Noguchi, Y. Matsuka, C. Shinohara, T. Kimura, K. Oka, K. Okura, O. Rodis, F. Kawano, Educational effects using a robot patient simulation system for development of clinical attitude, European Journal of Dental Education 22(3) (2018) e327-e336.

[86] K. Yu, T. Matsunaga, H. Kawana, S. Usuda, K. Ohnishi, Frequency-based analysis of the relationship between cutting force and CT number for an implant-surgery-teaching robot, IEEJ Journal of Industry Applications 6(1) (2017) 66-72.

[87] J. Li, Z. Shen, W.Y.T. Xu, W.Y.H. Lam, R.T.C. Hsung, E.H.N. Pow, K. Kosuge, Z. Wang, A Compact Dental Robotic System Using Soft Bracing Technique, IEEE Robotics and Automation Letters 4(2) (2019) 1271-1278.

[88] J. Li, W.Y.H. Lam, R.T. Chiu Hsung, E.H.N. Pow, Z. Wang, A Customizable, Compact Robotic Manipulator for Assisting Multiple Dental Procedures, 2018 3rd International Conference on Advanced Robotics and Mechatronics (ICARM) (2018) 720-725.

[89] J. Li, W.Y.H. Lam, R.T.C. Hsung, E.H.N. Pow, C. Wu, Z. Wang, Control and motion scaling of a compact cable-driven dental robotic manipulator, 2019 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM) (2019) 1002-1007.

[90] J. Li, J. Lam, M. Liu, Z. Wang, Compliant Control and Compensation for A Compact Cable-Driven Robotic Manipulator, IEEE Robotics and Automation Letters 5(4) (2020) 5417-5424.

[91] Y.Z. Tao, T. Xu, W. Tsang, H. Y. Li, J. Wang, Z., A Compact Asymmetrical Manipulator for Robotic Dentistry, Proceedings of the 9th IEEE International conference on CYBER technology in automation, Control and Intelligent Systems (2019) 164-168.

[92] J.L. Ortiz Simon, A.M. Martinez, D.L. Espinoza, J.G. Romero Velazquez, Mechatronic assistant system for dental drill handling, International Journal of Medical Robotics and Computer Assisted Surgery 7(1) (2011) 22-26.

[93] T.M. Iijima, T. Shimono, T. Ohnishi, K. Usuda, S. Kawana, H., Development of a Multi DOF Haptic Robot for Dentistry and Oral Surgery, Proceedings of the 2020 IEEE/SICE (2020) 52-57.

[94] L. Chen, The application of robots and eye tracking devices in a general dentist's clinic, 2013 IEEE Third International Conference on Consumer Electronics - Berlin (ICCE-Berlin) (2013) 5-7.

[95] I.H. Bula, E. Stapleton, L. Kopacek, P. Topalov, A., Cost oriented autonomous mobile service robot, IFAC PapersOnLine (2019) 91-94.

[96] J.A. Rodrigues, P.A. dos Santos, P.P. Garcia, S.A. Corona, L.C. Loffredo, Evaluation of motivation methods used to obtain appropriate oral hygiene levels in schoolchildren, International journal of dental hygiene 1(4) (2003) 227-232.

[97] J.A. Rodrigues, P.A. dos Santos, W. Baseggio, S.A. Corona, R.G. Palma-Dibb, P.P. Garcia, Oral hygiene indirect instruction and periodic reinforcements: effects on index plaque in schoolchildren, Journal of Clinical Pediatric Dentistry 34(1) (2009) 31-34.

[98] M. Yasemin, Y. Kasimoğlu, S. Kocaaydin, E. Karsli, E.B.T. Ince, G. Ince, Management of dental anxiety in children using robots, Institute of Electrical and Electronics Engineers Inc.2016.

[99] M. Ahire, N. Dani, R. Muttha, Dental health education through the brushing ROBOTUTOR: A new learning experience, Journal of Indian Society of Periodontology 16(3) (2012) 417-420.

[100] Y. Kasimoglu, S. Kocaaydin, E. Karsli, M. Esen, I. Bektas, G. Ince, E.B. Tuna, Robotic approach to the reduction of dental anxiety in children, Acta Odontol Scand 78(6) (2020) 474-480.

[101] J. Dong, S.Y. Hong, Design of Z axis actuator & quick tool change assembly for an endodontic micro robot, ASME 2010 International Mechanical Engineering Congress and Exposition 10 (2010) 507-511.

[102] J. Dong, H. Everett, The development of endodontic micro robot, 2007 ASME International Mechanical Engineering Congress and Exposition 2 (2007) 201-204.

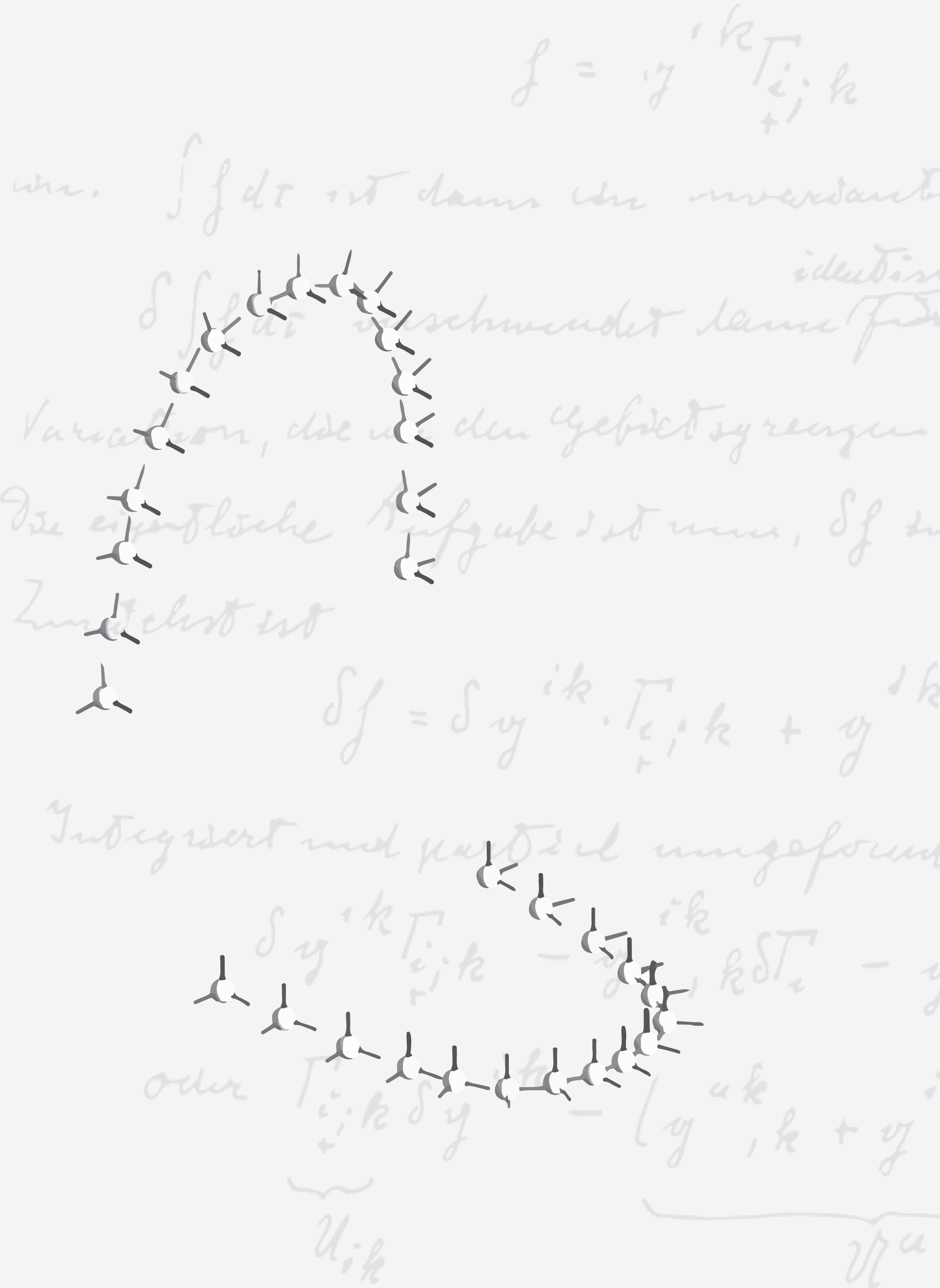
[103] T. Gulrez, A.K. Shahid, U. Sana, N.G. Chaudhary, Visual guided robotic endodontic therapeutic system, International Conference on Information and Emerging Technologies, IEEE, 2010, pp. 1-6.

[104] C.A. Nelson, S.G. Hossain, A. Al-Okaily, J. Ong, A novel vending machine for supplying root canal tools during surgery, Journal of medical engineering & technology 36(2) (2012) 102-116.

[105] G.C. Burdea, Stanley M. Dunn, C.H. Immendorf, M. Mallik, Real-time sensing of tooth position for dental digital subtraction radiography, IEEE Transactions on Biomedical Engineering 38(4) (1991) 366-378.

[106] G.C. Burdea, S.M. Dunn, G. Levy, Evaluation of robot-based registration for subtraction radiography, Medical image analysis 3(3) (1999) 265-274.

[107] J. Grischke, L. Johannsmeier, L. Eich, L. Griga, S. Haddadin, Dentronics: Towards robotics and artificialintelligence in dentistry, Dental Materials (2020) 14.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Chapter 4

Robot technology in analyzing tooth removal, a proof of concept

This chapter is based on the following publication:
Robot Technology in Analyzing Tooth Removal - a Proof of Concept
T.C.T. van Riet, W.M. de Graaf, R. van Antwerpen, J. van Frankenhuyzen, J. de Lange and J. Kober

Published in: Proceedings of the 42nd Annual International Conference of the IEEE Engineering in Medicine & Biology Society, 2020

Abstract

A measurement setup is proposed that, for the first time, is capable of capturing the combination of high forces and subtle movements exerted during tooth removal procedures in high detail and in a reproducible manner by using robot technology. The outcomes of a design process from a collaboration between clinicians, mechanical and software engineers together with first results are presented in this proof of concept.

Clinical relevance

By measuring all aspects of tooth removal in a single setup a strong database can be build that will deliver the data needed to gain scientific understanding of what makes (un)successful tooth removal. It gives a unique opportunity to model the procedure, evaluate techniques, understand and predict adverse events as well as to create new evidence-based teaching methods.

Introduction

Tooth removal, or exodontia, is one of the most commonly performed surgical procedures on our planet. Despite its high prevalence, surprisingly little is known about this procedure. During these procedures, dental surgeons use a combination of subtle movements and strong forces to free a tooth from its surrounding bony socket. Previous (very limited) research aimed at measuring just the total amount of forces necessary for exodontia [1-5]. The precise direction (in three dimensions) of the involved forces and the movements of the dental surgeon were, to the authors' knowledge, never before subject to research. The latter is probably due to the limitations of available instruments to, precisely, measure these parameters in a "key-hole" environment. It has led to a large scientific gap, which becomes more evident when looking at the education of dental students. Tooth removal is the most invasive procedure dental students need to learn during their training but it is also the single procedure for which adequate preclinical training possibilities are absent or largely inadequate [6, 7]. Up until today students mostly learn their skills from textbooks with only minor instructions and train their skillset on actual patients [7]. Students in well-developed countries, where extensive preventive dentistry programs are present, are suffering from decreased exposure to 'learning by experience' because less teeth need to be removed in general. This contributes to low confidence levels in tooth removal procedures of young dentists and an increase in referrals to (more expensive) oral and maxillofacial surgery practices[7, 8]. Complete data on every aspect of these procedures is needed to be able to understand what makes (un-)successful tooth removal and to scientifically describe and model the procedure. This dataset should additionally contain clinical parameters and perioperative data to be able to find relevant parameters in successful tooth removal. It would facilitate the design of evidence-based educational instruments but, next to that, it has the potential to help clinicians predict clinical outcomes (i.e. complicated treatments) and could lead to more (cost-) efficient referrals to oral and maxillofacial surgeons.

The goal of this project is to design a measurement setup that captures the high forces and subtle movements involved in tooth removal procedures in detail. The design of the setup and integration of, amongst others, a collaborative robot and 6-axis force-torque sensor are shown in this article together with first results as a proof of concept.

Material and Methods

Challenges in detailed measuring of tooth removal

Several challenges had to be overcome during the design of the measurement setup. Dental surgeons use a combination of high forces and subtle motions to loosen a tooth from its bony socket. It is necessary to measure these sub-millimeter movements in three dimensions and at a high rate to be able to analyze movements in full detail and, for example, en- able analysis of adverse events like tooth fracture. These measurements should take place without restricting dental surgeons in their movements in any way. Forces and torques should be measured in three dimensions in the center of rotation of the tooth, simultaneously with the movements. Clinically important parameters such as periodontal health, amount of roots, root size, age of the patient, and restorative state should be easily integrated into the measurements. Preferably, these measurements should all be performed on patients in an in vivo setup.

Multiple sessions with a team of clinicians, mechanical engineers and computer scientists led to inevitable com- promises in the setup. One of the major concessions to the ideal setup was the use of an in vitro measurement setup. Simultaneous and reproducible recordings of position/orientation/force/torque measurements are essential in this fundamental research. Compared to in vitro measurements, accurate sub-millimeter movement tracking and registration of forces/torques and their directions in vivo is questionable. One of the main issues is that the mobility of the patient is difficult to compensate for, which is especially true for the lower jaw, which is not rigidly fixated to the human skull. The force/torque sensor would need to be integrated in the forceps between the surgeon's hand and the tooth, which is unrealistic due to very limited space and high forces. Next to that, in vivo tooth removal requires considerable counterforce from the surgeons' second hand, which would interfere with the force measurements. Finally, we made the assumption, that the forceps and the tooth are rigidly connected once the tooth is grabbed. Therefore, we do not need to measure the movement of the tooth itself and can place the force/torque sensor under the jaw. To capture the clinicians' movement, several techniques were proposed of which optical tracking (infrared) and robot technology were the most promising. Robot assisted motion capture was preferred due to the high accuracy associated with robotic positional measurements. Next to that, by rigidly fixating the standard dental forceps to the end-effector, the surgeon can hold the forceps as they would do in clinical circumstances. Compared to optical trackers it prevents the need for markers and it avoids visibility issues of the tracking system during these 'key hole' surgical procedures.

An overview of the measurement setup

The measurement setup, see Fig. 1, consists of:

- a holding device for the upper- and lower jaw in an adjustable frame (Section II-C)
- 7 dental forceps (Section II-C)
- a six-axis force/torque (FT-) sensor (Section II-D)
- a compliant robot arm (Section II-D)
- a video camera (Section II-D)
- the Robot Operating System (ROS) (Section II-D)
- a graphical user interface (GUI) (Section II-E)

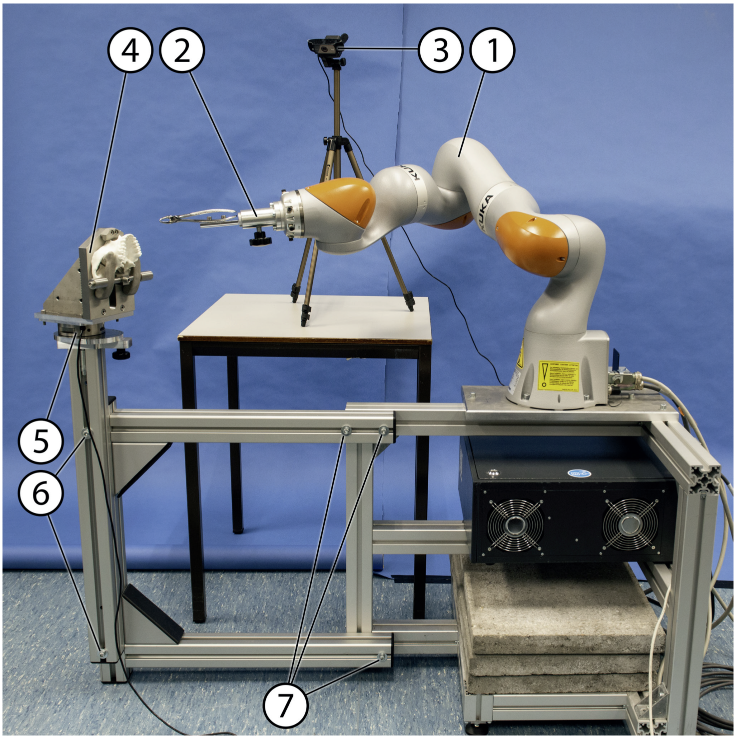


Fig. 1: Overview of the setup. (1) robot arm, (2) forceps holding device, (3) video camera, (4) upper jaw holding device, (5) force torque sensor, (6) bolts to adjust frame vertically, (7) bolts to adjust frame horizontally

The adjustable frame and holding devices

To add to the readability of this subsection, numbers put between parentheses are referring to Fig. 2 (numbers 1 to 16) and Fig. 3 (numbers 17 to 32). A framework of a 60 by 60 millimeter aluminum profile (Item Industrietechnik, Solingen, Germany) was designed to mechanically integrate the different components (Fig. 1). The framework is adjustable; meaning the position of the holding devices for the upper and lower jaws can be changed relative to the robot and placed at different heights. This is necessary to mimic clinical circumstances in which the position of the upper and lower jaw are, respectively, vertical and horizontal. For ergonomic reasons, the patient is positioned higher when removing teeth from the upper jaw. The addition of a rotational plate (14,29) between the frame and the holding devices mimics the turning of the patients head and leads to a more clinical representative situation in which the clinician can maintain an ergonomic pose during the extraction procedure. The plate is located just below the FT-sensor (13,28) and can be rotated by pulling a locking bolt (16,32) on the bottom plate (15,30). The locking bolt falls into one of the position holes upon its release and can be further tightened to eliminate any slack. The position holes allow a 137.5-degree rotation in 11 steps of 12.5 degree increment in either direction (a total range of 275 degrees). Next to the ergonomic advantages, the usage of an adjustable frame largely overcomes an important issue of working with a robot arm. When any of the robot's joints reaches a joint limit, it needs to adjust other joints to enable the end-effector to reach the desired position. This can involve a rigorous movement of the robot, which inevitably leads to some resistance for the clinician. By placing the most relevant joints in a neutral position just before starting the experiment, reaching joint limits can be avoided. This is enhanced by placing the upper and lower jaw in a favorable position relative to the robot arm. The frame was provided with a scale (millimeter) to measure the exact position of the holding devices for calibration purposes, see Section II-D.

Essential for reproducible, accurate and thus meaningful measurements is a completely rigid fixation of both upper and lower jaw. Two separate holding devices had to be designed. First because the above-mentioned difference in ergonomic position (horizontal/vertical) of both jaws. Second, because the anatomical differences between the two jaws do not facilitate the design of a single device to fit both. In general, non-corrosive and smooth surface materials were used to facilitate cleaning which is especially necessary when working with (fresh) human material.

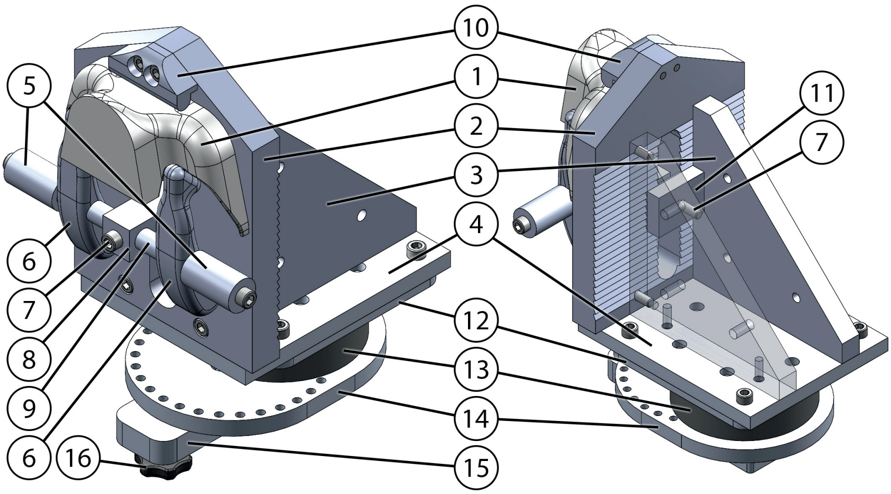


Fig. 2: Holding device for upper jaw: (1) upper jaw, (2) surface plate, (3) support plate, (4) ground plate, (5) axle boxes, (6) clamping arms, (7) clamping bolt, (8) sliding block, (9) clamp axis, (10) front block, (11) clamping nut, (12) top plate of sensor build-up, (13) force/torque sensor, (14) rotation plate, (15) bottom plate, (16) locking bolt

The shape of the upper jaw is geometrically unsuitable to fixate (inverted trapezoid shape) and can be very thin at certain points. As is known from facial trauma surgery, other parts of the midface (located just above the upper jaw) have better properties in terms of fixation because of the strength and shape of the bone. This counts for both the paranasal region (besides the nose) and, more lateral, the connection between upper jaw and zygomatic bone ('zygomatic buttresses). For holding the upper jaw, see Fig. 2, a clamping nut (7) was placed in an angular position relative to grooves on the main plate (4). Tightening the clamping bolt will force the 3D-printed titanium clamping arms (6), which were manufactured through selective laser melting (material: Ti6AI4V-ELI), to push the maxilla (1) downwards and forwards into a 45-degree angle. This way the frontal part of the maxilla, with its strong paranasal zones is fixated underneath a ridge (10). The ridge's geometry allows the upper jaw to slide slightly under it and prevents it from tilting upwards. Vertical grooves in this ridge minimizes translation from left to right. Sideward motion is further limited by tightening the axle boxes on the clamp axis (5) against the clamping arms. The arms push the strong zygomatic buttresses downwards and inwards. The rough surface of the clamps ensure grip even when remnants of muscle attachments are not completely removed during preparation of the skull. The shape of the clamp's head is designed to fit the natural shape of the zygomatic buttress, which reduces the risk of iatrogenic fractures during any of the experiments. Compared to the upper jaw, the lower jaw can be geo- metrically adjusted to make it more suitable for fixation. Its thick and strong cortical lining lends itself for fixation even when the bone is reduced in size, see Fig. 3. Similar to the fixation of the upper jaw a clamping nut (21) is placed in an angular position to the grooves of the surface plate (20). By tightening the clamping bolt, the clamp axis will force the jaw in a 45-degree angle downwards and forwards against the front block (25). The design of the front block ensures that the jaw can slide slightly under it to prevent the jaw from tilting upwards, while vertical grooves prevent translation sideward. Further translation is limited by sliding the side blocks (24) on the clamp axis against the sides of the jaw and locking them on the axis with a bolt. The design of the blocks is lean to facilitate the movement of the clinician, even when removing dorsally located molars.

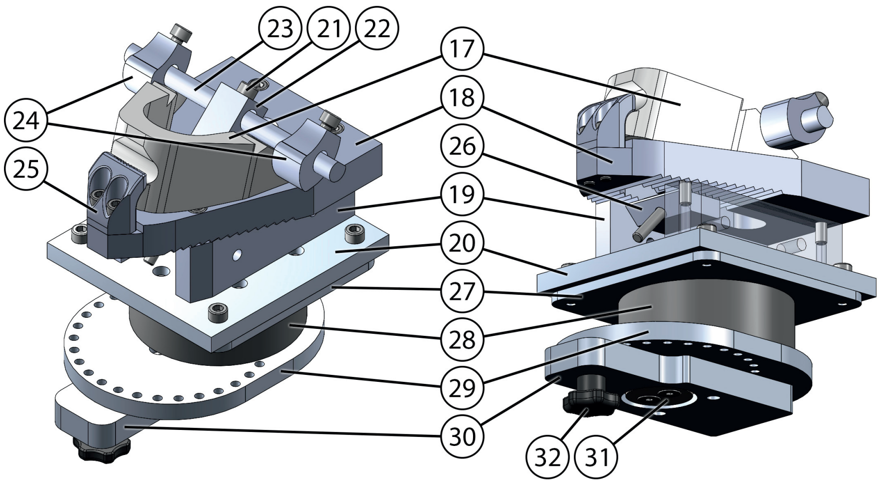


Fig. 3: Holding device for lower jaw: (17) lower jaw, (18) surface plate, (19) supporting plate, (20) ground plate, (21) clamping bolt, (22) sliding block, (23) clamp axis, (24) side blocks, (25) front block, (26) clamping nut, (27) top plate of sensor build-up, (28) force-torque sensor, (29) rotation plate, (30) bottom plate, (31) rotation axis, (32) locking bolt

To remove teeth, dental surgeons have a large variety of forceps at their disposal. To enhance grip on the tooth, the forceps are designed to specifically fit a certain type of tooth. For these experiments, seven dental forceps (Aesculap, B.Braun, Melsungen, Germany) are used: the left upper molar, right upper molar, upper premolar, upper incisor, lower molar, lower premolar and lower incisor forceps. They are fixated to the end-effector through a custom aluminum holder with two bolts (5mm), see Fig. 4. The aluminum holder is fixated in the end-effector by tightening one clamping bolt. The partially flat design of the custom aluminum frame ensured a reproducible position of the dental forceps in the end-effector.

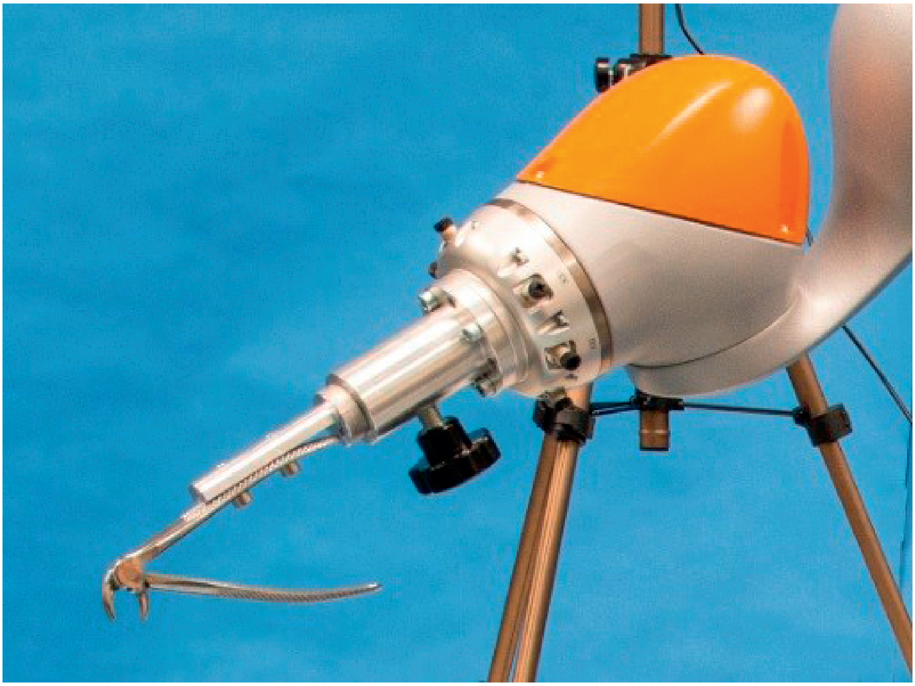


Fig. 4: Holding device for dental forceps.

The robot and force-torque measurements

To obtain sub-millimeter precision and accurate repeatability of movements during the procedure, the KUKA LBR iiwa 7 R800 is used. This robot is a 7-degree of freedom collaborative robot with 7 rotational joints and recording position and orientation data of the dental forceps at 100Hz. The integrated torque and rotational sensors enable the robot to detect external forces, which makes this robot collaborative and highly suitable for integration in this measurement setup. An ATI 16 bit Delta transducer is used for recording the force and torque data in 6 axis at a speed of 20Hz. A Logitech C920 Pro HD webcam is used to record a video stream of the experiment. The latter will facilitate the interpretation of data patterns when analyzing the data later on.

The platform Robotic Operating System (ROS) is used for software integration of the force/torque sensor, the video camera, and the collaborative robot[9]. ROS is an open source framework that allows for easy integration of several hardware sensors with robotic control and simulation. It provides hardware abstraction, device drivers, and libraries. The image pipeline repository is used to convert the image data from the video camera to the ROS framework. For controlling the KUKA, the iiwa stack repository is used which contains high level commands to collaborate with the robot through the ROS framework[10]. A custom ROS driver was written to read out the serial data from the FT- sensor and enable its usage in the ROS environment.

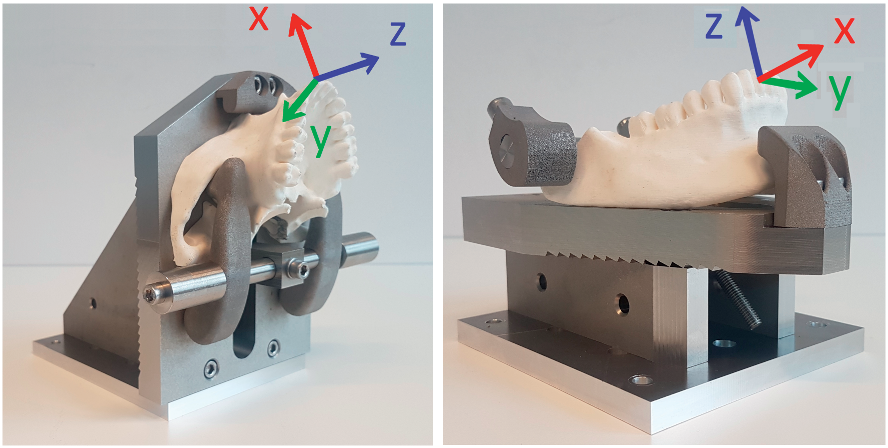
To enable the clinician to freely move the forceps, the robot mode is switched to a passive mode (impedance control). Impedance control enables a dynamic collaboration between the clinician and the robot. In this mode, all 7 joints are acting as separate spring-damper systems. The stiffness and damping constants can be tuned by the user for each individual joint. High values will result in rigid joint motion, whereas lower values will result in more compliant/floating motion. To prevent joints drifting into joint limits and to facilitate the clinician during the experiments, joints numbers a2 and a5 are set to a higher stiffness and damping value compared to the other joints (Fig. 1). It results in a more compliant motion of the dental forceps.

Both the FT-sensor and robot need to be calibrated before each experiment to register the position and orientation of the teeth. The robot is used for calibration of the position and orientation of the teeth. Because of the orientation difference of the upper and lower jaw (vertical/horizontal), two calibration tools were necessary. A lower incisor dental forceps is used for calibration in the lower jaw, due to the 90-degree angle and its straight design. For the upper jaw, a straight dental elevator (Usto-Lux, Ustomed, Germany) is used for calibration. The calibration is done by touching the center of the crown holding the tool in line with the z-axis of the tooth (see Fig. 5). The tool's position and orientation was then registered using the graphical user interface (see below, Section II-E). By combining the exact position of the holding device (using the scale provided on the setup's frame) and the positional information of the robot, a mathematical conversion can be made to determine the position and orientation of the teeth. Because the teeth in the upper jaw are positioned horizontally and the teeth in the lower jaw are positioned vertically, the z-axis of the teeth in the upper jaw is oriented along the x-axis of the robot's world frame, as opposed to the lower jaw in which the z-axis is aligned with the z-axis of the robot's world frame. Therefore, teeth in the upper jaw need a different transformation to the world frame than teeth in the lower jaw. The calibration method, as described above, enables the forces, torques and rotations of all teeth in both upper and lower jaw to be expressed in exactly the same reference frame, easing data analysis.

Graphical User Interface

To improve the workflow during the experiments, a Graphical User Interface (GUI) is designed as a platform where all components of the setup as well as the experiments can be managed simultaneously. The GUI allows meta-information to be added to the experiments. It consists of a pre-operative, perioperative and post-operative window in which data are shown and can be edited, if necessary. In the pre-operative screen, clinical data such as periodontal or restorative state can be filed. To optimize the flow of the experiments, predefined joint positions are determined in which most relevant joints are in their neutral status (Section II-C). These predefined starting positions are different for upper and lower jaw because of their different positions relative to the robot. They can be requested and executed from within the preoperative part of the GUI. During the experiments, the GUI shows graphical information on actual measurements to enable live monitoring of the experiment. A summary of the experiment is shown and certain 'events' can be added to the experiment in the postoperative section. As an example, a marking can be added at a point in time where a complication has happened. The postoperative part also offers the opportunity to trim non-useful data, for example the time between the tooth being removed and the moment where the experiment is actually stopped in the GUI (usually a few seconds later).

The experiments took place in an in-hospital anatomy laboratory. Samples were obtained through the body donation program from the Department of Medical Biology, Section Clinical Anatomy and Embryology, of the Amsterdam UMC at the location Academic Medical Center in The Netherlands. The bodies from which the samples were taken were donated to science in accordance with Dutch legislation and the regulations of the medical ethical committee of the Amsterdam UMC at the location Academic Medical Center. The setup was tested with experiments on both conserved and fresh frozen cadaver jaws. A band saw was used to reduce the cadaver heads to the proportions as necessary to fit the holding devices. For the lower jaw, this meant an oblique 45-degree bone cut from the gonial angle of the mandible towards the retromolar area. For the upper jaw, a horizontal cut starting at the level of the infra-orbital rim was made. The cut was continued dorsally to the level of the articular tubercle and then connected to the oropharynx. See Fig. 5a and 5b. Soft tissue was largely removed by using standard surgical blades. Care was taken not to remove any of the attached gingiva, as periodontal health was one of clinical parameters. As dental notation system, the ISO system is used (International Standards Organization number 3950, Fédération Dentaire International).



(a) Upper jaw holder. (b) Lower jaw holder.

Fig. 5: Representation of the anatomical preparation of the upper- and lower jaw to fit the holding devices. The reference frames for upper- and lower teeth are shown.

Results

In order to provide a comprehensive overview of the data that can be obtained using this measurement setup, while also safeguarding the readability of this article, representative examples of data on movements, forces, and clinical data are shown. One of the main goals of this setup was to visualize what movements happen during tooth removal. To the authors best of knowledge, this has never been done before. In textbooks on oral surgery usually a short and basic movement pattern is advised for successful tooth removal[11]. Which movement pattern to choose is largely based on tooth root morphology. For example, a central upper incisor, which has only 1 root that usually has a round shape, is advised to 'rotate' out of the bony socket. For an upper molar with 3 roots, a movement from buccal to the palatal side is advised, largely luxating towards the buccal side. Fig. 6 shows the movements recorded during removal of an upper central incisor (tooth number 21). In this figure, the described pattern from the textbook can be clearly recognized. Rotations around x and y-axis are absent whilst a recurrent rotation around the tooth's axis is evident. The data shows both a clockwise and counterclockwise rotation around the tooth's axis that increases towards the clockwise side before the tooth is taken out. At the end of the movement, a slight increase in movements around the x and y-axis shows a wiggle to release the tooth.

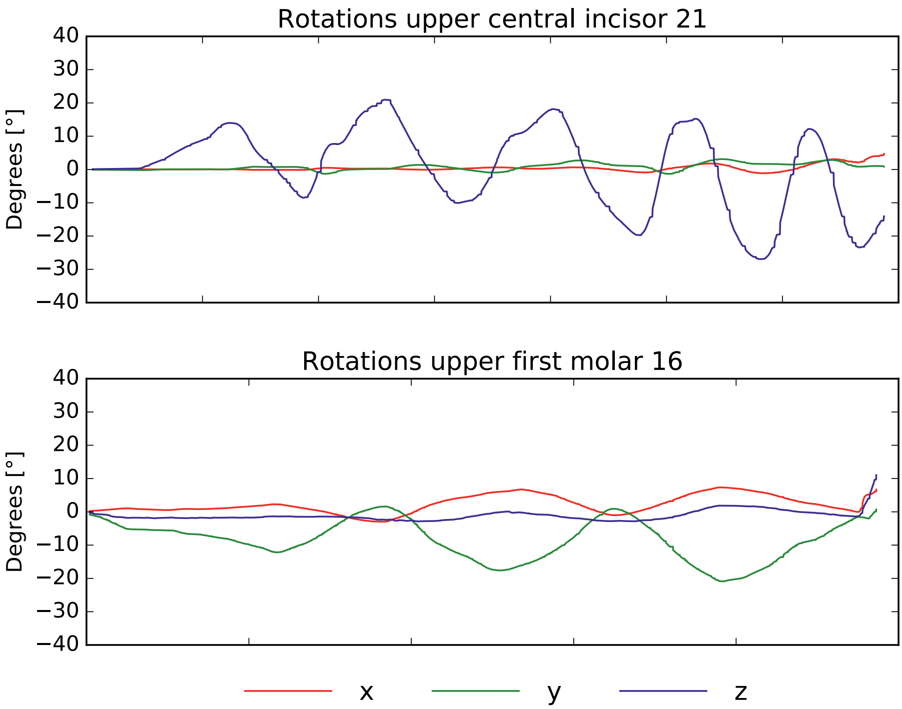


Fig. 6: Comparison of rotations of an upper incisor (21) and upper first molar (16)

When compared to the movements during removal of a first upper molar (tooth number 16) on the right side, a difference in movement pattern can be found. This first molar had, as usual, 3 roots. This means that rotation of the tooth is geometrically unfavorable. In Fig. 6, this can be recognized by the flat character of z-axis meaning no rotation takes place throughout the entire procedure. Rotation around the y-axis shows a buccal movement which increases over time. Movement around the x-axis (mesiodistal movement) shows a slight movement towards the mesial side during this buccal movement, which means the tooth is moved in the direction of the opening of the mouth.

Forces and torques

When explaining tooth removal to dental students, usually one of the first things that is explained is that, the idea of 'pulling' a tooth is incorrect. A tooth needs to be 'pushed' out. In terms of forces, one could expect a negative force in the tooth's root axis (z-axis). Fig. 7 shows the forces exerted during removal of a central upper incisor. It can be appreciated that, during the first phase of the treatment, the tooth is actually pushed into its socket. During this phase, only a little movement (rotation) can be distinguished. Later during the treatment, we can see a clear turnaround in terms of forces. Pushing into the socket becomes pulling whilst movements are increasing, meaning the tooth is coming loose.

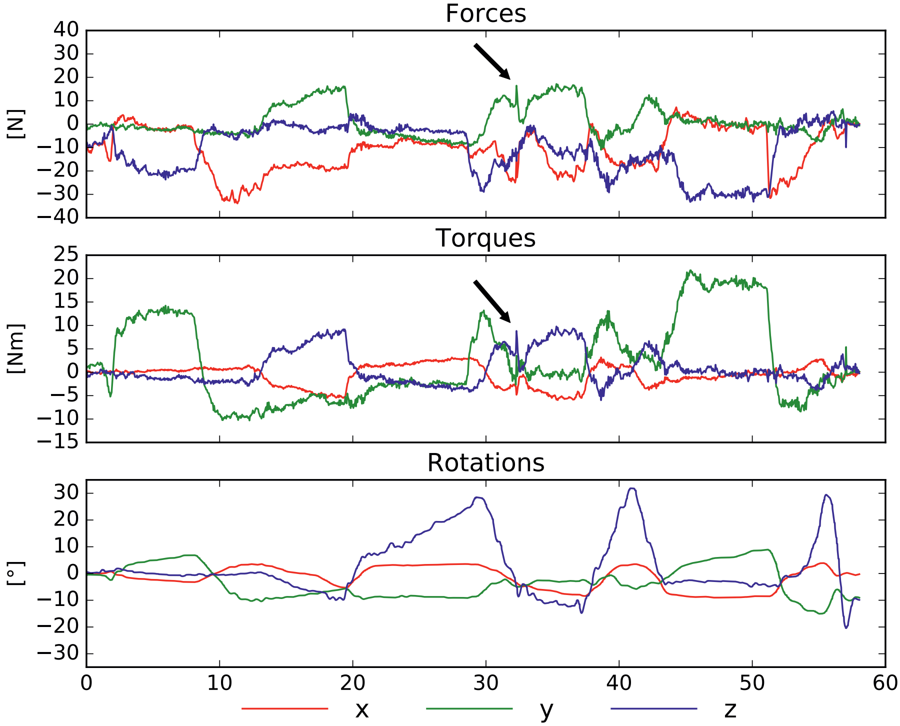


Fig. 7: Removal of a central upper incisor (21) by an experienced surgeon

Clinical data

To gain a representative dataset, most experiments during the testing phase have been performed by the same experienced oral and maxillofacial surgeon. To test if the differences between an experienced and an inexperienced clinician can be visualized, a dental intern was asked to perform experiments as well. In total, the surgeon removed 76 teeth of fresh frozen cadavers of which in 5 (7%) cases a fracture of a root occurred. The dental intern removed 21 teeth, also of fresh frozen cadaver head of which in 9 (43%) cases a fracture of a root occurred. To see if the data can deliver us further insight in what the differences between the two clinicians are, a comparison of a removal of the same type of tooth between the dental intern and the experienced oral and maxillofacial surgeon can be made. Without the necessity of an in-depth analysis, we can see major differences between the removal a central upper incisor when this procedure is performed by a dental intern (Fig. 8) and an experienced oral and maxillofacial surgeon (Fig. 7). Both teeth were central upper incisor with a composite restoration, a healthy periodontium and a root length of 14mm.

The dental student:

- exerts more than twice the amount of forces in the beginning of the procedure
- shows a less recognizable plan in terms of movements consisting of a mixture of rotational and buccopalatinal movements
- fractures the root of the tooth. This was clinically noted to happen at T(seconds) = 33. Here a small spike in the forces and torques can be observed

The surgeon manages to keep forces and torques at a relative low and stable amount whilst increasing the movements (loosen the tooth).

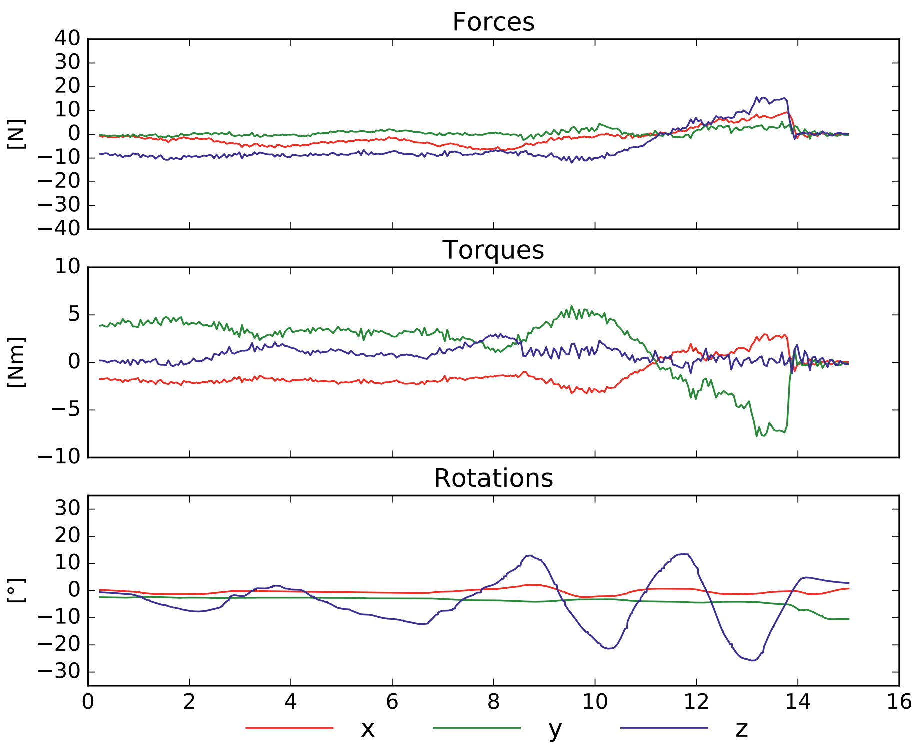


Fig. 8: Removal of a central upper incisor (11) by a dental student. The arrows indicate the spikes that occur at the instance the tooth fractures.

Discussion

In this study, a measurement setup is proposed that is the result of a strong collaboration between clinicians, mechanical and software engineers. It is capable of, for the first time, capturing the combination of high forces and subtle movements exerted during tooth removal procedures in high detail by using, amongst others, robot technology. First outcomes of experiments are used as a proof of the concept and show promising results. The dataset, which can be built with this setup, offers a unique insight in one of the oldest and most performed surgical procedures worldwide.

It is remarkable how underdeveloped the scientific under- standing of tooth removal is. Only a few attempts have been undertaken in which moments were measured in an in vivo setting, in contrast to this study where an in vitro setup is proposed [1-5, 12]. The studies that have been performed thus far used either a strain gauge or manometer attached to, or integrated in, a dental forceps. They were therefor limited to measuring forces and moments, not the movements of the clinician. The outcomes are very limited and heterogeneous, which shows the difficulty of analyzing tooth removal in vivo conditions. For example, Cicciu et al. [1] found a 25 fold increase in forces used in upper premolar removal compared to lower premolar removal whilst Lehtinen [2] and Ojala [5] found the forces between upper and lower canines to be indifferent. This shows that a benchmark to compare our results to is unfortunately not available.

The lack of technical possibilities to measure subtle (sub- millimeter) movements and high forces in all directions in an in vivo condition is the main reasons why an in vitro setup was chosen to study tooth removal. Its design for in vitro measurements is also one of the major drawbacks of this setup. It will be unsure how data can be translated into in vivo circumstances. This is even more true, since there is very limited in vivo data available to correlate the outcomes to. Next to that, the setup is limited to the use of dental forceps. The elevator is also frequently used in tooth removal procedures, but its usage is much more diverse (different positions relative to the tooth for example) and we would need to measure the movement of the teeth themselves, which made it unsuitable for a first proof of concept. Finally, the setup does not provide the possibility to measure clamping forces between the tooth and dental forceps. This would require mechanical changes to the dental forceps itself and might interfere with the normal usage of a dental forceps by the clinician. Despite its disadvantages, the authors believe that, especially when using fresh frozen cadavers, the setup can be used to gain a unique and relevant new insight into tooth removal techniques.

Mechanically the development of the rigid fixation method for a human upper and, to a lesser extent, lower jaw was most challenging. Several designs were 3D-printed in plastic and tested on conserved cadaver jaws on ease-of-fixation and rigidity of the fixation method before the final design was chosen and manufactured in stainless steel. When first testing the stainless steel setup a slight mobility of the jaw holders was noted due to the locking bolt in the rotational plate, which was a prefabricated and gave some slack. It was later customized to a locking pin that could be tightened by rotation, which resulted in a strong and complete rigid fixation of the jaws. During the experiments with fresh frozen jaws, out of 146 experiments, only 2 times an experiment failed because of loosening of the jaw within the holding device. Both times, it involved an upper jaw and loosening was due to improper tightening of the holding device at the start of the experiment.

For the measurement of movements, a robot was added to the setup. One of the major concerns when using the robot in a 'compliant' mode was the robot not being fully passive at all times. Especially when joint limits are approached with some pace, the robot showed resistance when adapting its joint position to enable certain positions or movements. To overcome this problem a 'best fit' starting position of the end-effector of the robot was to be found where most (relevant) joints were in a neutral position to ensure as little resistance as possible. Although it is difficult to measure the exact value of the resistance, it seems relatively small in comparison with the large amounts of forces exerted. The upper jaw was fixated with the occlusal plane in a vertical way and the lower jaw with its occlusal plane horizontal to mimic the clinical situation, which required different "preset" joint positions for upper and lower jaws. These positions, that were optimized based on preference from the surgeons, were programmed starting position for all experiments. The combination of an adjustable frame and a rotational plate ensured roughly the same starting position for all experiments in upper and lower jaw. Pre-programming the same joint positions at the start of each experiment also added to the reproducibility of the experiments. Despite all efforts on creating a setup that comes as close to a clinical setting as possible, it must be noted that some resistance seems inevitable and this should be taken into account when interpreting results of these experiments. Despite a slight learning curve was noted when it comes to working with a passive robot arm, the feedback the authors received on clinical representativeness in general was very positive.

To calibrate the position of the tooth and its orientation relative to the FT-sensor and the robot a different dental instrument was used for both upper and lower jaw. It was aligned with the tooth axis by the clinician based on the orientation of the crown of the tooth. Despite efforts made to be as precise as possible, some comments should be made. Firstly, even in an in vitro setting, it can be quite challenging to align a tool in all axis at the same time. Secondly, the crown forms only a small portion of the tooth. It is common knowledge in the field of dentistry that roots tend to divert to some extend (usually distally). To add to the precision of the measurements in future experiments it can be considered to use CT-data to calibrate the position of the entire jaw by using anatomical landmarks rather than calibrating each tooth separately. This could also reduce duration of the experiments.

Conclusions and future work

It is the goal of this research group to acquire data on every aspect of tooth removal. With this setup, a dataset can be build that contains high quality data on every aspect of tooth removal. Data driven modelling will be used to analyze the large amount of data. A model is necessary to be able to understand what makes tooth removal (un-) successful. Clinicians could learn from a model what parameters are essential to look for in clinic and to help predict the level of difficulty of an upcoming procedure. It could help them to decide when referral is necessary based on their own competence. The setup allows for different teaching instruments, i.e., plastic models or conserved cadavers, to be tested on representativeness. The derived dataset will be used to create new and evidence based learning material for dental students and young dentists. In a later phase, some parts of the setup can be transformed for the use in an in vivo experiment to enable a correlation to clinical data.

References

[1] M. Cicciù, E. Bramanti, F. Signorino, A. Cicciù, F. Sortino, Experimental study on strength evaluation applied for teeth extraction: an in vivo study, The open dentistry journal 7 (2013) 20-6.

[2] R. Lehtinen, T. Ojala, Rocking and twisting moments in extraction of teeth in the upper jaw, International journal of oral surgery 9 (1980) 377-382.

[3] A.J. MacGregor, G.E. Tomlinson, An apparatus for measuring the forces of dental extraction, The British journal of oral surgery 17(1) (1979) 71-6.

[4] V. Ahel, I. Brekalo, J. Ahel, G. Brumini, Measurement of tooth extraction forces in upper incisors, Collegium antropologicum 30(1) (2006) 31-5.

[5] T. Ojala, Rocking moments in extraction of teeth in the lower jaw, Int J Oral Surg 9(5) (1980) 367-72.

[6] C. Hanson, T. Wilkinson, M. Macluskey, Do dental undergraduates think that Thiel-embalmed cadavers are a more realistic model for teaching exodontia?, European Journal of Dental Education 22(1) (2018) e14-e18.

[7] H.S. Brand, C.C.J. van der Cammen, S.M.E. Roorda, J.A. Baart, Tooth extraction education at dental schools across Europe, BDJ Open 1 (2015) 15002-15002.

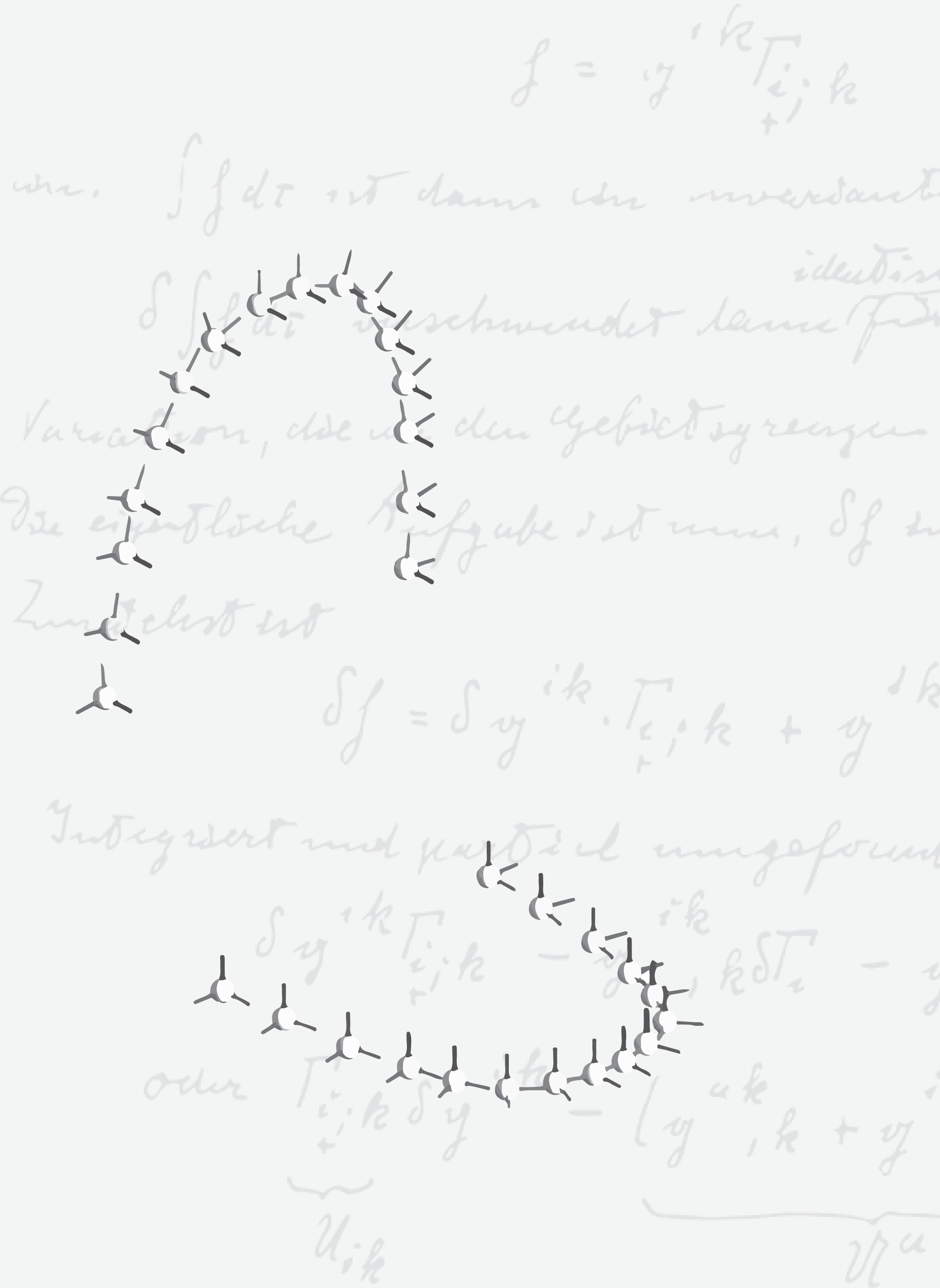
[8] P. Onclin, Recent increase in simple extractions in OMF-surgeries in the Netherlands studied, Nederlands Tijdschrift voor Tandheelkunde 123(07/08) (2016) 365-372.

[9] M. Quigley, K. Conley, B.P. Gerkey, J. Faust, T. Foote, J. Leibs, R. Wheeler, A.Y. Ng, ROS: an open-source Robot Operating System, ICRA Workshop on Open Source Software, 2009.

[10] C. Hennersperger, B. Fuerst, S. Virga, O. Zettinig, B. Frisch, T. Neff, N. Navab, Towards MRI-Based Autonomous Robotic US Acquisitions: A First Feasibility Study, IEEE Trans Med Imaging 36(2) (2017) 538-548.

[11] B. Stegenga, MKA Chirurgie, 2nd ed., van Gorcum2013.

[12] V. Ahel, T. Cabov, S. Spalj, B. Peric, D. Jelusic, M. Dmitrasinovic, Forces that fracture teeth during extraction with mandibular premolar and maxillary incisor forceps, Br J Oral Maxillofac Surg 53(10) (2015) 982-7.



Chapter 5

Using robot technology to analyze forces and torques in tooth removal

This chapter is based on the following publication:
Using robot technology to analyze forces and torques in tooth removal
T.C.T. van Riet, W.M. de Graaf, J. Kober and J. de Lange

Published in: Advances in Oral and Maxillofacial Surgery, 2023

Abstract

This study aimed to capture both forces and torques exerted during tooth removal in clinically relevant dimensions and high detail. An ex vivo measuring setup was designed consisting of, amongst others, a compliant robot arm and a six-axis force/torque sensor. Fresh-frozen cadavers were used to match the clinical situation as closely as possible. Complete data was successfully recorded in 110 tooth removal experiments. The highest peak force was 99 Newton. An increase in forces in the dorsal region was objectified in both average and total forces exerted. Extrusion and buccal forces were found to be most dominant in both upper and lower jaw. A strong limitation exists in our scientific understanding of tooth removal procedures. In this study, for the first time, forces and torques are presented in high detail and in all (clinically relevant) dimensions. Despite the limited data size and ex vivo circumstances, the hereby-presented data show a reliable order of magnitude when considering forces in tooth removal and could serve as a benchmark for future research in this field. A better understanding of these procedures could aid in the development of evidence-based and improved educational material.

Introduction

In 1952, Captain Donald Kitzis from the Dental Corps of the United States Army stated that 'exodontia, as a scientific field of endeavor, has been sadly lacking in fundamental precepts' and closes his article hoping that 'this article will stimulate some thought along these lines in order that the practice of exodontia be placed on a more scientific foundation' [1]. Being one of the oldest en most frequently performed invasive procedures; the lack of scientific progress of tooth removal procedures is impressive. Since then, only several papers have been written on this subject, measuring forces in limited ways and only on a selection of teeth on either animals [2], patients [3, 4] or more recently, in a laboratory setting [5]. Measurements of torques (rotational forces) are mostly absent and, together with the limited available data on forces, leads to a strong limitation in our scientific understanding of tooth removal procedures.

The existing knowledge gap has its influence on the quality of education and previous efforts closing it had mostly educational purposes in mind [3, 5]. With strong evidence-based education being absent a wide variety of educational approaches are currently practiced, ranging from readers and cadaver training to none at all, in which students practice on patients from the start [6, 7]. Especially in developed countries, due to the successes of preventive dentistry, the possibility to practice on patients has been reduced, leading to less confidence among young dentists and an increase in unnecessary referrals to maxillofacial surgeons [6, 8].

This is in contrast to other aspects of dental training such as restorative dentistry, for which sophisticated training modalities have been developed, ranging from virtual training with haptic feedback [9] to robotic patient simulators [10, 11]. The scientific evidence for most initiatives where robot technology is deployed in dentistry, including educational purposes, should be considered as low [12].

The goal of this project is to capture both forces and torques exerted during tooth removal in clinically relevant dimensions and high detail by using, amongst others, robot technology. The results of a series of experiments on fresh-frozen cadavers are presented in a descriptive manner and could improve our scientific understanding of these procedures.

Materials and Methods

Experiments

To capture forces and torques in a reliable manner and matching the clinical circumstances as closely as possible, an *ex vivo* measuring setup was designed and fresh-frozen cadavers were used. Material was obtained from the clinical anatomy and embryology section of the department of medical biology. This material was donated to science in accordance with Dutch legislation and the regulations of the medical ethical committee. In total, seven Caucasian cadavers were used for this study and extractions were performed by three senior oral and maxillofacial surgeons. Cadaver material was prepared with a band saw to reduce the material to the necessary proportions for the holding device and excess soft tissue was removed. Care was taken not to remove any of the attached gingiva. The ISO (International Standards Organization number 3950, Fédération Dentaire International) system was used as dental notation system.

Measurement Setup

The design process as well as a more detailed description of the setup can be found in previous work [13]. An overview of the setup is presented in Figure 1. To add to the readability of this article, only its main components are summarized. The setup consisted of;

- a compliant robot arm (KUKA LBR iiwa 7 R800) which passively follows the movements of the clinician for registration purposes (frequency 100Hz) and functions as a calibration tool to allow for determination of the position and orientation of each tooth.
- a six-axis force/torque (FT) sensor (ATI industrial automation 16 bit Delta transducer) for registration of forces and torques at 20Hz.
- a video-camera (Logitech C920 Pro HD) to record a video stream of the experiments.
- an interchangeable custom-built upper and lower jaw holding device.
- a custom-build frame (Item Industrietechnik, Solingen, Germany) adjustable both horizontally and vertically as well as a custom-built rotational plate to ensure a clinical representative situation in which an ergonomic pose can be maintained.
- the open source framework Robot Operating System (ROS) for integration of all components.

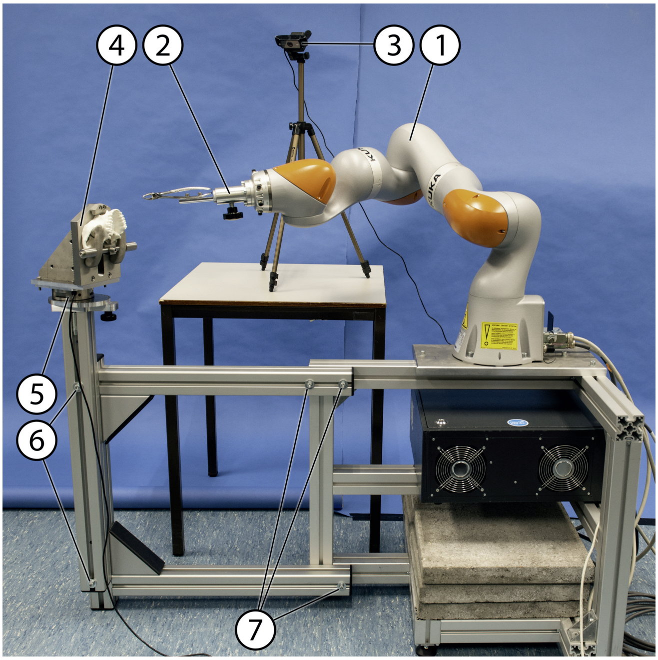


Figure 1: Overview of the setup with a 3D-printed upper jaw in situ. (1) passive robot arm (2) forceps holding device, (3) video camera, (4) upper jaw holding device (the lower jaw holding device not shown in this figure), (5) six-axis force/torque sensor, (6) bolts to change vertical position, (7) bolts to change horizontal position. The holding device for the lower jaw is not displayed.

A graphical user interface (GUI) was designed for the registration of metadata, including:

- preoperative: tooth number, periodontal health, restorative state, surgeon involved.
- perioperative: recorded data is shown live on screen. Landmarks can be added at any given time in case of events such as crown fractures or other complications.
- postoperative: quality of the experiment, any complications and a free text field to add any specific remark.

Metadata was added to enable to construct a complete database for future use on the one hand and to help to explain certain findings during data-analysis, such as outliers, on the other. Because of the limited number of experiments in combination with the expected variability of the data, at this point, not all of the above-mentioned metadata could be used for in-depth analysis in our result section.

Calibration, reference frame and validation

At the beginning of each experiment the location and orientation of each tooth was calibrated. To do so, the robot arm, with a straight periosteal elevator mounted in the forceps-holding device, was positioned parallel to the axis of each tooth and in the center of each crown. The expected rotational center was estimated 2mm below this point. A mathematical translation from the center of the force/torque sensor to the center of rotation of each tooth was performed. If necessary, axis were mirrored to align the tooth frames in clinically relevant dimensions. For example, a force in buccal direction on a left upper first molar needs to be mirrored along the mesiodistal axis to enable a useful comparison with the buccal forces on a right upper first molar. The mathematical translations were validated on a mounted plastic jaw. Exaggerated forces and torques in all directions were performed on all four first molars in a standardized order. After translation, it was checked that the tooth frames were correctly aligned for all quadrants.

Data availability

The processed data required to reproduce these findings are available to download from https://www.doi.org (digital object identifier: 10.4121/16847026, license: CC BY 4.0).

Results

Basic characteristics

In total seven fresh-frozen Caucasian specimens were obtained for this study on which 127 experiments were performed. In 110 (86.6%) of these experiments full data was successfully recorded. The largest part of these procedures happened uneventful (n=94, 85.5%). In other experiments data was successfully recorded but some complications were present of which a fracture of the boney wall was seen most frequently (n=9, 8.2%) and less often crown or root fractures (combined n=9, 8.2%). Most teeth had sound periodontal (n=60, 54.5%) and restorative (n=45, 42.7%) states. A complete overview of the basic characteristics of the experiments material is supplied in appendix table A.1.

Forces and Torques in tooth removal

Results are shown as cumulative forces (Newton-second or 'impulse') either along an axis or in a direction (Figure 2). It is important to note that the duration of the experiments are not compensated for in this outcome. To benefit the readability of this article, the results of the average forces and torques, in which time the duration is compensated for, are shown in the appendix (appendix figure A.1, A.2 and A.3).

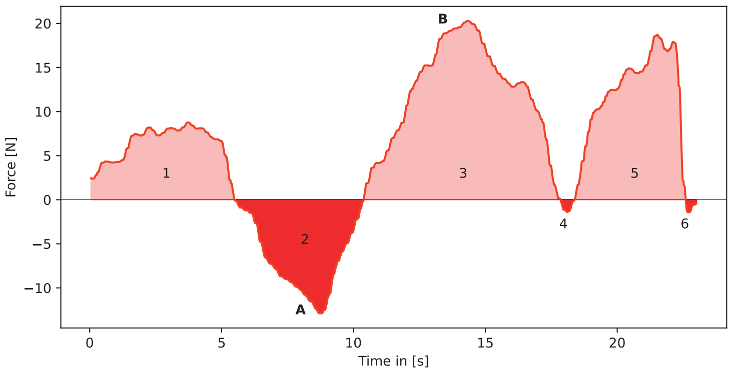


Figure 2: a representative force measurement in the buccolingual axis of an upper second molar. The Area Under the Curve (AUC) of both positive (1+3+5) and negative values (2+4+6) represent the cumulative forces exerted along the buccolingual axis. The positive values (1+3+5) are in buccal direction, the negative values (2+4+6) are in lingual direction. The letters A and B show the peak forces measured in the lingual and buccal directions, respectively.

The total amount of cumulative forces exerted during tooth removal along each axis, regardless of its direction, are shown in Figure 3 as an average and standard deviation for each pair of teeth. It shows the averages of the cumulative forces measured during the experiments for each group of teeth. The average of cumulative forces measured during all of the experiments is 420 Ns (SD = 336 Ns) and removal took the surgeon 20.1 seconds (SD = 12.6 sec). The lowest amount of cumulative forces and torques can be found in the upper central incisor group (U1) and measures 150 Ns (SD = 96 Ns). On average, the highest cumulative forces were found in the lower second molars (L7, 1061 Ns, SD = 653 Ns) and highest cumulative torques in the upper second molars (U7, 130 Nms, SD = 61 Nms).

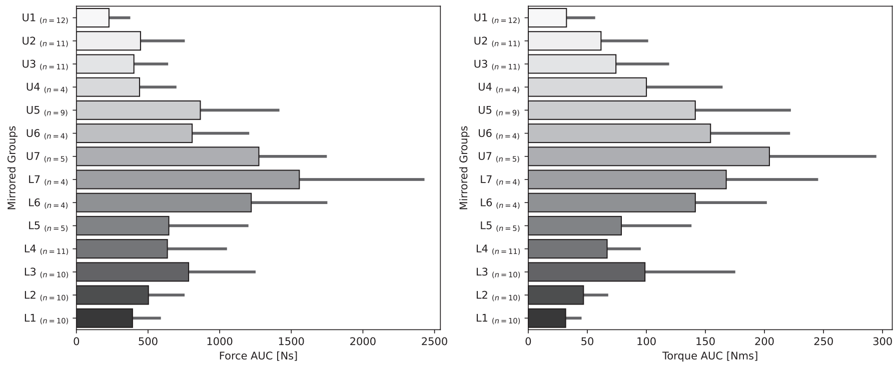


Figure 3: the average amount of all cumulative forces (left figure) and torques (right side) measured during the experiments per set of teeth. U = upper. L = lower. The numbers stand for mirrored groups, meaning U4, for example, contains force data of both the 14 and 24. The error bars show the standard deviation of each group. Ns = Newton second. Nms = Newtonmeter second. n = number of experiments in each group. AUC = area under the curve.

Direction of Forces and Torques

The reference frames were mathematically translated into six matching directions of forces and torques. In Figure 4, the cumulative forces exerted in these directions are presented. In both upper and lower jaw, the extrusion and buccal cumulative forces are found to be most dominant. Only in the central upper incisors the intrusive cumulative forces seem more pronounced compared to the extrusive cumulative forces. Increasing cumulative forces can be found more distally in the dental arch. Cumulative forces along the mesiodistal plane are lowest with a preference towards the mesial side in the upper jaw.

The lowest peak force was measured in an upper central incisor in which forces did not reach above 9N (extrusion) in any direction. The highest peak force was 99N (intrusion), which was measured in an upper second premolar.

The cumulative rotational forces and their directions are shown in Figure 5. The most dominant cumulative torques are found in buccoversion in the lower jaw, which are more balanced with palatoversion in the upper jaw. Besides that, a strong mesiobuccal rotation was found in the upper molar area, but otherwise mesiobuccal and palatal/lingual cumulative rotational forces are found to be relatively low.

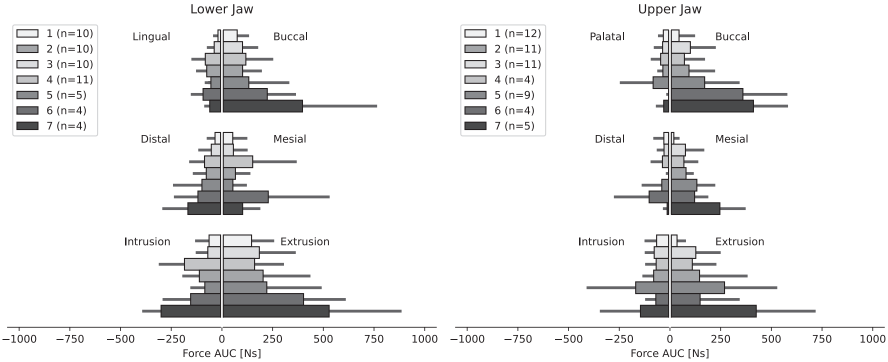


Figure 4: average cumulative forces and their directions separated in all six directions. The error bars show the standard deviation of each group. Ns = Newton second. n = number of experiments in each group. AUC = area under the curve.

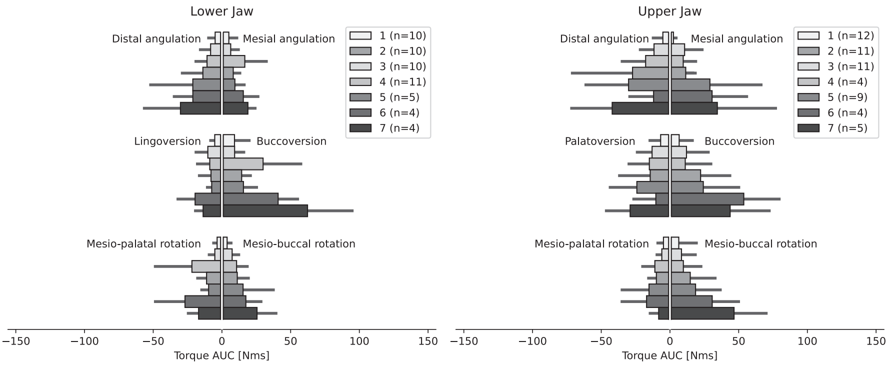


Figure 5: average cumulative rotational forces (torques) and their directions separated in all six directions. The error bars show the standard deviation of each group. Nms = Newtonmeter second. n = number of experiments in each group. AUC = area under the curve.

Discussion

The goal of this project was to capture forces and torques exerted in tooth removal procedures in clinically relevant dimensions and in high detail. A descriptive analysis of experiments in an ex vivo setup was presented.

In total, 110 measurements on successful tooth removal procedures were included. Despite the limited size of the dataset, it seems to supply a reliable order of magnitude when looking at forces and torques in tooth removal. In terms of forces, the increase in amount of total force necessary to remove more dorsally located teeth is eminent. The most dominant directions of forces seem to be the buccal side and extrusion for both upper and lower jaw. When the results are compensated for time (see appendix figures A.1, A.2 and A.3) the differences become less apparent. This means that some of the differences found in figure 3, 4 and 5 can be explained by the duration of the treatment. Other relevant findings in this study are the highest and lowest peak forces. A 10-fold increase was found in the measured peak forces between an upper second premolar (intrusive direction) and upper central incisor (extrusive direction).

A large standard deviation was found in our outcomes, showing a high variance in forces, torques and time for removal even within groups of the same teeth. This finding was expected and corresponds well with our clinical experience. The amount of forces and their direction varies largely based on anatomic factors, such as the total root surface, amount and curvature of roots, but also of patient factors such as bone morphology and mineral density [14, 15]. Although metadata was present that could (partially) explain some of the variance, the dataset was too small to make any reliable conclusion in this matter.

Most recent studies focused on measuring forces in limited directions and/or with only a selection of teeth. A useful comparison to previous literature is difficult since the existing scientific data is scarce and heterogeneous both in study design as in outcome. For example, Ahel et al.[4, 15] and Lethinen et al.[16] measured forces distinguishing between 'twisting' (rotational) and 'rocking' (buccolingual or buccopalatal) directions in an in vivo setup. Respectively, only incisors and teeth in the upper jaw were included. Cicciu et al., next to twisting and rocking forces, also distinguished 'grasping' forces in an in vivo study on the removal of a selection of premolars [17]. Dietrich et al. measured forces exerted with a unidirectional vertical extraction system in an in vivo setup, but molars were not included [14, 18]. Most recently, Sugahara et al. published data gained from simulating an extraction force performed by students and professionals in an in vitro laboratory setting. Forces were measured in three dimensions on a simulated mandibular molar [5].

Although the data in this study was of relatively high quality, it should be carefully interpreted in terms of clinical representativeness. This caution is related to the fact that the data was gathered ex vivo. Whilst the feedback from the surgeons was very positive in terms of clinical representativeness, it is not known in what way the freezing process influenced the biomechanical properties of tooth removal. In addition, the availability of only Caucasian cadavers for this study should be taken into account.

There are some disadvantages to our measurement setup. Despite efforts in setting the correct stiffness and damper of each of the robots axis, it must be noted that minor resistance of the robot can be felt during the experiments. Especially when reaching a 'joint limit' the robot will actively move other joints to facilitate freedom of movement, which inevitably leads to some resistance. Another disadvantage of this setup is the limitation of using only a dental forceps, whilst elevators are important and frequently used tools. The constantly changing position of the elevators relative to the tooth make it a less appropriate tool to start building a reliable dataset. Since elevators are frequently used, it would be interesting to evaluate forces and movements exerted with these instruments in the near future. In opposite of previously mentioned studies, we did not measure clamping forces [17]. Lastly, since counteracting forces had to be prevented, the surgeon was allowed to only use one hand during the experiments, which make it slightly unnatural but, moreover, the second hand might give useful feedback in clinical practice. Regardless of these disadvantages, we believe that, with existing techniques, it would be very challenging to gather the same quality dataset in an in vivo setup.

To the authors' best knowledge this is the first time that forces and torques exerted during tooth removal have been measured, let alone in high detail and in all its dimensions. Using fresh-frozen cadavers, an extensive measurement setup, experienced surgeons and including all teeth from both lower and upper jaws, we are convinced to have gained important insights. The data show a reliable order of magnitude when considering forces and torques in tooth removal and can be used as benchmark for comparison with future projects. Data gained from plastic educational models and different kinds of conserved cadaver material can be compared to see what we can learn from their differences. Furthermore, the current database can be extended to see what influence certain clinical parameters have on extraction forces. Eventually, our goal is to improve our understanding of these complex procedures to the extent that evidence-based educational tools can be created to acquire preclinical skills, for example, through force-based learning [19-21].

References

[1] D. Kitzis, From theory to practice in exodontia, Oral Surgery, Oral Medicine, Oral Pathology 5(11) (1952) 1185-1193.

[2] M. Chiba, S. Ohshima, K. Takizawa, T. Matsuda, Measurement of the Force to Extract the Rat Mandibular Incisor, Journal of Dental Research 59 (1980) 1886-1886.

[3] A.J. MacGregor, G.E. Tomlinson, An apparatus for measuring the forces of dental extraction, The British journal of oral surgery 17(1) (1979) 71-6.

[4] V. Ahel, I. Brekalo, J. Ahel, G. Brumini, Measurement of tooth extraction forces in upper incisors, Collegium antropologicum 30(1) (2006) 31-5.

[5] K. Sugahara, H. Bessho, A. Nishiyama, Y. Koyama, M. Koyachi, T. Toyoda, K. Kasahara, A. Watanabe, M. Takano, A. Katakura, The utility of custom-developed tooth extraction simulator - A comparative analysis from beginner to trainer, Journal of Oral and Maxillofacial Surgery, Medicine, and Pathology 33(1) (2021) 43-47.

[6] H.S. Brand, C.C.J. van der Cammen, S.M.E. Roorda, J.A. Baart, Tooth extraction education at dental schools across Europe, BDJ Open 1 (2015) 15002-15002.

[7] C. Hanson, T. Wilkinson, M. Macluskey, Do dental undergraduates think that Thiel-embalmed cadavers are a more realistic model for teaching exodontia?, European Journal of Dental Education 22(1) (2018) e14-e18.

[8] P. Onclin, Recent increase in simple extractions in OMF-surgeries in the Netherlands studied, Nederlands Tijdschrift voor Tandheelkunde 123(07/08) (2016) 365-372.

[9] I.R. de Boer, P.R. Wesselink, J.M. Vervoorn, Student performance and appreciation using 3D vs. 2D vision in a virtual learning environment, Eur J Dent Educ 20(3) (2016) 142-7.

[10] S. Abe, N. Noguchi, Y. Matsuka, C. Shinohara, T. Kimura, K. Oka, K. Okura, O.M.M. Rodis, F. Kawano, Educational effects using a robot patient simulation system for development of clinical attitude, European Journal of Dental Education 22(3) (2018) e327-e336.

[11] T.C.T. van Riet, K.T.H. Chin Jen Sem, J.T.F. Ho, R. Spijker, J. Kober, J. de Lange, Robot technology in dentistry, part two of a systematic review: an overview of initiatives, Dent Mater 37(8) (2021) 1227-1236.

[12] T.C.T. van Riet, K.T.H. Chin Jen Sem, J.T.F. Ho, R. Spijker, J. Kober, J. de Lange, Robot technology in dentistry, part one of a systematic review: literature characteristics, Dent Mater 37(8) (2021) 1217-1226.

[13] T.C.T. van Riet, W.M. de Graaf, R. van Antwerpen, J. van Frankenhuyzen, J. de Lange, J. Kober, Robot Technology in Analyzing Tooth Removal - a Proof of Concept, Annu Int Conf IEEE Eng Med Biol Soc 2020 (2020) 4721-4727.

[14] T. Dietrich, I. Schmid, M. Locher, O. Addison, Extraction force and its determinants for minimally invasive vertical tooth extraction, J Mech Behav Biomed Mater 105 (2020) 103711.

[15] V. Ahel, T. Cabov, S. Spalj, B. Peric, D. Jelusic, M. Dmitrasinovic, Forces that fracture teeth during extraction with mandibular premolar and maxillary incisor forceps, Br J Oral Maxillofac Surg 53(10) (2015) 982-7.

[16] R. Lehtinen, T. Ojala, Rocking and twisting moments in extraction of teeth in the upper jaw, International journal of oral surgery 9 (1980) 377-382.

[17] M. Cicciù, E. Bramanti, F. Signorino, A. Cicciù, F. Sortino, Experimental study on strength evaluation applied for teeth extraction: an in vivo study, The open dentistry journal 7 (2013) 20-6.

[18] E. Muska, C. Walter, A. Knight, P. Taneja, Y. Bulsara, M. Hahn, M. Desai, T. Dietrich, Atraumatic vertical tooth extraction: a proof of principle clinical study of a novel system, Oral Surg Oral Med Oral Pathol Oral Radiol 116(5) (2013) e303-10.

[19] S.F. Hardon, T. Horeman, H.J. Bonjer, W. Meijerink, Force-based learning curve tracking in fundamental laparoscopic skills training, Surg Endosc 32(8) (2018) 3609-3621.

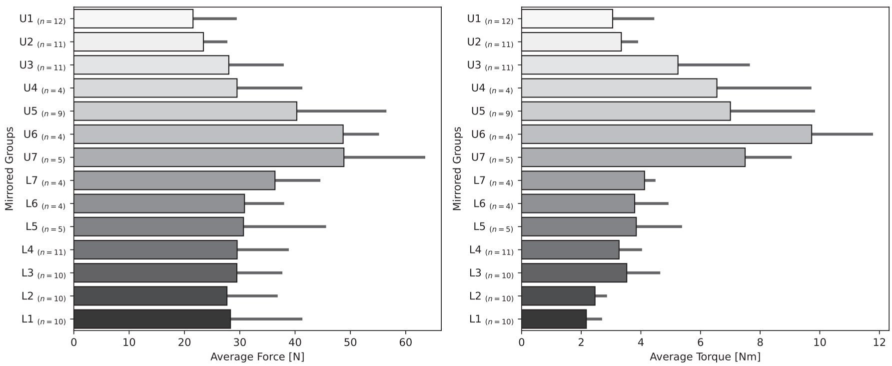
[20] M.G. Beuling, T.C.T. van Riet, J. van Frankenhuyzen, R.V. Antwerpen, B. de Blocq van Scheltinga, A.H.H. Dourleijn, D. Ireiz, S. Streefkerk, J.C. van Zanten Jan de Lange, J. Kober, D. Dodou, Development and testing of a prototype of a dental extraction trainer with real-time feedback on forces, torques, and angular velocity, Annu Int Conf IEEE Eng Med Biol Soc 2022 (2022) 3285-3290.

[21] W.M. de Graaf, T.C.T. van Riet, J. de Lange, J. Kober, A Multiclass Classification Model for Tooth Removal Procedures, J Dent Res 101(11) (2022) 1357-1362.

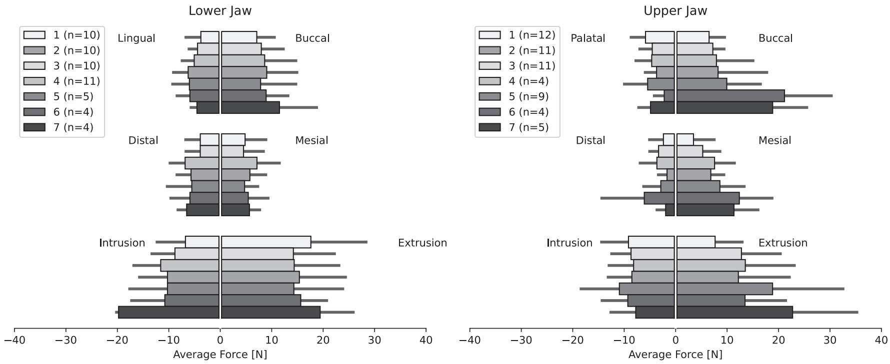
Supplementary Materials

Appendix Table A.1: base characteristics of experimental material and experiments. mm = millimeter.

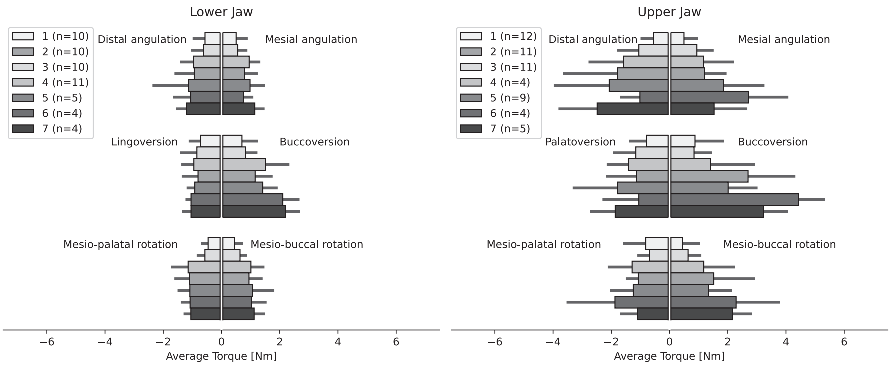
Base Characteristics	Total number
Fresh-frozen specimens	**7**
Upper jaws with teeth	6
Lower jaws with teeth	6
Total number of experiments	**127**
Successful experiments:	**110**
Without complications	94
Boney wall fracture	9
Root fracture (late)	6
Crown fracture/failure (with root removal)	3
Unsuccessful experiments:	**17**
Insufficient fixation of jaw	8
Early crown fracture/failure (without root removal)	5
Robot / software errors	
Excessive slippage of the forceps	3
	1
Periodontal state (out of 110 experiments)	
- sound (pocket depth <3mm)	82
- recessions	33
- mild decay (pocket depth 3-5mm)	16
- severe decay (pocket depth >5mm)	12
Restorative state (out of 110 experiments)	
- sound	47
- direct restoration large (≥ 2 surfaces)	25
- indirect restoration	20
- direct restoration small (≤ 2 surfaces)	18



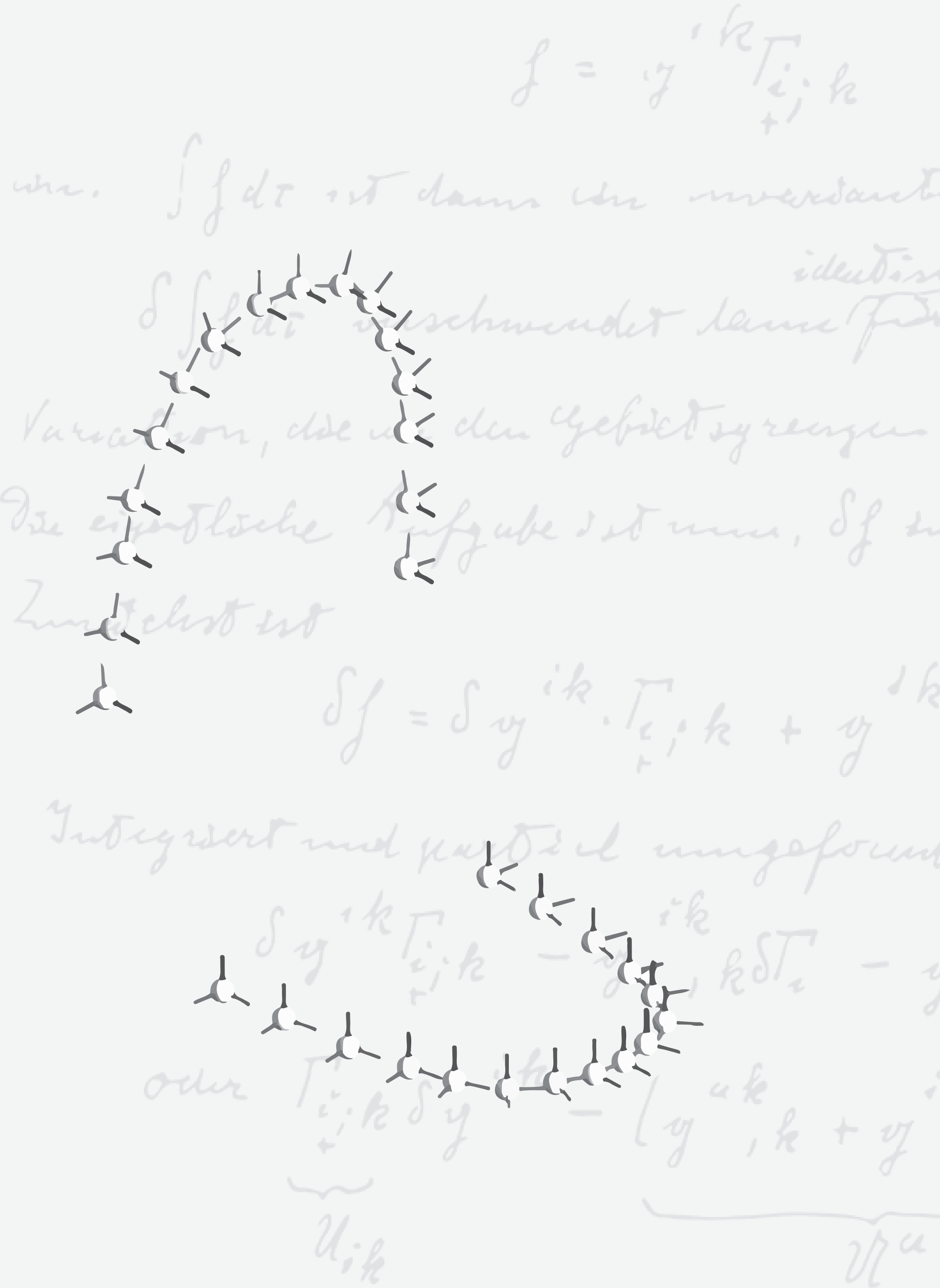
Appendix Figure A.1: the average amount of all forces (left figure) and torques (right side) in all directions combined. U = upper. L = lower. The numbers stand for mirrored groups, meaning U4, for example, contains force data of both the 14 and 24. The error bars show the standard deviation of each group. N = Newton. Nms = Newtonmeter. n = number of experiments in each group.



Appendix Figure A.2: average forces and their directions separated in all six directions. The error bars show the standard deviation of each group. N = Newton. n = number of experiments in each group.



Appendix Figure A.3: average rotational forces (torques) and their directions separated in all six directions. The error bars show the standard deviation of each group. Nm = Newtonmeter. n = number of experiments in each group.



Chapter 6

Analysis of movements in tooth removal procedures using robot technology

This chapter is based on the following publication:
Analysis of movements in tooth removal procedures using robot technology
T.C.T. van Riet, W.M. de Graaf, J. de Lange and J. Kober

Published in: PLoS One, 2023

Abstract

Being one of the oldest en most frequently performed invasive procedures; the lack of scientific progress of tooth removal procedures is impressive. This has most likely to do with technical limitations in measuring different aspects of these keyhole procedures. The goal of this study is to accurately capture the full range of motions during tooth removal as well as angular velocities in clinically relevant directions. An *ex vivo* measuring setup was designed consisting of, amongst others, a compliant robot arm. To match clinical conditions as closely as possible, fresh-frozen cadavers were used as well as regular dental forceps mounted on the robot's end-effector. Data on 110 successful tooth removal experiments are presented in a descriptive manner. Rotation around the longitudinal axis of the tooth seems to be most dominant both in range of motion as in angular velocity. Buccopalatal and buccolingual movements are more pronounced in the dorsal region of both upper and lower jaw. This study quantifies an order of magnitude regarding ranges of motion and angular velocities in tooth removal procedures. Improved understanding of these complex procedures could aid in the development of evidence-based educational material.

Introduction

In 1934, George Christiansen simplified tooth removal as removing a calcified substance from a bony socket lined by a fibrous membrane [1]. In his detailed paper, he provided expert instructions on what ideal movements in tooth removal should look like. In 1952, expert opinions on movements strategies from 'authorities in the field of exodontia' were summarized by Donald Kitzis [2]. Expert opinions, such as the aforementioned, regarding optimal tooth removal strategies lack, to date, a strong scientific background. This lack of scientific development is remarkable, since tooth removal is one of the most common and oldest surgical procedures worldwide.

In contrast to movement patterns, some literature is available in which forces exerted during tooth removal are measured and analyzed. Scientific attempts to objectify these forces, however, are often restricted in their design. They are either limited to a small selection of teeth *in vivo* [3, 4], animal studies [5] or measured in an laboratory setting using a single tooth [6]. A scientific gap seems to exists in our knowledge of tooth removal [7]. In an effort to bridge this gap, the authors recently reported on forces and torques measured in experiments on fresh frozen cadavers [8]. The lack of scientific understanding of tooth removal has serious consequences for the education of dental students and most previous work in this field state to do so for educational reasons [6, 9]. It is well known that students often feel unprepared before performing their first tooth removal on patients [10]. Preclinical training models are largely absent and, if used, rarely valued as representative [10]. Up until today, direct practice on patients, without significant preclinical training, is the most widely used training modality. However, in well-developed countries where preventive dentistry prevails, the opportunities to practice these procedures on patients are reducing. This situation potentially leads to less confident young dentists and more unnecessary referrals to oral and maxillofacial surgeons [11].

To benefit, amongst others, the development of new educational material, it is necessary to improve our knowledge of these complex procedures. Previous research aimed at analyzing forces in tooth removal, but research initiatives analyzing motion patterns are missing in literature [7]. The purpose of this study is to capture the full range of motions and angular velocities in a series of tooth removal experiments on fresh frozen cadavers. As explained in previous work describing a 'proof of concept', we hypothesized that robot technology will allow us to record high-frequency and high-resolution data of movements in tooth extraction [9]. Results will be presented in a descriptive manner and recommendations for future research will be discussed.

Materials and Methods

Overview of the experiment

To capture movements during tooth removal in a reliable manner, an *ex vivo* measuring setup was considered most valuable, which is explained in detail in previous work [9]. Fresh frozen cadavers were obtained from the clinical anatomy and embryology section of the department of medical biology of the Amsterdam university medical center (Amsterdam UMC). The donation process was in accordance with Dutch legislation and the regulations of the medical ethical committee of the Amsterdam UMC. No separate approval was necessary by the medical ethical committee for anatomical studies according to local regulations. The authors state that every effort was made to follow all local and international ethical guidelines and laws that pertain to the use of human cadaveric donors in anatomical research [12].

Cadavers were selected by a single anatomy laboratorian based on the presence of multiple teeth and reduced to the necessary proportions by the first author to fit the measurement setup in the anatomical laboratory. This procedure has been described in detail in previous work [9]. A plastic model of the jaws in their reduced proportion is presented in Fig. 1 and 2. Still in frozen condition, the lower jaw was reduced with an oblique cut using a reciprocating saw from the retromolar area to the gonial angle. The upper jaw was reduced by a horizontal cut at the infra-orbital level and a vertical cut behind the temporal root. Soft tissues were removed after defrosting with a scalpel, but care was taken not to remove any attached gingiva. The teeth itself and their directly surrounding hard and soft tissues were left intact with a wide margin as to ensure similar conditions throughout the experiments. To ensure clinically representative and generalizable results, 3 experienced oral and maxillofacial surgeons performed the procedures. They were instructed to perform tooth removal, as they would do in a regular clinical setting. Use of an elevator was not allowed, as the constantly changing position of the elevator relative to the tooth makes it unsuitable for our study goal. The ISO (International Standards Organization number 3950, Fédération Dentaire International) system was used as dental notation system.

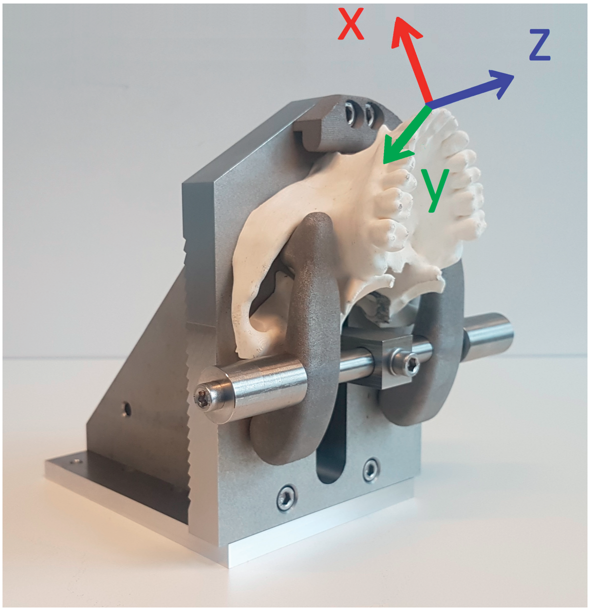


Fig 1: Upper jaw holding device. The white plastic model represents the reduced shape of the cadaveric upper jaw as prepared by the anatomical laboratorian. The reference frame is presented in 3 colored arrows. The X-axis (red arrow) represents the buccopalatal of buccolingual axis. The Y-axis (green arrow) represents the mesiodistal axis. The Z-axis (blue axis) represents the longitudinal axis.

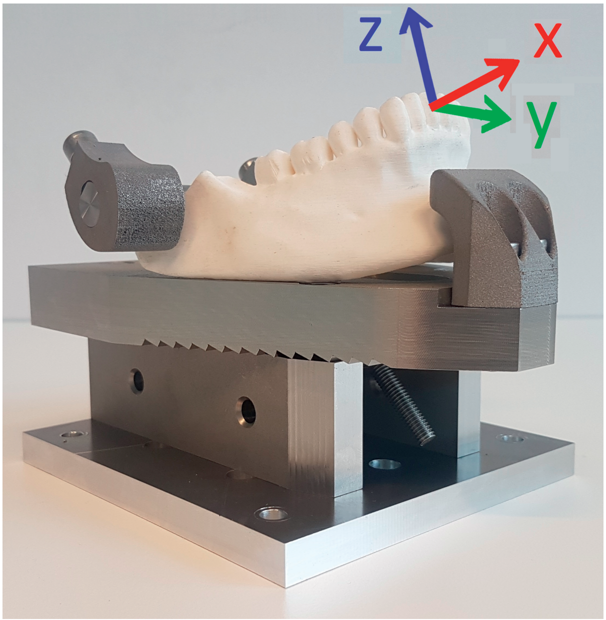


Fig 2: Lower jaw holding device. The white plastic model represents the reduced shape of the cadaveric lower jaw as prepared by the anatomical laboratorian. The reference frame is presented in 3 colored arrows. The X-axis (red arrow) represents the buccopalatal of buccolingual axis. The Y-axis (green arrow) represents the mesiodistal axis. The Z-axis (blue axis) represents the longitudinal axis.

Measurement setup

An overview of the setup is presented in Fig 3. Summarizing, the main components, consisted of:

- a compliant robot arm (KUKA LBR iiwa 7 R800). It passively, compensated for gravity, followed the movements of the clinician at a frequency of 100 times per second (hertz, Hz). The robot arm also functioned as a calibration tool to allow for determination of the position and orientation of a tooth. Based on clinical experience and due to anatomical restrictions such as the shape of the alveolar process, the relative position of the roots to the cortical lining and the periodontal ligament rotational movements are considered significantly more important compared to translational movements (or displacement) [2, 13]. This study, therefore, focused on rotational movements only.
- a 6-axis force/torque (FT) sensor (ATI industrial automation 16 bit Delta transducer) for registration of forces and torques in 3 dimensions at 20Hz.
- a video camera (Logitech C920 Pro HD) to record a video stream of the experiments.
- a custom-build and interchangeable upper and lower jaw-holding device (Fig 1 and 2).

The open-source framework Robot Operating System (ROS) was used for integration of all components. Metadata was added in a custom-build graphical user interface (GUI) to enable construction of a complete database for future analysis and to help to explain certain findings such as outliers. Metadata included, but was not limited to, the restorative and periodontal state of each tooth as these might influence the procedures in severe cases. Prior to each experiment, the surgeon was asked to determine the periodontal health by using a standard dental probe. States were divided into healthy (<3mm pocket depth), mild (3-5mm pocket depth) and severe periodontitis (>5mm pocket depth). Restorative states were classified into sound (no restorations), direct restorations (small <2 and large >2) and indirect restorations. The GUI also allowed for a direct post-experimental manual trim of the recorded data and the recording of any complications. The final few seconds of the procedures were excluded from the dataset. It is during this period where the tooth is taken out of its socket and extreme values are recorded, which should be considered as meaningless. The occurrence of any complications during the experiments were noted in the GUI. Experiments were classified as successful if the tooth was removed without complications or minor complications that did not influence the standard procedure. Experiments were classified as unsuccessful in case of serious issues, which might lead to unrepresentative results such as instant failure of indirect restorations or robot hardware/software issues. Visual inspection by the surgeon was performed after the procedure to determine complications which were sub-classified into boney wall fractures, root fractures or simple crown fractures (with removal of the root). Furthermore, after successful removal, anatomical features such as the root length and amount of roots were noted in the GUI. Because of the limited number of experiments in combination with the expected variability in this dataset, not all of the metadata was used in our analysis.

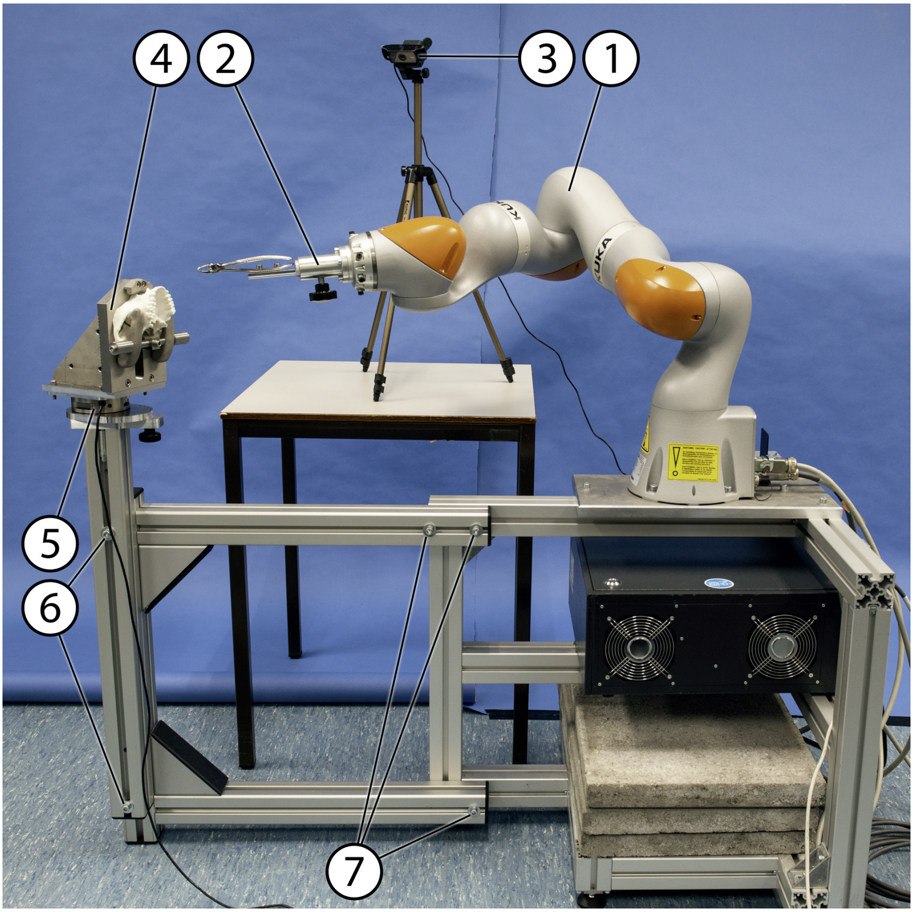


Fig 3: Overview of the setup. (1) passive robot arm (2) forceps holding device, (3) video camera, (4) upper jaw holding device (the lower jaw holding device not shown in this figure), (5) 6-axis force/torque sensor, (6) bolts to change vertical position, (7) bolts to change horizontal position

Calibration and reference frame

The location and orientation of each tooth was calibrated before the start of an experiment. This step was essential to determine position and orientation of the tooth. It allowed for translation of the movements toward clinically relevant dimensions. The reference frames for all teeth in both upper and lower jaw were identical and can be found in Fig. 1 and 2. The translation of movement data to a single reference frame enabled us to group 'mirrored' sets of teeth, for example the first premolars on the upper jaw (14 and 24) or lower second incisor (32 and 42). This was done so to create larger groups and to ease the interpretation of our results. For the calibration step, a straight periosteal elevator was mounted in the forceps-holding device and positioned parallel to the expected axis of each tooth and on top of the center of each crown. The flat part of the elevator pointed towards the lingual or palatal side. A mathematical translation was performed for each of the dental extraction forceps to align the axis according to the tooth frames (Table 1). The expected rotational center of the teeth was estimated 2mm below the center of the crown, as pointed out by the calibration tool.

Table 1: tooth reference frame after mathematical translation

Axis	Positive values	Negative values
Rotation around the bucco-palatal/lingual (X-)axis	Mesial angulation	Distal angulation
Rotation around the mesiodistal axis (Y-)axis	Buccoversion	Palatoversion / Linguoversion
Rotation around the longitudinal (Z-)axis	Mesiopalatal / Mesiolingual	Mesiobuccal

Data availability

The processed data required to reproduce our findings are available to download from https://www.doi.org (digital object identifier: 10.4121/20485383).

Results

Overview of experiments

A total of 127 experiments were performed on seven fresh-frozen Caucasian specimens. In 110 (86.6%) of these experiments full data was successfully recorded. The main reason (n = 8, 6.3%) for failure of experiments was insufficient fixation of the jaw causing displacement during the experiments, potentially leading to incorrect measurements. Other reasons were fracture of the teeth (n = 5, 3.9%), robot or software errors (n = 3, 2.4%) and excessive slippage of the forceps (n = 1, 0.8%). In the group of 110 successful experiments, most procedures happened without complications (n=94, 85.5%). In other experiments, data was successfully recorded but minor complications were present of which a fracture of the boney wall was seen most frequently (n=9, 8.2%). Most teeth had sound periodontal (n=60, 54.5%) and restorative states (n=45, 42.7%). For a complete overview of the basic characteristics, see Table 2.

Table 2. Base characteristics of experimental material and experiments. mm = millimeter.

Base Characteristics	Total number
Fresh-frozen specimens	7
Upper jaws with teeth	6
Lower jaws with teeth	6
Total number of experiments	127
Successful experiments:	110
Without complications	94
Boney wall fracture	9
Root fracture	6
Crown fracture/failure (with root removal)	3
Unsuccessful experiments:	17
Insufficient fixation of jaw	8
Crown fracture/failure (without root removal)	5
Robot / software errors	3
Excessive slippage of the forceps	1
Periodontal state (out of 110 experiments)	
- healthy (pocket depth <3mm)	82
- recessions	33
- mild periodontitis (pocket depth 3-5mm)	16
- severe periodontitis (pocket depth >5mm)	12
Restorative state (out of 110 experiments)	
- sound	47
- direct restoration large (≥ 2 surfaces)	25
- indirect restoration	20
- direct restoration small (≤ 2 surfaces)	18

Axis dominance

After translation of the data towards the same tooth frame (Table 1), movement data can be visualized as shown in Fig 4. It shows typical results of the removal of a central upper incisor and an upper first molar from the same cadaver jaw.

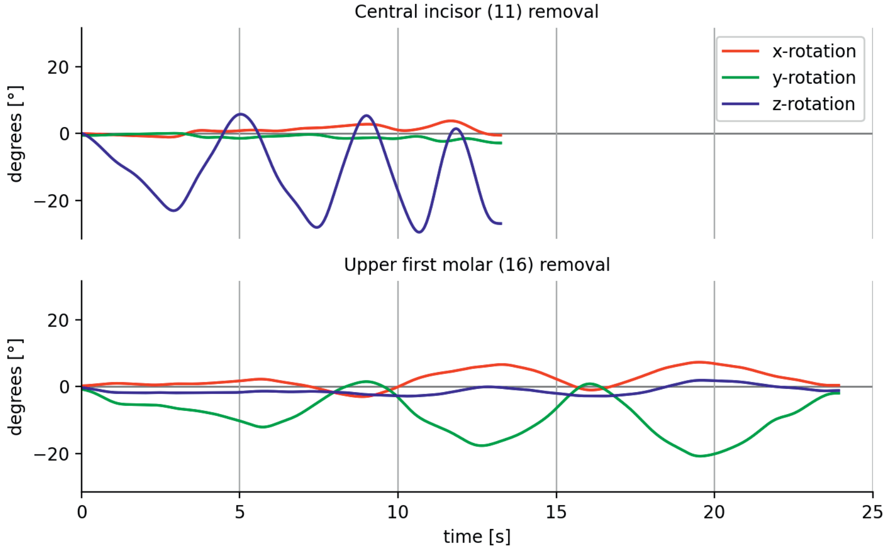


Fig 4. Visualization of movement data. Data recorded during removal of an upper central incisor (upper graph) and an upper first molar (lower graph). Movement around the longitudinal axis (blue line) was most dominant in the removal of a central upper incisor. Movement around the mesiodistal rotation (green line) was most dominant in removal of an upper first molar. In the upper first molar, rotation around the longitudinal axis was limited in contrast to the central incisor. X-rotation = rotation around the bucco-palatal or lingual axis. Y-rotation = rotation around the mesiodistal axis. Z-rotation = rotation around the longitudinal axis.

To determine along what axis most movement took place, the parameter 'axis dominance' was developed. It was calculated, or normalized, by dividing the line length of a single axis by the sum of the length of all 3 (Fig 4). The resulting parameter expresses the relative dominance in terms of amount of rotation along each axis. Results per group of teeth are shown in Fig 5. A clear dominance can be seen for rotations around the longitudinal axis of the tooth, especially in the upper frontal region. More dorsally, rotations around the mesial distal axis become more pronounced. Rotations around the buccopalatal or buccolingual axis (mesial/distal angulation) seem less dominant in all teeth.

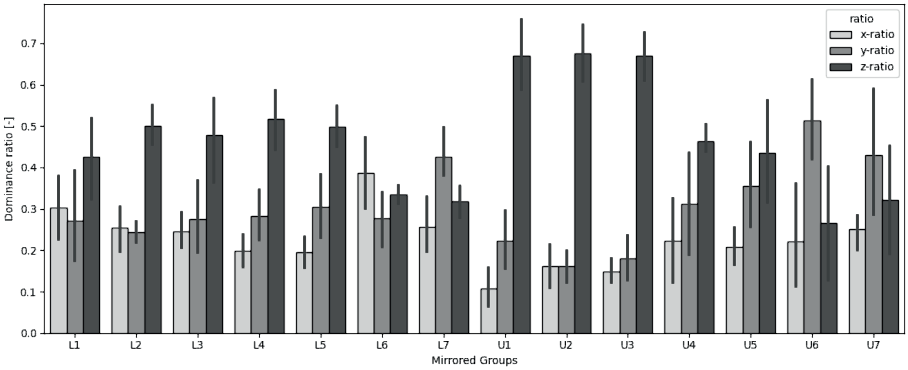


Fig 5. Axis dominance. Presented per 'mirrored' group of teeth and their standard deviation. The axis dominance was defined as the percentage of rotation that takes place around each specific axis relative to the other 2. X-ratio = rotation around the bucco-palatal or lingual axis. Y-ratio = rotation around the mesiodistal axis. Z-ratio = rotation around the longitudinal axis. L = lower. U = upper.

Range of motion and angular velocity

For each 'mirrored' group of teeth (i.e. the 14 and 24) maximum rotations as well as maximum angular velocities were calculated for all 6 directions separately. The averages of maximum rotations in both directions can be interpreted as a 'range of motion' along that axis and are presented in Fig. 6. The largest range of motion can be seen in rotations around the longitudinal axis of the tooth, more so in the frontal region. Lowest range of motion was found in the direction of mesial and distal angulation, especially in the upper jaw.

The averages of the maximum angular velocity measured in each experiment per group of teeth are presented in Fig 7. Both in upper and lower jaw, highest angular velocities were seen in rotation around the longitudinal axis of the tooth, being more prominent in the upper jaw. This effect was less pronounced in the dorsal region of the upper jaw. A more constant angular velocity was detected across groups in the lower jaw.

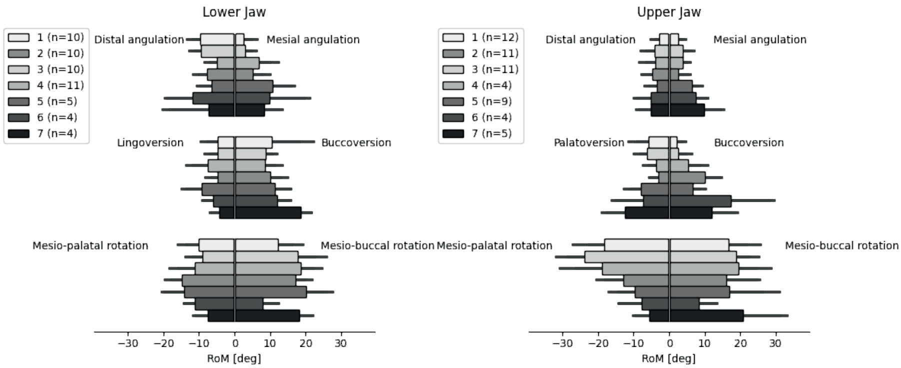


Fig 6. Range of motion. Averages of maximum rotations presented as a 'range of motion' along that axis. RoM = range of motion. deg = degree.

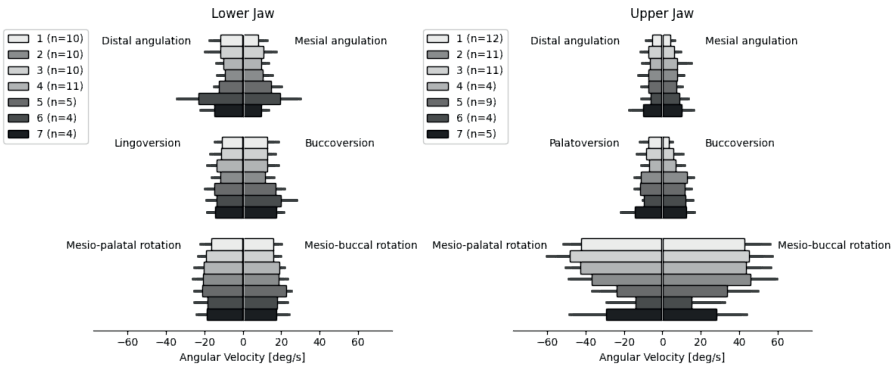


Fig 7. Angular Velocity. Averages of maximum angular velocity in all clinically relevant dimensions. deg/s = degree per second

Discussion

The goal of this project was to capture movements of a clinician during successful tooth removal procedures in an accurate and reproducible manner. We hypothesized that this could be done through the use of robot technology. A descriptive analysis of experiments in an *ex vivo* setup was presented in clinically relevant dimensions. In total, 110 measurements on successful tooth removal procedures were included in this study.

In previous work, we reported on the forces and torques that were measured in all 6 directions during these procedures [8]. In this study, we focus on the direction, range and speed of movements.

For the ease of interpretation of this complex data, the parameter 'axis dominance' was developed. In this study, we found the most dominant axis of movement to be around the longitudinal axis of the tooth. It was also around this axis where the highest velocities were found and widest ranges of motion. More dorsally, movements along the buccopalatal or buccolingual axis became more relevant. Movement in mesial or distal angulation seemed less apparent, which is well in line with our clinical experience.

A useful comparison to previous literature is difficult since scientific data on this topic is, to our knowledge, non-existing. Most studies concerning analysis of tooth removal have focused on measuring forces and did so in a limited fashion [7]. Some studies distinguished between 'twisting' (around the tooth's axis) and 'rocking' (buccolingual or buccopalatal) forces, indirectly describing some sort of movement [3, 14, 15]. What remains, for now, is a comparison of our results to our clinical experience. With rotations around the tooth axis being most prominent and buccopalatal/lingual movements being relatively more important in the dorsal area, this seems to correspond well.

A large standard deviation was found in our outcomes, showing significant variance in movements and velocity, even within groups of the same teeth. These findings might be expected, based on clinical experience and has several causes. Firstly, the extent of movement and its direction varies largely on both anatomic factors (i.e. root morphology, amount of roots, presence of adjacent teeth) and patient factors (i.e. bone morphology, mineral density) [14, 16]. Although metadata was present that could partially explain some of this variance, due to the relative small sample size, no valuable correlation to these factors can be made at this point. Further research with a larger data sample could be valuable to determine any influences these factors have on tooth removal strategies. Another relevant factor that affects our results is the variety in surgeons. As experiments were performed by 3 different surgeons an increased variance in our results is to be expected. Especially since the surgeons did not receive any specific instructions or calibration, other than to remove teeth as they would do in a clinical setting. Finally, variance in our results might be caused by the calibration step, which is prone to error. Utmost care was taken to align the straight elevator correctly, but small deviations are inevitable as a significant part of the teeth is not visible in this phase and minor misjudgments might occur. Improvements to the calibration step, for example using imaging data and single registration of the jaw instead of individual teeth are necessary in future projects.

The outcomes of this study should be carefully interpreted. Mainly, because it is unknown in what way fresh-frozen cadavers relate to the clinical situation and because of the small data sample. We aimed for 100 successfully recorded procedures to enable a first and representative analysis. It can be concluded that our results should be regarded as a first presentation of the right order of magnitude when considering movements and velocities in tooth removal. A confirmation of the data in a larger sample is necessary.

Some disadvantages of the setup should be discussed. To minimize any restrictions of the robot arm in terms of movement, besides compensation for gravity, an optimal starting position for upper and lower jaw was determined in which the joints were least likely to reach a 'joint limit'. When a 'joint limit' of the robot is reached, it needs to move other joints to facilitate further movement in a specific direction. This could deliver some resistance, which might prevent the surgeon moving in a specific direction and therefore influencing the movement pattern. With the use of predefined optimal starting positions, these restricted movements were prevented as much as possible, but a minimal effect might be present. Despite this issue, feedback from the surgeons was positive regarding the clinical representativeness of their removal strategies. Another disadvantage is the use of dental forceps over elevators, which are frequently used in clinics. Due to the constantly changing position relative to the tooth, the use of elevators was excluded from this study.

Future work should focus on improving the measurement setup first, especially regarding the calibration step, which can be considered as cumbersome and potentially lead to calibration errors. This could be overcome by the use of registration of image data, obtained prior to the experiments (CT-imaging). After that, the database should be extended to evaluate in which manner clinical features influence tooth removal strategies. Preferably this data is gathered in an *in vivo* research setting, but this is considered very challenging [9]. The data gathered in this and future work can be used to improve dental education in tooth removal in an evidence-based manner [17].

To the authors' best knowledge, this is the first time that different aspects of motion in tooth removal have been measured and analysed. We hypothesized that this could be done through the use of robot technology. Despite the mentioned shortcomings of this innovative work, the data presented here seems to define some order of magnitude when considering range of motion and angular velocities during tooth removal. We are convinced that we have gained important first scientific insights into tooth removal procedures and that robot technology was essential in doing so. The current database is, however, limited and its extension is essential to confirm our results in future research. An extensive dataset can be used to find clinically relevant factors influencing our proposed parameters. Finally, improved understanding of these complex procedures can be used to improve educational tools in an evidence-based manner [17, 18].

References

[1] G.W. Christiansen, Problems in Oral Surgery of Interest to the General Practitioner**Read at a meeting of the Cleveland Dental Society, May 7, 1934, The Journal of the American Dental Association (1922) 21(11) (1934) 1989-1999.

[2] D. Kitzis, From theory to practice in exodontia, Oral Surgery, Oral Medicine, Oral Pathology 5(11) (1952) 1185-1193.

[3] V. Ahel, I. Brekalo, J. Ahel, G. Brumini, Measurement of tooth extraction forces in upper incisors, Collegium antropologicum 30(1) (2006) 31-5.

[4] M. Cicciù, E. Bramanti, F. Signorino, A. Cicciù, F. Sortino, Experimental study on strength evaluation applied for teeth extraction: an in vivo study, The open dentistry journal 7 (2013) 20-6.

[5] M. Chiba, S. Ohshima, K. Takizawa, T. Matsuda, Measurement of the Force to Extract the Rat Mandibular Incisor, Journal of Dental Research 59 (1980) 1886-1886.

[6] K. Sugahara, H. Bessho, A. Nishiyama, Y. Koyama, M. Koyachi, T. Toyoda, K. Kasahara, A. Watanabe, M. Takano, A. Katakura, The utility of custom-developed tooth extraction simulator - A comparative analysis from beginner to trainer, Journal of Oral and Maxillofacial Surgery, Medicine, and Pathology 33(1) (2021) 43-47.

[7] M.G. Beuling, P.C.G. Agterbos, T.C.T. van Riet, J.P.T.F. Ho, R. de Vries, J. Kober, J. de Lange, Forces and movements during tooth extraction: A scoping review, Advances in Oral and Maxillofacial Surgery 9 (2023).

[8] T.C.T. van Riet, W.M. de Graaf, J. Kober, J. de Lange, Using robot technology to analyze forces and torques in tooth removal, Advances in Oral and Maxillofacial Surgery 9 (2023).

[9] T.C.T. van Riet, W.M. de Graaf, R. van Antwerpen, J. van Frankenhuyzen, J. de Lange, J. Kober, Robot Technology in Analyzing Tooth Removal - a Proof of Concept, Annu Int Conf IEEE Eng Med Biol Soc 2020 (2020) 4721-4727.

[10] H.S. Brand, C.C.J. van der Cammen, S.M.E. Roorda, J.A. Baart, Tooth extraction education at dental schools across Europe, BDJ Open 1 (2015) 15002-15002.

[11] P. Onclin, Recent increase in simple extractions in OMF-surgeries in the Netherlands studied, Nederlands Tijdschrift voor Tandheelkunde 123(07/08) (2016) 365-372.

[12] J. Iwanaga, V. Singh, S. Takeda, J. Ogeng'o, H.J. Kim, J. Morys, K.S. Ravi, D. Ribatti, P.A. Trainor, J.R. Sanudo, N. Apaydin, A. Sharma, H.F. Smith, J.A. Walocha, A.M.S. Hegazy, F. Duparc, F. Paulsen, M. Del Sol, P. Adds, S. Louryan, V.P.S. Fazan, R.K. Boddeti, R.S. Tubbs, Standardized statement for the ethical use of human cadaveric tissues in anatomy research papers: Recommendations from Anatomical Journal Editors-in-Chief, Clin Anat 35(4) (2022) 526-528.

[13] B. Stegenga, MKA Chirurgie, 2nd ed., van Gorcum2013.

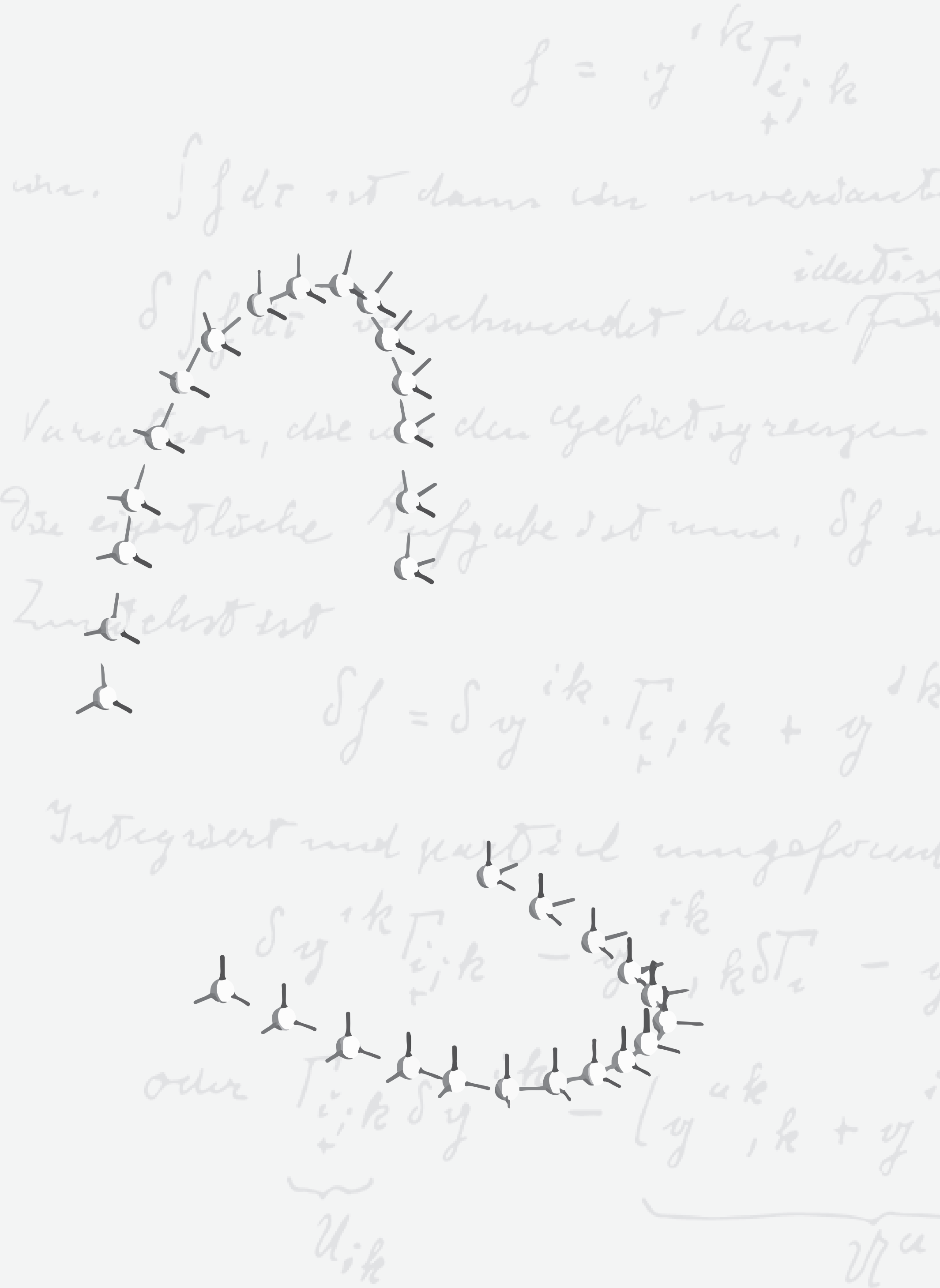
[14] V. Ahel, T. Cabov, S. Spalj, B. Peric, D. Jelusic, M. Dmitrasinovic, Forces that fracture teeth during extraction with mandibular premolar and maxillary incisor forceps, Br J Oral Maxillofac Surg 53(10) (2015) 982-7.

[15] R. Lehtinen, T. Ojala, Rocking and twisting moments in extraction of teeth in the upper jaw, International journal of oral surgery 9 (1980) 377-382.

[16] T. Dietrich, I. Schmid, M. Locher, O. Addison, Extraction force and its determinants for minimally invasive vertical tooth extraction, J Mech Behav Biomed Mater 105 (2020) 103711.

[17] M.G. Beuling, T.C.T. van Riet, J. van Frankenhuyzen, R.V. Antwerpen, B. de Blocq van Scheltinga, A.H.H. Dourleijn, D. Ireiz, S. Streefkerk, J.C. van Zanten Jan de Lange, J. Kober, D. Dodou, Development and testing of a prototype of a dental extraction trainer with real-time feedback on forces, torques, and angular velocity, Annu Int Conf IEEE Eng Med Biol Soc 2022 (2022) 3285-3290.

[18] W.M. de Graaf, T.C.T. van Riet, J. de Lange, J. Kober, A Multiclass Classification Model for Tooth Removal Procedures, J Dent Res 101(11) (2022) 1357-1362.



Chapter 7

A multiclass classification model for tooth removal procedures

This chapter is based on the following publication:
A Multiclass Classification Model for Tooth Removal Procedures
W.M. de Graaf, T.C.T. van Riet, J. de Lange and J. Kober

Published in: Journal of Dental Research, 2022

Abstract

Objectives:

Surprisingly little is known about tooth removal procedures. This might be due to the difficulty of gaining reliable data on these procedures. To improve our understanding of these procedures, machine-learning techniques were used to design a multiclass classification model of tooth removal based on force, torque and movement data recorded during tooth removal.

Methods:

A measurement setup consisting of, amongst others, robot technology was used to gather high quality data on forces, torques and movement in clinically relevant dimensions. Fresh frozen cadavers were used to match the clinical situation as closely as possible. Clinically interpretable variables or 'features' were engineered and feature selection took place to process the data. A Gaussian Naïve Bayes model was trained to classify tooth removal procedures.

Results:

Data of 110 successful tooth removal experiments were available to train the model. Out of 75 clinically designed features, 33 were selected for the classification model. The overall accuracy of the classification model in four random subsamples of data was 86% in the training set and 54% in the test set. In 95% and 88%, respectively, the model correctly classifies the (upper or lower) jaw and either the right class or a class of neighboring teeth.

Significance:

This manuscript discusses the design and performance of a multiclass classification model for tooth removal. Despite the relatively small dataset, the quality of the data was sufficient to develop a first model with reasonable performance. The results of the feature engineering, selection process as well as the classification model itself can be considered as a strong first step towards a better understanding of these complex procedures. It has the potential to aid in the development of evidence-based educational material and clinical guidelines in the near future.

Introduction

Aulus Cornelius Celsus (c. 25BC-50AD) described tooth removal procedures for the first time in his ‘De Medicina’ with an instruction: ‘it is to be shook; which must be continued till it move easily’ [1]. In modern textbooks, descriptions of these complex procedures have not changed significantly [2]. Being one of the oldest and most commonly performed surgical procedures worldwide, the lack of scientific progress in this field is surprising. Scientific attempts to increase our understanding of these procedures are relatively rare, heterogeneous and mostly focused on extraction forces [3-6]. Analyzing different aspects of tooth removal, especially in clinical situations, requires measurements of subtle movements and high forces in a confined space (intra-orally), which might explain the knowledge gap in this field [7].

Through a collaboration between computer scientists, mechanical engineers, and oral- and maxillofacial (OMF-) surgeons, a setup was designed to measure different aspects of tooth removal procedures [7]. With the use of compliant robotics, data was gathered on (rotational) forces and movements in all their dimensions, directions, in high detail and at a high frequency. Whilst individual parts of data can be explained and understood with traditional statistical methods, analyzing their combination is complex. Machine learning can be particularly useful to understand and analyze complex or large datasets with many variables, in which it has the potential to detect relationships. It can be considered essential to make use of the data as a whole. A classification model is an example of machine learning technology, which consists of an algorithm capable of predicting which tooth was removed, based on a variety of complex data. It could aid in finding which variables are most relevant in tooth removal procedures and to evaluate how procedures differ between certain teeth. This can be of use for, amongst others, the development of evidence-based education material.
The goal of this project was to build and validate a first and exploratory classification model for tooth removal based on force, torque and movement data. By evaluating which variable (or ‘feature’) is selected by the algorithm, a unique insight in this ancient procedure is presented. This manuscript describes our methods data collection using robot technology, the feature design process as well as the models’ performance.

Materials and Methods

Data collection

An ex-vivo measurement campaign was designed to collect relevant data. Seven fresh frozen cadavers were obtained from the clinical anatomy and embryology section of the department of medical biology of the Amsterdam university medical center (Amsterdam UMC). The donation process was in accordance with Dutch legislation and the regulations of the medical ethical committee of the Amsterdam UMC. Extractions were performed by three senior oral and maxillofacial surgeons. An extensive measurement setup was used, as described in more detail in previous work [7]. An overview of the setup is presented in Figure 1. In short, data on position, orientation and movements was gained through a compliant robot arm (KUKA LBR iiwa 7 R800) passively following the movements of an OMF-surgeon (frequency 100Hz). A six-axis force/torque (FT) sensor (ATI industrial automation 16-bit Delta transducer) was used to register forces and torques at 20Hz. An open-source framework was used for integration of the components (Robot Operating System, ROS). A custom graphical user interface (GUI) was designed to allow for the addition of metadata on the experiments itself (e.g., reason in case of any failed measurements) and on the clinical status of the teeth (e.g., restorative and periodontal state). In total, the setup gathers thirteen-dimensional time series for each individual tooth removal procedure. Six-dimensional time series from the force/torque sensor, consisting of three dimensions ('XYZ') for both forces and torques. A further seven-dimensional time series are gathered from the robot arm - three dimensions for the position of the end-effector ('XYZ') and a four-dimensional representation of the orientation of the end-effector in quaternions [8]. For data analysis, Python was used (Python Software Foundation. Python Language Reference, version 3.9) [9] and the Scikit-learn 1.0.1 module [10]. A calibration step was performed just prior to each experiment, to determine the position and orientation of each tooth [7]. Reporting guidelines were used to structure this report [11, 12].

Preprocessing the data

Because each measurement started and stopped manually, some meaningless data was gathered just prior and after each experiment. Raw data was therefore manually trimmed, using the custom user interface, directly after each experiment. Using data from the calibration step, raw data from the force/torque sensor and robot arm were mathematically transformed from their own reference frames to the clinically relevant tooth frame [7]. It results in one unified reference frame in which, for example, a

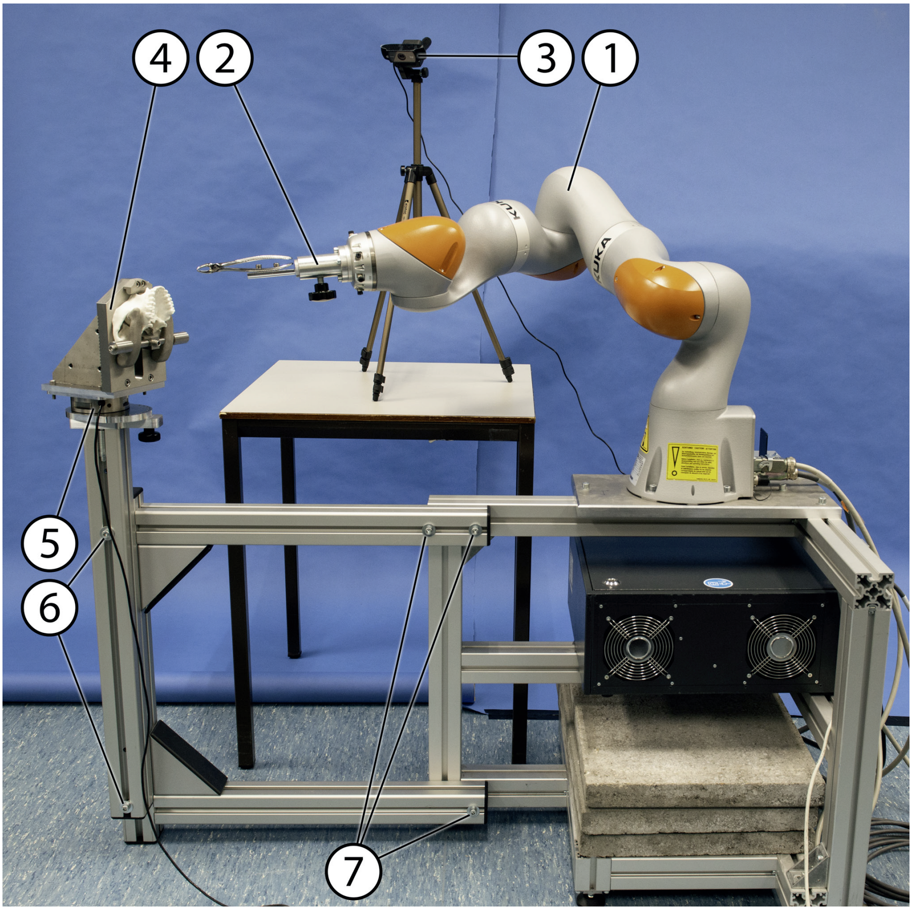


Figure 1. Overview of the setup with a 3D-printed upper jaw in situ. (1) passive robot arm (2) forceps holding device, (3) video camera, (4) upper jaw holding device (the lower jaw holding device not shown in this figure), (5) 6-axis force/torque sensor, (6) bolts to change vertical position, (7) bolts to change horizontal position.

positive value on the X-axis in force and movement data are both in a buccal direction. A negative value on the X-axis means a force or movement in the lingual direction. This also holds for the Y-axis (mesial/distal or proximal/distal along the dental arch curve) and Z-axis (intrusion/extrusion). Time series data were filtered for noise reduction purposes with a low-pass Butterworth filter [13]. Data of the force/torque sensor (20Hz) were up sampled to match the frequency of the movement data (100Hz) using a standard Fast Fourier Transformation [14].

Feature Design and selection

Based on the existing force/torque and movement data, additional variables – so called ‘features’ - can be computed. These features can be best compared to the (independent) ‘variables’ we know from traditional statistics. They were designed in multiple brainstorming sessions between computer scientists and OMF-surgeons. An effort was made to design clinically interpretable features, e.g., rotational velocity or peak forces/torques in every direction. For a complete overview of all features, see Appendix Table 1. Each of these features have their own predictive power to distinguish between different classes of teeth.

Teeth were grouped together as ‘classes’ to optimize model performance for a small dataset. To ease the clinical interpretability of this model, four classes were chosen as an output for the model. These classes were the same for both upper (U) and lower (L) jaw: incisors (U1/U2, L1/L2), cuspids (U3, L3), bicuspids (U4/U5, L4/L5) and molars (U6/U7, L6/L7).

The goal of feature selection is to determine what features should be included in order to optimally classify tooth removal procedures with a minimum set of features [15, 16]. Several approaches are available to select the most important features of which ‘regularization’ is one [17]. A model including a regularization term trades off simplicity and performance by weighting different features. The model is simplified by discarding uninformative features at the cost of a reduction in classification accuracy. This way, only features with high importance will remain. For this study, logistic regression with L2 (or ‘ridge regression’) regularization was used. L2 regularization was chosen over L1 (or ‘lasso regression’) because it is more suitable to avoid overfitting of a model. In contrast to L1 regularization, features are not removed from the model in L2, but it tends to reduce extreme weights leading to a more even distribution of the weight of the features. The actual selection is then performed by applying a threshold for feature importance, which, in our study was chosen to be the mean of the overall feature importance [10].

Designing a classification model

Because features can differ in terms of scale, standardization (i.e., variance scaling) of the features was performed to even out their scales. In the standardization process, every feature is scaled down to a mean of zero and a standard deviation of one. It prevents the algorithm to mistakenly give importance to features that have larger scales.

As a classification algorithm, Gaussian Naïve Bayes (GNB) was used. It is a probabilistic machine-learning algorithm, which can be used for a variety of classification tasks. Our dataset has limited size and high variance, with an approximately Gaussian (or normal) distribution. Naïve Bayes classifiers are well known for their performance on problems with a small amount of training data [18], whilst logistic regression models – used for feature selection in this paper - are more prone to overfitting for such problems. Accuracy, precision, recall and F1-score were calculated for each tooth class to evaluate the model performance. To reduce the risk of selection bias and to more accurately estimate the model's predictive performance, a stratified 4-fold cross validation was performed. In this cross validation, 4 random subsamples of data are used to calculate the performance metrics with the same class proportions (stratified), due to the small sample size.

Data availability

Data required to reproduce these findings, are available to download from https://www.doi.org (digital object identifier: 10.4121/19665990).

Results

Clinical characteristics

A total of 127 experiments were performed on seven fresh-frozen Caucasian specimens. In 110 (86.6%) experiments, data was successfully recorded. A heterogeneous group of teeth in terms of restorative and periodontal states was included (Appendix Table 2).

Feature design

In total, 75 features were designed, of which 33 remained after regularization. An overview of these selected features is given in Table 1. The relationship between 2 strong prediction features, the sum of delivered torques and average torques on all three axes is shown in Figure 2. It is an example of how these features can be used to distinguish different classes of teeth. Whilst the sum of torques in all directions can be high for both upper- and lower jaw bicuspids and molars, it seems that average torques in the lower jaw are higher in the dorsal area compared to the upper jaw. Also, in both upper- and lower jaw incisors, average torques did not reach above 6Nm.

Table 1. An overview of selected features. AUC = area under the curve, n = number, N = Newton, Ns = Newton second, Nms = Newton meter second, deg = degree, deg/s = degrees per second, (+) = only positive values on specified axis, (-) = only negative values on specified axis, X-axis = buccolingual, Y-axis = mesiodistal, Z-axis = longitudinal axis. X+Y+Z = sum of all axes. In case of rotational data (torques and all rotational data features), a rotation around the mentioned axis takes place.

Force and torque data features	Axis	Direction	n = 17
sum (AUC) of Forces (Ns)	X+Y+Z X-axis (+) Y-axis (-) Z-axis (-)	all buccal distal extrusion	4
Average Forces (N)	X+Y+Z Y-axis (+)	all mesial	2
sum (AUC) of Torques (Nms)	X+Y+Z Y-axis (+) Z-axis (+) Z-axis (-)	all buccoversion mesiobuccal rotation mesiopalatal-lingual rotation	4
Average torques (Nm)	X+Y+Z X-axis (+) Y-axis (+) Z-axis (+)	all mesial angulation buccoversion mesiopalatal-lingual rotation	4
Peak forces (N)	X+Y+Z	all	1
Peak torque (Nm)	X+Y+Z	all	1
Percentage of amount of force, relative to the sum of all three axis (%)	Z-axis	intrusion/extrusion	1
Rotational data features	**Axis**	**Direction**	**n =16**
Percentage of amount of rotation, relative to the sum of all three axes (%)	Y-axis Z-axis	bucco-palato/linguoversion mesiopalatal-lingual rotation	2
Maximum rotations (deg)	Y-axis (+) Z-axis (-)	buccoversion mesiopalatal-lingual rotation	2
Average rotations (deg)	Y-axis (+) Y-axis (-) Z-axis (+) Z-axis (-)	buccoversion linguoversion mesiobuccal rotation mesiopalatal-lingual rotation	4
Variation of rotation on a single axis (deg)	Z-axis	mesiobuccal/ mesiopalatal-lingual rotation	1
Maximum rotational velocity (deg/s)	Y-axis (+) Y-axis (-) Z-axis (+) Z-axis (-)	buccoversion linguoversion mesiobuccal rotation mesiopalatal/lingual rotation	4
Variation of rotational velocity on a single axis (deg/s)	X-axis Y-axis Z-axis	mesial-distal angulation bucco-palato/linguoversion mesiobuccal- mesiopalatal/ lingual rotation	3

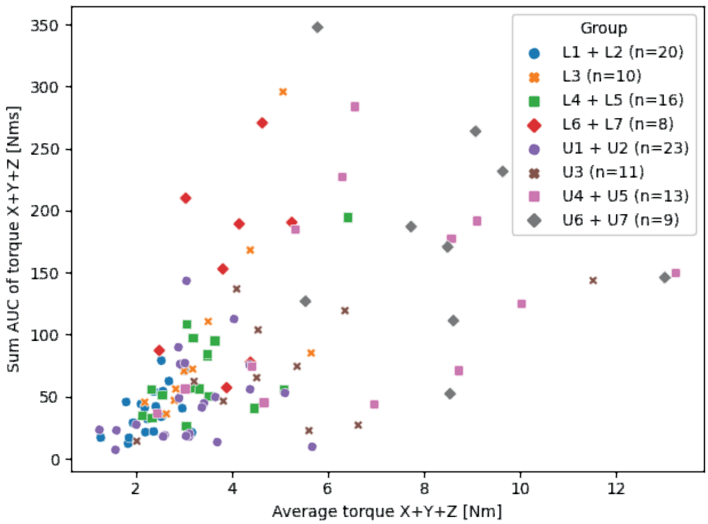


Figure 2. Plot of all 110 data points showing the relationship between two features, the AUC of the torque magnitude (sum of torques on all three axes combined) and average torques (on all three axes combined). L = lower, U = upper, AUC = area under the curve, Nms = Newton meter second, Nm = Newton meter, n = number

Model Performance

A summary of the performance of the model is given in Table 2. On average, the accuracy was 86% in the training set and 54% in the test set (unseen data). The data is presented in two confusion matrices, which show the cumulative results of the four subsamples (Figure 3). In the test set (unseen data), in 104 out of 110 experiments (95%) the correct jaw (upper/lower) was classified. Also, 97 experiments (88%) were either correctly classified or as a neighboring class.

Table 2: Performance metrics of the classification model for both training and test set. n = number

	Subsample 1	Subsample 2	Subsample 3	Subsample 4	Average
Training set	n=82	n=82	n=83	n=83	
Accuracy	84%	88%	86%	86%	86%
Precision	87%	90%	88%	87%	88%
Recall	84%	88%	86%	86%	86%
F1-score	85%	88%	86%	86%	86%
Test set	n=28	n=28	n=27	n=27	
Accuracy	64%	54%	56%	44%	54%
Precision	84%	61%	65%	44%	55%
Recall	64%	54%	56%	44%	54%
F1-score	71%	53%	57%	47%	57%

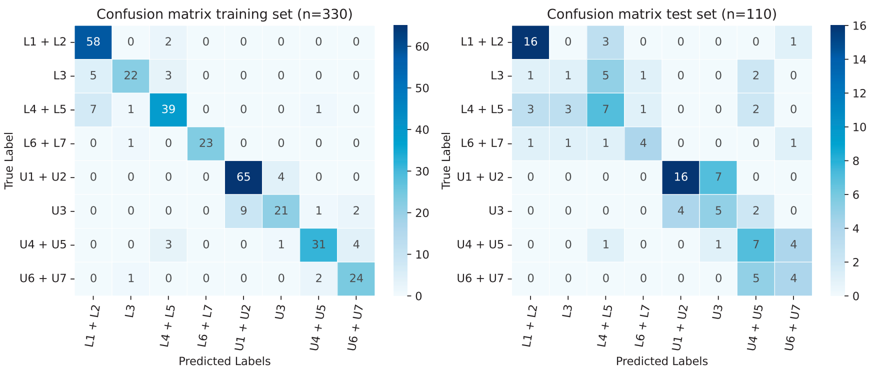


Figure 3. Confusion matrix in which the cumulative predictions of the four-fold cross validation are presented. The training set, containing 330 teeth is shown on the left side and the test set containing 110 on the right side. The center diagonal represents correctly predicted labels. L = lower. U = upper. n = number.

Discussion

The goal of this project was to build a classification model for tooth removal. The measurement campaign was described in short as well as the process of feature design. A classification model, which is capable of predicting tooth classes based on force and movement data, was presented.

The overall accuracy of the model, after cross validation in four subsamples of data, was 86% in the training set and 54% in the test set (unseen data). The model correctly predicts the (upper or lower) jaw in 95% of the experiments. In 88%, it predicts either the correct class or a class of neighboring teeth. This means that, based on variables derived from complex force and movement data, the algorithm is capable of determining to which 'tooth class' a measurement belongs to, with reasonable performance. These results seem reasonable, given the heterogeneity in the data due to surgeon and patient factors in combination with a relatively small dataset to train the model on. Another factor that might explain the relative low accuracy and precision might be an incorrect class selection. If tooth removal strategies are similar for certain classes, for example, bicuspids and cuspids in the lower jaw, the models' performance will decrease. It could be valuable, in future research and for educational purposes, to let the model optimize the class selection instead, i.e., perform clustering. An important finding in this study is that the collected data is of sufficient quality to use for modern learning techniques. Further data collection is necessary to allow for the use of clinical metadata and to further increase the models' performance and generalizability.

The feature design and selection processes are an essential part of building a classification model. The evaluation of which features are most relevant for the algorithm to classify an experiment, is an important first step to improve our fundamental understanding of these complex procedures. Whilst a detailed discussion on the relevance of each feature falls outside the scope of this article, a few key findings are highlighted here. In terms of force and torque data, in each group of features the sum of forces and torques on all three axes combined were selected. This means that the sum of all forces and torques in an experiment is descriptive for classification purposes, rather than forces in individual directions. When looking at rotational and velocity data, features containing rotation around the Y-axis (buccoversion and/or palato/linguoversion) and around the axis of the tooth (Z-axis) were selected most frequently. This is in contrast to rotation around the X-axis (mesial and/or distal angulation) which was selected only once. These findings seem to correlate well with our clinical experience and seem in accordance with the limited available textbook instructions that mostly focus on rotations or movements around the longitudinal axis and buccolingual axis of a tooth [2]. Some of the selected features, on the other hand, are less well understood. For example, the selection of an average torque feature (mesial angulation) that does not match with an unselected rotational feature in the same direction. It might have to do with the position of the teeth, for example, a more mesial angulation is expected in dorsally located teeth, especially if a neighboring (mesial) tooth is absent. The latter has not been taken into account and these findings need additional analysis in future work.

Due to the pioneering character of this study, no direct comparison is possible with previous literature. The available scientific literature on tooth removal procedures is surprisingly scarce and limited to the evaluation of exerted forces using a variety of methodologies and heterogeneous outcomes [3, 5, 6, 19, 20]. When this project started, many uncertainties in terms of achievability existed [7]. One of the most important downsides to our dataset and therefore our model, is that the data was collected *ex vivo*. Whilst the participating, experienced, oral- and maxillofacial surgeons considered the fresh frozen material as clinically representative, it is unknown in what way the freezing process influences the biomechanical properties of tooth removal. This

should be taken into account when interpreting our results. Due to the uncertainties that coincide with the development of a novel measurement setup, we aimed for 100 successful experiments on fresh frozen material. This should be considered as a small dataset and its size has a strong effect on the strength of our model. For example, recorded metadata such as periodontal health, root length or type of surgeon could not be incorporated in this model, nor could differences in outcome be evaluated. Also, radiological metadata was unavailable which could contain relevant variables, such as bone density, which is preferable to incorporate in future research initiatives.
With currently available technology, it will be very challenging to gain the same quality of data in a clinical situation. Efforts should nevertheless be made to correlate results found in fresh frozen cadavers to the clinical situation. Moreover, a translation should be made between this theoretical model and clinical use. Two possibilities are discussed. Firstly, improved (evidence-based) preclinical educational methods can be developed. Previous scientific efforts also had educational reasons at heart [6, 21]. The authors are planning to enhance the measurement setup to a much simpler version that is to be used for dental training. Using a force/torque sensor, students are able to receive direct feedback on their performance whilst practicing on plastic or cadaver models. Results of this study can be used to decide which feedback (or which feature) is most relevant during removal of specific teeth, to optimize force-based learning methods [22]. Data from this study might also, in the near future, be useful in the development of virtual learning methods in an evidence-based manner. Secondly, it could be evaluated if metadata, after enlarging the database, can be used to develop a clinically relevant classification for expected tooth removal complexity. This, potentially, could help the clinician to decide whether referral for an extraction is deemed necessary, based on their own competences.

Concluding, this manuscript discussed the design and performance of a multiclass classification model for tooth removal. Despite the relatively small dataset, the quality of the data was sufficient to develop a first model with reasonable performance. The results presented in this manuscript can be considered as a strong first step towards an improved understanding of these complex procedures. This improved understanding could potentially aid in the development of evidence-based educational material and clinical guidelines for tooth removal in the near future.

References

[1] J. Greive, Aulus Cornelius Celsus: on medicine. In eight books. Translated with notes critical and explanatory., Book VII, Dickinson and company, Edinburgh, 1814, p. 338.

[2] B. Stegenga, MKA Chirurgie, 2nd ed., van Gorcum2013.

[3] V. Ahel, I. Brekalo, J. Ahel, G. Brumini, Measurement of tooth extraction forces in upper incisors, Collegium antropologicum 30(1) (2006) 31-5.

[4] M. Cicciù, E. Bramanti, F. Signorino, A. Cicciù, F. Sortino, Experimental study on strength evaluation applied for teeth extraction: an in vivo study, The open dentistry journal 7 (2013) 20-6.

[5] T. Dietrich, I. Schmid, M. Locher, O. Addison, Extraction force and its determinants for minimally invasive vertical tooth extraction, J Mech Behav Biomed Mater 105 (2020) 103711.

[6] K. Sugahara, H. Bessho, A. Nishiyama, Y. Koyama, M. Koyachi, T. Toyoda, K. Kasahara, A. Watanabe, M. Takano, A. Katakura, The utility of custom-developed tooth extraction simulator - A comparative analysis from beginner to trainer, Journal of Oral and Maxillofacial Surgery, Medicine, and Pathology 33(1) (2021) 43-47.

[7] T.C.T. van Riet, W.M. de Graaf, R. van Antwerpen, J. van Frankenhuyzen, J. de Lange, J. Kober, Robot Technology in Analyzing Tooth Removal - a Proof of Concept, Annu Int Conf IEEE Eng Med Biol Soc 2020 (2020) 4721-4727.

[8] J.H. Challis, Quaternions as a solution to determining the angular kinematics of human movement, BMC Biomed Eng 2 (2020) 5.

[9] G.a.D.J. van Rossum, Fred L, Python reference manual, Centrum voor Wiskunde en Informatica Amsterdam1995.

[10] F.a.V. Pedregosa, G. and Gramfort, A. and Michel, V. and Thirion, B. and Grisel, O. and Blondel, M. and Prettenhofer, P. and Weiss, R. and Dubourg, V. and Vanderplas, J. and Passos, A. and Cournapeau, D. and Brucher, M. and Perrot, M. and Duchesnay, E., Scikit-learn: Machine Learning in {P}ython, Journal of Machine Learning Research 12 (2011) 2825-2830.

[11] W. Luo, D. Phung, T. Tran, S. Gupta, S. Rana, C. Karmakar, A. Shilton, J. Yearwood, N. Dimitrova, T.B. Ho, S. Venkatesh, M. Berk, Guidelines for Developing and Reporting Machine Learning Predictive Models in Biomedical Research: A Multidisciplinary View, J Med Internet Res 18(12) (2016) e323.

[12] F. Schwendicke, T. Singh, J.H. Lee, R. Gaudin, A. Chaurasia, T. Wiegand, S. Uribe, J. Krois, I.e.-o.h. network, I.T.U.W.H.O.f.g.A.I.f.H. the, Artificial intelligence in dental research: Checklist for authors, reviewers, readers, J Dent 107 (2021) 103610.

[13] R.E. Challis, R.I. Kitney, The design of digital filters for biomedical signal processing. Part 3: The design of Butterworth and Chebychev filters, J Biomed Eng 5(2) (1983) 91-102.

[14] A.P. Yoganathan, R. Gupta, W.H. Corcoran, Fast Fourier transform in the analysis of biomedical data, Med Biol Eng 14(2) (1976) 239-45.

[15] Z. Bursac, C.H. Gauss, D.K. Williams, D.W. Hosmer, Purposeful selection of variables in logistic regression, Source Code Biol Med 3 (2008) 17.

[16] T.R. Brick, R.E. Koffer, D. Gerstorf, N. Ram, Feature Selection Methods for Optimal Design of Studies for Developmental Inquiry, J Gerontol B Psychol Sci Soc Sci 73(1) (2017) 113-123.

[17] C.M. Bishop, Pattern Recognition and Machine Learning, Springer2006.

[18] H. Zhang, The Optimality of Naive Bayes, FLAIRS Conference, 2004.

[19] R. Lehtinen, T. Ojala, Rocking and twisting moments in extraction of teeth in the upper jaw, International journal of oral surgery 9 (1980) 377-382.

[20] M. Chiba, S. Ohshima, K. Takizawa, T. Matsuda, Measurement of the Force to Extract the Rat Mandibular Incisor, Journal of Dental Research 59 (1980) 1886-1886.

[21] R. Lehtinen, T. Ojala, Apparatus for simulating extraction forces, International journal of oral and maxillofacial surgery 15 (1986) 444-445.

[22] S.F. Hardon, T. Horeman, H.J. Bonjer, W. Meijerink, Force-based learning curve tracking in fundamental laparoscopic skills training, Surg Endosc 32(8) (2018) 3609-3621.

Supplementary Materials

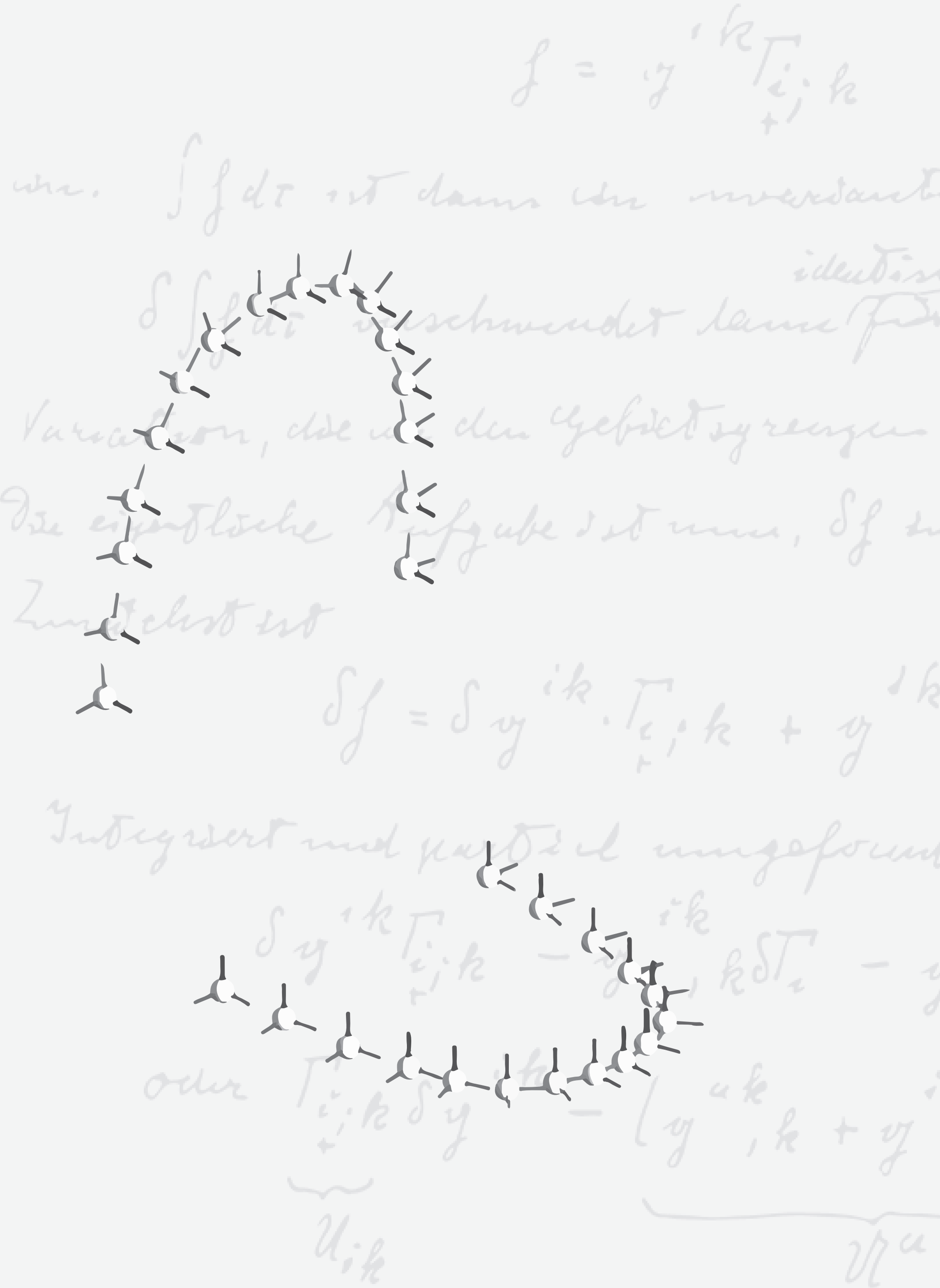
Appendix Table 1. An overview of all features designed through a collaboration between a clinician and a computer scientist. AUC = area under the curve, n = number, N = Newton, Ns = Newton second, Nms = Newton meter second, deg = degree, deg/s = degrees per second, (+) = only positive values on specified axis, (-) = only negative values on specified axis, X-axis = buccolingual, Y-axis = mesiodistal, Z-axis = longitudinal axis. X+Y+Z = sum of all axes. In case of rotational data (torques and all rotational data features), a rotation around the mentioned axis takes place.

Force and torque data features	Axis	Direction	n = 42
Sum (AUC) of forces (Ns)	X+Y+Z	all	7
	X-axis (+)	buccal	
	X-axis (-)	lingual	
	Y-axis (+)	mesial	
	Y-axis (-)	distal	
	Z-axis (+)	intrusion	
	Z-axis (-)	extrusion	
Sum (AUC) of torque (Nms)	X+Y+Z	all	7
	X-axis (+)	mesial angulation	
	X-axis (-)	distal angulation	
	Y-axis (+)	buccoversion	
	Y-axis (-)	palato-linguoversion	
	Z-axis (+)	mesiopalatal rotation	
	Z-axis (-)	lingual rotation	
Average forces (N)	X+Y+Z	all	7
	X-axis (+)	buccal	
	X-axis (-)	lingual	
	Y-axis (+)	mesial	
	Y-axis (-)	distal	
	Z-axis (+)	intrusion	
	Z-axis (-)	extrusion	
Average torques (Nm)	X+Y+Z	all	7
	X-axis (+)	mesial angulation	
	X-axis (-)	distal angulation	
	Y-axis (+)	buccoversion	
	Y-axis (-)	palato-linguoversion	
	Z-axis (+)	mesiopalatal rotation	
	Z-axis (-)	lingual rotation	
Peak forces (N)	X+Y+Z	all	4
	X-axis	buccal/palatal-lingual	
	Y-axis	mesial/distal	
	Z-axis	intrusion/extrusion	
Peak torque (Nm)	X+Y+Z	all	4
	X-axis	mesial/distal angulation	
	Y-axis	buccoversion/palato-linguoversion	
	Z-axis	mesiopalatal/lingual rotation	
Percentage of amount of force, relative to the sum of all three axis (%)	X-axis	buccal/palatal-lingual	3
	Y-axis	mesial/distal	
	Z-axis	intrusion/extrusion	
Percentage of amount of torque, relative to the sum of all three axis (%)	X-axis	mesial/distal angulation	3
	Y-axis	buccoversion/palato-linguoversion	
	Z-axis	mesiopalatal/lingual rotation	

Rotational data features	Axis	Direction	n = 33
Percentage of amount of rotation, relative to the sum of all three axes (%)	X-axis Y-axis Z-axis	mesial-distal angulation bucco-palato/linguoversion mesiobuccal- mesiopalatal/lingual rotation	3
Variation of rotation on a single axis (deg)	X-axis Y-axis Z-axis	mesial-distal angulation bucco-palato/linguoversion mesiobuccal- mesiopalatal/lingual rotation	3
Maximum rotations (deg)	X-axis (+) X-axis (-) Y-axis (+) Y-axis (-) Z-axis (+) Z-axis (-)	mesial angulation distal angulation buccoversion linguoversion mesiobuccal rotation lingual rotation	6
Average rotations (deg)	X-axis (+) X-axis (-) Y-axis (+) Y-axis (-) Z-axis (+) Z-axis (-)	mesial angulation distal angulation buccoversion linguoversion mesiobuccal rotation lingual rotation	6
Average rotational velocity (deg/s)	X-axis (+) X-axis (-) Y-axis (+) Y-axis (-) Z-axis (+) Z-axis (-)	mesial angulation distal angulation buccoversion linguoversion mesiobuccal rotation lingual rotation	6
Maximum rotational velocity (deg/s)	X-axis (+) X-axis (-) Y-axis (+) Y-axis (-) Z-axis (+) Z-axis (-)	mesial angulation distal angulation buccoversion linguoversion mesiobuccal rotation lingual rotation	6
Variation of rotational velocity on a single axis (deg/s)	X-axis Y-axis Z-axis	mesial-distal angulation bucco-palato/linguoversion mesiobuccal- mesiopalatal/lingual rotation	3

Appendix Table 2: base characteristics of experimental material and experiments. mm = millimeter.

Base Characteristics	Total number
Fresh-frozen specimens	**7**
Upper jaws with teeth	6
Lower jaws with teeth	6
Total number of experiments	**127**
Successful experiments:	**110**
Without complications	94
Boney wall fracture	9
Root fracture (late)	6
Crown fracture/failure (with root removal)	3
Unsuccessful experiments:	**17**
Insufficient fixation of jaw	8
Early crown fracture/failure (without root removal)	5
Robot / software errors	
Excessive slippage of the forceps	3
	1
Periodontal state (out of 110 experiments)	
- sound (pocket depth <3mm)	82
- recessions	33
- mild decay (pocket depth 3-5mm)	16
- severe decay (pocket depth >5mm)	12
Restorative state (out of 110 experiments)	
- sound	47
- direct restoration large (≥ 2 surfaces)	25
- indirect restoration	20
- direct restoration small (≤ 2 surfaces)	18



Chapter 8

General discussion

General discussion

The aim of this thesis was to improve fundamental knowledge of tooth removal. We hypothesized that challenges in gaining high quality data regarding these complex procedures could be overcome using robot technology. Our second hypothesis was that we could use modern machine learning techniques to improve our understanding of these complex procedures.

State of the Art – Robot technology in dentistry

Summary of findings

In **Chapter 2**, we provided dental practitioners and researchers with a comprehensive, transparent and evidence-based overview of the main characteristics of literature regarding robot initiatives in dentistry. The overall quality of the study designs and the average level of technological readiness was low. In those cases where technology reaches the level of commercial availability, articles supporting their value in clinical or economical terms are either non-existing or very limited. We found that, on average, six articles were published on this topic per year in the last decade [1]. The largest group of articles (80%) was classified as basic research. This means that the technology has not yet been compared to any existing techniques nor tested in, for example, a series of patients. In 84% of all papers, the first author had a technological background and 36% of all papers did not have an author with a medical/dental background. In **Chapter 3**, we constructed a comprehensive overview of the different robotic initiatives in all fields of dentistry. Our review showed that most research in this field has been limited to those situations where physical contact with a human can be avoided, i.e., education or manipulation of dental materials such as orthodontic wire. We described a shift from the use of industrial robots in early experiments towards more human-compliant robotic systems and systems specifically designed for dentistry [2]. Despite the important limitations found in literature, commercial robotic solutions are available, mainly in orthodontics and implantology. The implantology robot 'Yomi' (Neocis, Miami, Florida, USA), for example, is marketed as being the first and only Food and Drug Administration approved robot device for dental surgery. Its capabilities have been described in other reviews, referring to either grey literature or non-scientific papers [3-5]. Scientific data supporting the functionality of commercially available robotic systems in dentistry seems limited in clinical terms but also in terms of cost-effectiveness.

Limitations

For both reviews, the absence of a clear definition of a 'Robot' or 'Robotics' has been an issue. This has been overcome by including all articles in which the author described the mentioned technology as such. This resulted in an overestimation of developments in this field. On the other hand, by excluding grey literature or patents, we might have underestimated the developments as a certain 'lag' might occur between technological developments and appearance as such in scientific literature. Certain metrics required interpretation of the authors, such as the technological readiness of the projects, which introduces room for errors.

Contribution to existing knowledge

The authors believe to have constructed a comprehensive overview of robotic developments in dentistry with a transparent methodology. A review as such was missing in scientific literature. By interpreting the technological readiness of the initiatives, the reader is presented a clear state of art when considering robot technology in their work field. The reviews also warns for the lack of clinical research supporting some of the commercially available solutions, in contrast to other reviews [3, 4].

Using robot technology to gain understanding of tooth removal procedures

Summary of findings

In **Chapter 4**, design challenges are introduced when measuring subtle sub-millimeter movements in combination with high forces in a confined 'key-hole' environment. Design considerations from a collaboration between computer scientists, engineers and clinicians are presented. In order to gain high quality data an in vitro measurement setup was designed. Its main purpose was to measure forces, torques and movement data in and around all axes. To determine the influence of different clinical features, such as periodontal health or restorative states, a graphical user interface was designed that allows for the registration of a variety of metadata. In **Chapter 5 and 6** results concerning force and movements measurements, respectively, of over 100 fresh frozen samples are presented. Forces and movements were translated to the clinical relevant 'tooth frame' which allows for, amongst other, easy interpretation and comparison of our data. As this is pioneering research, we aimed for an arbitrary 100 samples to allow for a meaningful first analysis. The amount of forces and movements varies largely based on anatomic factors, such as the total root surface, number and curvature of roots, but also of patient factors such as bone morphology and mineral density [6, 7]. Our sample size was too small to make reliable conclusions regarding the effect of these clinical circumstances. Data were analyzed in a descriptive manner and results should be interpreted as a right order of magnitude.

Limitations

Several limitations should be taken into account when interpreting our results. As an elevator is an important tool in tooth removal procedures, the absence of data gathered with an elevator is an obvious shortcoming of this research. Because of the constantly changing position of the elevator relative to the tooth, it is more difficult to use for our research goals. Despite the position of a forceps relative to the tooth is more stable and experienced surgeons were instructed to reduce the amount of slippage as much as possible, some slippage of the forceps is inevitable. Therefore, our results in terms of motion should be regarded as movements of the forceps, not necessarily the tooth. As discussed in the aforementioned chapters, resistance caused by the robot during the experiments was an issue. When reaching a joint limit, the robot has to adjust other joints to enable movement in a certain direction. To reduce this effect, we developed a fixed starting position of the robot for both upper- and lower jaw with favorable joint starting positions.
Also, it is important to note that there is no benchmark to correlate our results to. To confirm our findings, our results should be compared to other datasets, preferably from clinical studies. The latter is especially important, as it is unknown in what way the freezing process influences the biomechanical properties of tooth removal.

Contribution to existing knowledge

In a recent review, we showed that our approach is unique [8]. For the first time forces were measured in and around all axis. Furthermore, motion patterns in tooth removal procedures were never before subject to research. This research delivers an insight into different technical aspects of tooth removal. They are well in line with textbook instructions on how to remove teeth and might therefore serve as a first 'evidence' of these instructions as they can be recognized in treatment strategies by experts [9]. Results can be used to develop new educational methods or instruments. Our results can be used as a benchmark for future projects.

Modern learning techniques in tooth removal

Summary of findings

In **Chapter 7** we present a classification model for tooth removal. Together with computer scientists, engineers and clinicians, brainstorm sessions were held in which we developed 'features' of tooth removal, based on the data presented in chapters 5 and 6. In total, we designed 75 features, such as 'amount of rotation around the longitudinal axes or the total amount of force delivered in the buccal direction . The importance of each feature to distinguish, for example, a molar from an incisor, was weighted in a feature selection step. It reduced the amount of features to 33. A Gaussian Naïve Bayes classification model was trained using the remaining features, with acceptable results. Especially so, given the expected variety in our dataset in combination with the relatively small data sample. On average and after 4-fold cross validation, the model was capable of determining the correct tooth classes in 86% (training set). In unseen data (test set), the average accuracy reached 54%. The model correctly classified the upper- or lower jaw, in 95% of the experiments.

Limitations

As stated previously, the sample size of our study is small and a high variety in our data is to be expected due to patient and anatomical factors. By including data from three different surgeons, the variety of our data is increased even further. This is beneficial for the 'generalizability' of our results, as a variety of techniques have been included. On the other hand, the heterogeneity of the data in combination with a small dataset makes it more difficult to train and interpret a classification model.

Contributions to existing knowledge

This study showed that the gathered data was of sufficient quality to use in a modern learning algorithm. It is a new way of looking at tooth removal procedures and opens doors to evidence based education in this field. For example, the degree of rotation around the longitudinal axis and the degree of rotation around the mesiodistal axis were selected for the model. From a clinical point of view, it is well known that these two rotations are essential in different tooth removal procedures. These metrics are also used in textbook instructions for tooth removal [9].

Future perspectives

Robot technology in dentistry

In our reviews, we found an average of 6 papers per year regarding robot usage in dentistry in that last decade. Despite this number remaining stable, we detected an increase in usage of open source control software, the use of compliant robots and robots specifically designed for dentistry in recent years. Together with robot technology improving on a wider scale and generally becoming less expensive, these developments might help to facilitate the progression of initiatives to higher levels of technology readiness more easily. It is important to note that, for now, scientific evidence regarding the functionality of commercially available systems is rarely available.

Development of new educational material

In a continued joint effort between the TU Delft, Amsterdam UMC and ACTA, our team of researchers is developing new (evidence-based) educational material for tooth removal. We have chosen a stepwise approach to enable us to evaluate different parts of education.

In the first step, the measurement setup has been adjusted make it suitable for educational purposes (Fig 1).

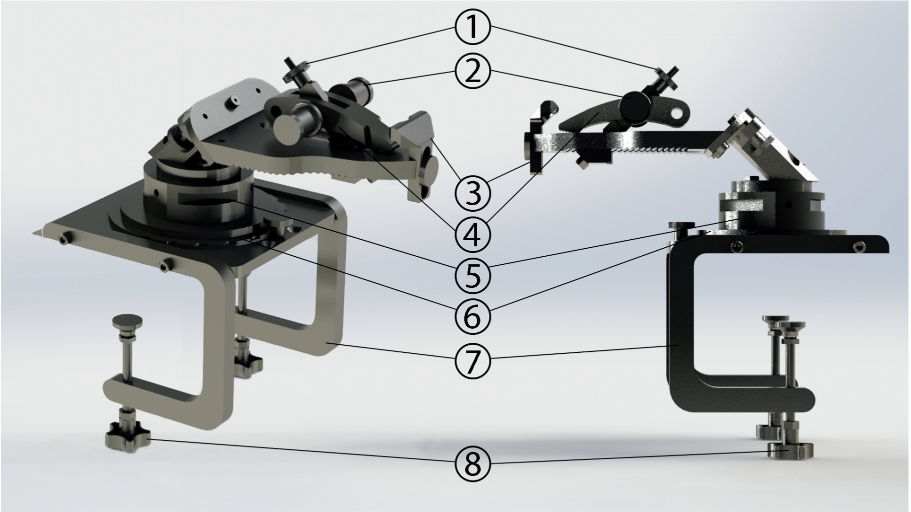


Figure 1: Jaw mount. (1) palatal mount clamping bolt, (2) axle boxes, (3) chin mount, (4) palatal mount, (5) six degrees-of-freedom force/torque sensor (available in the next version of our setup), (6) rotatable base (7) table mount claws, (8) table mount adjustment screws

The two separate holding devices have been merged into one. It can hold both plastic models and cadaver samples, rigidly. In the 2022-2023 curriculum, for the first time, students in their master phase are invited for a full day of education in tooth removal. They receive a lecture, with examples from our dataset and are encouraged to remove, on average, 10 plastic model teeth in the morning. In the afternoon, they have the opportunity to remove teeth from fresh frozen cadavers. The education is extensively evaluated through our in-house developed (and validated) questionnaires (see below). In parallel, we have tested and evaluated different types of feedback options for the setup [10]. It seems that force feedback is the most feasible option at this point. For next curriculum (2023-2024), therefore, a six-axis force-torque sensor will be integrated in the current setup. A team of bachelor students in Biomechanical Engineering, under supervision of our research team, is developing and testing a variety of interfaces for the force sensor. The updated version of our setup will also have the possibility of collecting data for future analysis. Again, students will be asked to evaluate the educational methods. If proven successful and enough data (from both students and experts) has been collected for the next step, we envision a fully virtual simulation of tooth removal education.

Evaluation of education in dental students and dentists

In parallel to the development of the educational methods, we have made an effort to create evidence-based evaluation tools for our education. Together with the department of Psychology, University of Amsterdam a questionnaire has been developed that measures self-confidence levels of dental students regarding their tooth removal skill (unpublished work). Amongst others, the following steps were taken in the validation process:

1. Semi-structured interviews with dental interns
2. Focus groups with experts from all three dental faculties (Groningen, Nijmegen and Amsterdam) to develop a clear construct as well as relevant domains
3. Item development and expert (content) validation in several feedback rounds
4. Cognitive pre-testing on dental interns using 'think aloud' and 'verbal probing' techniques
5. Pilot testing on dental students from all three dental faculties followed by an exploratory factor analysis

6. Pilot testing (second round) on dental students from ACTA followed by a confirmatory factor analysis
7. Additional validation tests are currently conducted such as: test and re-test, educational effect, expert vs novice

We believe that the combination of improved fundamental understanding of tooth removal procedures, together with a strong evaluation tool will help us to create meaningful educational material in the near future.

Clinical guidelines and evaluation of different tooth removal strategies

After our first series of experiments, as described in this thesis, we have made recommendations to improve our measurement setup. For example, the calibration step could be improved using imaging data. In a new series of more focused experiments on fresh frozen material, the measurement setup could be used to answer specific questions, such as:

- How can we, objectively, describe 'complex' procedures?
- How can we predict, based on clinical parameters such as root length, restorative states, periodontal stage, age and gender, which procedure will be more complex than the other?
- How can we predict when a tooth might fracture during the procedure and what adjustments in the procedure can be used to best avoid these events?

Answering these questions might deliver practical clinical guidelines and insights to general dentists, for example whether or not a specific patient should be referred for treatment.

Currently, our setup does not provide the possibility of measuring procedures in a clinical setting. Despite some technological challenges need to be overcome to get sufficient data in clinical experiments; an effort should be made to, at least partially, develop a database with clinical data to correlate our results to.

Conclusion

The aim of this thesis was to improve our fundamental knowledge of tooth removal. The following specific conclusion could be drawn, based on this thesis:

- robot technology in dentistry is still in its relative infancy and the overall quality of literature on this topic should be regarded as low (Chapter 2)
- commercially available robotic solutions lack scientific proof of their functionality (Chapter 3)
- through the use of robot technology (Chapter 4), we were able to present an order of magnitude when considering forces (Chapter 5), torques (Chapter 5) and motion patterns (Chapter 6) in tooth removal
- modern machine learning techniques can be used to improve our understanding of tooth removal procedures

References

[1] J. De Ceulaer, C. De Clercq, G.R. Swennen, Robotic surgery in oral and maxillofacial, craniofacial and head and neck surgery: a systematic review of the literature, Int J Oral Maxillofac Surg 41(11) (2012) 1311-24.

[2] J. Li, J. Lam, M. Liu, Z. Wang, Compliant Control and Compensation for A Compact Cable-Driven Robotic Manipulator, IEEE Robotics and Automation Letters 5(4) (2020) 5417-5424.

[3] Z.S. Haidar, Autonomous Robotics: A fresh Era of Implant Dentistry… is a reality!, Journal of Oral Research 6(9) (2017) 230-231.

[4] Y. Wu, F. Wang, S. Fan, J.K. Chow, Robotics in Dental Implantology, Oral Maxillofac Surg Clin North Am 31(3) (2019) 513-518.

[5] J. Grischke, L. Johannsmeier, L. Eich, L. Griga, S. Haddadin, Dentronics: Towards robotics and artificial intelligence in dentistry, Dent Mater (2020).

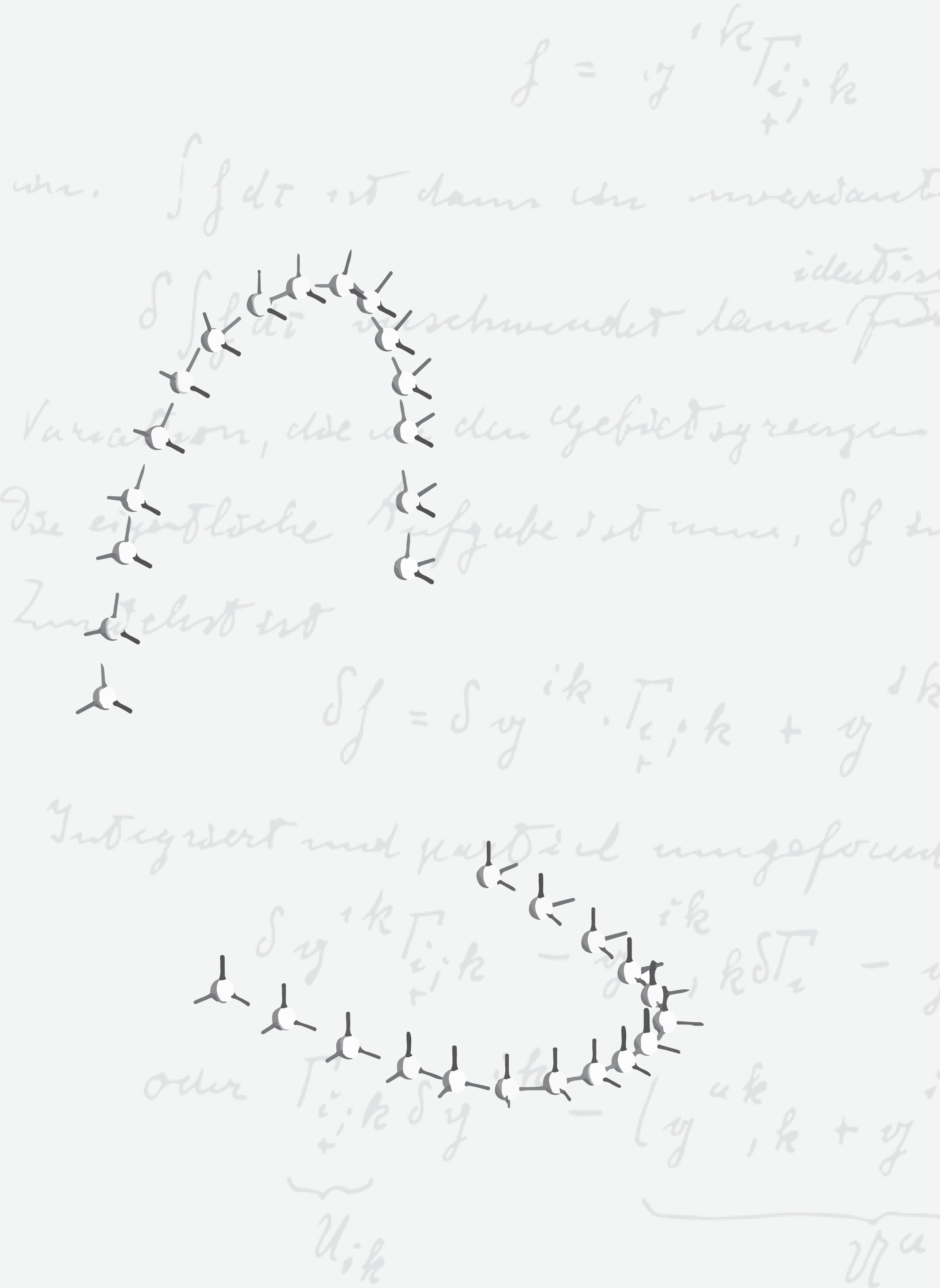
[6] V. Ahel, T. Cabov, S. Spalj, B. Peric, D. Jelusic, M. Dmitrasinovic, Forces that fracture teeth during extraction with mandibular premolar and maxillary incisor forceps, Br J Oral Maxillofac Surg 53(10) (2015) 982-7.

[7] T. Dietrich, I. Schmid, M. Locher, O. Addison, Extraction force and its determinants for minimally invasive vertical tooth extraction, J Mech Behav Biomed Mater 105 (2020) 103711.

[8] M.G. Beuling, P.C.G. Agterbos, T.C.T. van Riet, J.P.T.F. Ho, R. de Vries, J. Kober, J. de Lange, Forces and movements during tooth extraction: A scoping review, Advances in Oral and Maxillofacial Surgery 9 (2023).

[9] B. Stegenga, MKA Chirurgie, 2nd ed., van Gorcum2013.

[10] M.G. Beuling, T.C.T. van Riet, J. van Frankenhuyzen, R.V. Antwerpen, B. de Blocq van Scheltinga, A.H.H. Dourleijn, D. Ireiz, S. Streefkerk, J.C. van Zanten Jan de Lange, J. Kober, D. Dodou, Development and testing of a prototype of a dental extraction trainer with real-time feedback on forces, torques, and angular velocity, Annu Int Conf IEEE Eng Med Biol Soc 2022 (2022) 3285-3290.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Integriert und partiell umgeformt

Chapter 9

Appendices

Summary

This general summary presents a comprehensive overview of the research conducted in this PhD thesis, focusing on improving our scientific understanding of tooth removal procedures in dentistry.

Chapter 2

This chapter aims to provide a comprehensive overview of the characteristics of literature on robot technology initiatives in dentistry. The study screened a total of 911 articles, ultimately analyzing 94 articles. It showed that the number of articles concerning robot initiatives in dentistry has been increasing since 2013 to an average of six articles per year. The majority of these articles originate from East Asia. The research was primarily categorized as basic theoretical or basic applied research, and the technology readiness levels were generally low, reaching up to level three (proof of concept) in most cases. The first authors of the included articles mainly had a technical background, while dental or medical backgrounds were less common among the authors. The overall quality of the literature, particularly in terms of clinical validation, was considered low.

Chapter 3

This chapter presents a systematic review of physical robot initiatives in various fields of dentistry since 1985. The study aims to provide a comprehensive and evidence-based overview of the usage and applications of robot technology in dentistry. The review included 94 articles that focused on primary data related to physical robot technology. The literature revealed numerous interesting robot initiatives; however, there is a lack of scientific evidence regarding the benefits, results, and cost-efficiency of robotic solutions in dentistry, especially for commercially available systems. The study suggests that advancements in open-source control systems, human-compliant robot systems, and dentistry-specific robot technology may facilitate future technological development in dentistry.

Chapter 4

This chapter proposes a measurement setup capable of capturing the combination of high forces and subtle movements during tooth removal procedures in a detailed and reproducible manner using robot technology. The study involves collaboration between clinicians, mechanical engineers, and software engineers. The outcomes of the design process and the initial results are presented as a proof of concept. By measuring all aspects of tooth removal in a single setup, a strong database can be build that potentially improves our scientific understanding of the factors contributing to successful tooth removal. This setup also has the potential to evaluate techniques, predict adverse events, and create evidence-based teaching methods.

Chapter 5

The objective of this chapter is to capture both forces and torques exerted during tooth removal procedures in clinically relevant dimensions and high detail. An ex vivo measuring setup was used, which included a compliant robot arm and a six-axis force/torque sensor. The study used fresh-frozen cadavers to closely simulate the clinical situation. Data from 110 tooth removal experiments were successfully recorded. The study found that forces exerted in the dorsal region of both the upper and lower jaw were higher, with extrusion and buccal forces being the most dominant. The research highlights the limited scientific understanding of tooth removal procedures and emphasizes the importance of data collection and analysis to enable to improve educational material and evidence-based practices in this field.

Chapter 6

This chapter focuses on accurately capturing the full range of motions and angular velocities during tooth removal procedures using a compliant robot arm. The study used an ex vivo measuring setup, utilizing fresh-frozen cadavers and regular dental forceps mounted on the robot's end-effector. The data from 110 successful tooth removal experiments were presented descriptively. The study found that rotation around the longitudinal axis of the tooth was the most dominant motion, both in terms of range of motion and angular velocity. Buccopalatal and buccolingual movements were more pronounced in the dorsal region of both the upper and lower jaw. The research quantifies the ranges of motion and angular velocities involved in tooth removal procedures, which could aid in developing evidence-based educational material.

Chapter 7

This chapter addresses the lack of scientific knowledge on tooth removal procedures and proposes the use of a multiclass classification model for tooth removal. The measurement setup utilized robot technology to gather high-quality data on forces, torques, and movements during tooth removal procedures. Fresh-frozen cadavers were used to closely simulate the clinical situation. Clinically interpretable variables or "features" were engineered, and feature selection was performed to process the data. A Gaussian Naïve Bayes model was trained to classify tooth removal procedures. The study had data from 110 successful tooth removal experiments to train the classification model. Out of 75 clinically designed features, 33 were selected for the model. The overall accuracy of the classification model was 86% in the training set and 54% in the test set. The model correctly classified the jaw (upper or lower) in 95% of cases and either the correct class or a neighboring class of teeth in 88% of cases. This multiclass classification model represents a significant step towards better understanding tooth removal procedures. Despite the relatively small dataset, the quality of the data was sufficient to develop a model with reasonable performance. The results of the feature engineering, selection process, and classification model have the potential to contribute to the development of evidence-based educational material and clinical guidelines in the future.

In conclusion, in the chapters of this PhD thesis various aspects of robot technology and its applications in dentistry were explored, aiming to assess existing knowledge and evidence-based practices in this field. They highlight the increasing interest in robot initiatives in dentistry, the need for scientific validation and evidence-based practices, and the potential of robot technology to increase our fundamental understanding of tooth removal procedures. The studies emphasize the importance of data collection, analysis, and collaboration between different disciplines to enhance our fundamental understanding of tooth removal procedures, with a focus on improving dental education and ultimately patient care.

Samenvatting

Deze algemene samenvatting biedt een overzicht van het onderzoek dat is uitgevoerd in deze PhD-thesis, gericht op het verbeteren van onze wetenschappelijke kennis van tandheelkundige ingrepen waarbij tanden worden verwijderd, de extractieleer. Het onderzoek is gepresenteerd in zes kernhoofdstukken (2 t/m 6) die verschillende aspecten van dit onderwerp behandelen.

Hoofdstuk 2

In dit hoofdstuk lag de focus op het verkrijgen van een uitgebreid overzicht van verschillende kenmerken van de literatuur over robottechnologie in de tandheelkunde. Het onderzoek omvatte een grondige screening van 911 artikelen, waarbij uiteindelijk 94 artikelen werden geïncludeerd voor verdere analyse. Hieruit bleek dat het aantal artikelen over robottechnologie in de tandheelkunde sinds 2013 gestaag is toegenomen tot een gemiddelde van ongeveer 6 artikelen per jaar. Opvallend was dat het merendeel van deze artikelen afkomstig was uit Oost-Azië. De onderzoeken werden hoofdzakelijk gecategoriseerd als basaal wetenschappelijk onderzoek (theoretisch en/of toegepast), waarbij de niveaus van ontwikkeling van de technologie over het algemeen laag was. Het viel op dat de eerste auteurs van de geanalyseerde artikelen voornamelijk een technische achtergrond hadden, terwijl auteurs met een tandheelkundige of medische achtergrond minder vaak voorkwamen. Over het algemeen werd de kwaliteit van de literatuur, met name op het gebied van klinische validatie, als laag beoordeeld.

Hoofdstuk 3

Dit hoofdstuk beschrijft de resultaten van een systematisch literatuuronderzoek van verschillende robotsystemen en hun toepassingsgebied in verschillende tandheelkundige vakgebieden sinds 1985. Het doel was om een uitgebreid en op bewijs gebaseerd overzicht te bieden van het gebruik en de toepassingen van robottechnologie in de tandheelkunde. Hoewel er veel interessante robotinitiatieven werden geïdentificeerd, ontbrak het aan wetenschappelijk bewijs met betrekking tot de voordelen, resultaten en kostenefficiëntie van robotsystemen in de tandheelkunde, dit geldt ook voor systemen die reeds commercieel beschikbaar zijn. Het onderzoek suggereert dat de ontwikkeling van open-source besturingssystemen, interactieve robotsystemen en robottechnologie specifiek ontwikkeld voor de tandheelkunde de toekomstige ontwikkeling in de tandheelkunde kunnen bevorderen.

Hoofdstuk 4

In de hoofdstuk werd een meetopstelling voorgesteld waarmee de combinatie van hoge krachten en subtiele bewegingen die tijdens het extraheren optreden, gedetailleerd en reproduceerbaar kan worden vastgelegd met behulp van robottechnologie. Het onderzoek was kwam voort uit een samenwerking tussen clinici, werktuigbouwkundig ingenieurs en software-ingenieurs. De resultaten van het ontwerpproces en de initiële bevindingen werden gepresenteerd als een proof of concept . Door alle aspecten van tandheelkundige ingrepen in één opstelling te meten, is het mogelijk een sterke database te bouwen die ons begrip van de factoren die bijdragen aan succesvolle extracties kan verbeteren. Deze opstelling biedt ook mogelijkheden om verschillende extractietechnieken te evalueren, complicaties te voorspellen en evidence based onderwijsmethoden te ontwikkelen.

Hoofdstuk 5

Dit hoofdstuk was gericht op het nauwkeurig vastleggen van de krachten en momenten die worden uitgeoefend tijdens tandheelkundige extracties, in klinisch relevante dimensies en in hoog detail. Hiervoor werd gebruikgemaakt van een meetopstelling met een robotarm en een zes-assige kracht-/momentsensor. Verse bevroren kadavers werden gebruikt om de klinische situatie zo nauwkeurig mogelijk na te bootsen. Er werden met succes metingen uitgevoerd tijdens 110 tandheelkundige ingrepen. Uit het onderzoek bleek dat de krachten die werden uitgeoefend in het dorsale gedeelte van zowel de boven- als onderkaak hoger waren, met extrusie- en buccale krachten als de meest dominante. De studie benadrukt het beperkte wetenschappelijke begrip van tandheelkundige ingrepen waarbij tanden worden verwijderd en het belang van gegevensverzameling en -analyse om het onderwijsmateriaal op dit gebied te verbeteren.

Hoofdstuk 6

Dit hoofdstuk concentreerde zich op het nauwkeurig vastleggen van het volledige bewegingsbereik en de snelheden die tijdens tandheelkundige extracties worden bereikt met behulp van een robotarm. Het onderzoek maakte gebruik van een meetopstelling met verse bevroren kadavers en reguliere tandheelkundige extractietangen, gemonteerd op het uiteinde van de robotarm. De gegevens van 110 succesvolle tandheelkundige ingrepen werden descriptief gepresenteerd. Het onderzoek toonde aan dat rotatie rond de longitudinale as van de tand de meest dominante beweging was, zowel wat betreft het bewegingsbereik als de snelheid.

Buccopalatinaal- en buccolinguale bewegingen waren meer uitgesproken in het dorsale gedeelte van zowel de boven- als onderkaak.

Hoofdstuk 7

In dit hoofdstuk wordt de ontwikkeling van een classificatiemodel voor de extractieleer beschreven. Er werd gebruik gemaakt van hoogwaardige gegevens over krachten, koppels en bewegingen uitgevoerd tijdens extracties. Klinisch interpreteerbare variabelen of “features” werden ontwikkeld en geselecteerd om de gegevens te verwerken. Een ‘Gaussian Naïve Bayes-model’ werd getraind om extracties te classificeren. Het model werd getraind met gegevens van 110 ingrepen, waarbij 75 klinisch ontworpen kenmerken werden ontwikkeld. De algehele nauwkeurigheid van het classificatiemodel was 86% in de training set en 54% in de test set. Het model classificeerde de kaak (boven- of onderkaak) correct in 95% van de gevallen en de juiste klasse of een aangrenzende klasse van tanden in 88% van de gevallen, in de test set. Ondanks de relatief kleine dataset was de kwaliteit van de gegevens voldoende om een model met redelijke prestaties te ontwikkelen. De resultaten van het feature engineering-, selectieproces en het classificatiemodel hebben het potentieel om bij te dragen aan de ontwikkeling van op bewijs gebaseerd educatief materiaal en klinische richtlijnen in de toekomst.

Concluderend werden in de hoofdstukken van deze PhD-thesis verschillende aspecten van robottechnologie en de toepassingen ervan in de tandheelkunde onderzocht, met als doel de bestaande op dit gebied te beoordelen. Ze benadrukken de toenemende interesse in robotinitiatieven in de tandheelkunde, de behoefte aan wetenschappelijke validatie en op bewijs gebaseerde praktijken, en het potentieel van robottechnologie om ons fundamentele begrip van de extractieleer te vergroten. De studies benadrukken het belang van gegevensverzameling, analyse en samenwerking tussen verschillende disciplines om ons fundamentele begrip van extracties te verbeteren, met een focus op tandheelkundig onderwijs en uiteindelijk de patiëntenzorg.

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Chapter information

Chapter 2

Published as:

Robot technology in dentistry, part one of a systematic review: literature characteristics

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Author contributions:

Study design:	TR, JH, RS, JL
Conduct of study:	TR, KC, JH
Collection of data:	TR, KC, JH
Analysis and management of data:	TR, KC, JH
Preparation of manuscript:	TR, KC
Review of manuscript:	TR, KC, JH, RS, JK, JL

Funding sources:

Department and institutional funds.

Conflicts of interest:

None

Chapter 3

Published as:

Robot technology in dentistry, part two of a systematic review: an overview of initiatives

Authors:

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Collection of data:	TR, KC, JH
Analysis and management of data:	TR, KC, JH
Preparation of manuscript:	TR, KC
Review of manuscript:	TR, KC, JH, RS, JK, JL

Funding sources:

Department and institutional funds.

Conflicts of interest:

None

Chapter 4

Published as:
Robot Technology in Analyzing Tooth Removal - a Proof of Concept

Authors:
Tom C.T. van Riet, Willem M. de Graaf, Reinier van Antwerpen, Jan van Frankenhuyzen, J. de Lange, Jens Kober

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Collection of data:	TR, WG, JK
Analysis and management of data:	TR, WG, JK
Preparation of manuscript:	TR, WG
Review of manuscript:	TR, WG, RA, JF, JK, JL

Funding sources:
This research was supported by the Dutch Research Council (NWO) 'Open Mind' Grant (project
number 17394, 2018)

Conflicts of interest:
None

Chapter 5

Published as:
Using robot technology to analyze forces and torques in tooth removal

Authors:
Tom C.T. van Riet, Willem M. de Graaf, Jens Kober, J. de Lange

Author contributions:

Study design:	TR, WG, JK
Conduct of study:	TR, WG, JK
Collection of data:	TR, WG
Analysis and management of data:	TR, WG, JK
Preparation of manuscript:	TR, WG
Review of manuscript:	TR, WG, JK, JL

Funding sources:
This study was funded by the Dutch Research Council (NWO) “Open Mind 2018” Grant Project number 17394 and the Amsterdam University Medical Center “Innovation Impulse 2021,” for which no project number is available.

Conflicts of interest:
None

Chapter 6

Published as:
Analysis of movements in tooth removal procedures using robot technology

Authors:
Tom C.T. van Riet, Willem M. de Graaf, J. de Lange, Jens Kober

Author contributions:

Study design:	TR, WG, JK
Conduct of study:	TR, WG, JK
Collection of data:	TR, WG
Analysis and management of data:	TR, WG, JK
Preparation of manuscript:	TR, WG
Review of manuscript:	TR, WG, JK, JL

Funding sources:
This study was funded by the Dutch Research Council (NWO) "Open Mind 2018" Grant Project number 17394 and the Amsterdam University Medical Center "Innovation Impulse 2021," for which no project number is available.

Conflicts of interest:
None

Chapter 7

Published as:
A Multiclass Classification Model for Tooth Removal Procedures

Authors:
Willem M. de Graaf, Tom C.T. van Riet, J. de Lange, Jens Kober

Author contributions:

Study design:	TR, WG, JK
Conduct of study:	TR, WG, JK
Collection of data:	TR, WG
Analysis and management of data:	TR, WG, JK
Preparation of manuscript:	TR, WG
Review of manuscript:	TR, WG, JK, JL

Funding sources:
This study was funded by the Dutch Research Council (NWO) "Open Mind 2018" Grant Project number 17394 and the Amsterdam University Medical Center "Innovation Impulse 2021," for which no project number is available.

Conflicts of interest:
None

List of publications

In this thesis

Chapter 2
Robot Technology in denstistry, part one of a systematic review: literature characteristics
Authors: **T.C.T. van Riet**, K.T.H.C.J. Sem, J.P.T.F. Ho, R. Spijker, J. Kober, J. de Lange.
Published in: Dental Materials, 2021

Chapter 3
Robot Technology in denstistry, part two of a systematic review: an overview of initiatives
Authors: **T.C.T. van Riet**, K.T.H.C.J. Sem, J.P.T.F. Ho, R. Spijker, J. Kober, J. de Lange.
Published in: Dental Materials, 2021

Chapter 4
Robot Technology in Analyzing Tooth Removal – a Proof of Concept
Authors: **T.C.T. van Riet**, W.M. de Graaf, R. van Antwerpen, J. van Frankrenhuyzen, J. de Lange, J. Kober.
Published in: Proceedings of the 42nd Annual International Conference of the IEEE Engineering in Medicine & Biology Society, 2020

Chapter 5
Using robot technology to analyze forces and torques in tooth removal
Authors: **T.C.T. van Riet**, W.M. de Graaf, J. Kober and J. de Lange
Published in: Advances in Oral and Maxillofacial Surgery, 2023

Chapter 6
Analysis of movements in tooth removal procedures using robot technology
Authors: **T.C.T. van Riet**, W.M. de Graaf, J. de Lange and J. Kober
Published in: PLoS One, 2023

Chapter 7
A Multiclass Classification Model for Tooth Removal Procedures
Authors: W.M. de Graaf, **T.C.T. van Riet**, J. de Lange and J. Kober
Published in: Journal of Dental Research, 2022

Other international publications

Contributions of the Capsulorrhexis to Straylight
Authors: I. J. E. van der Meulen, L. A. Engelbrecht, **T. C. T. Van Riet**, R. Lapid-Gortzak, C. P. Nieuwendaal, M. P. Mourits, and T. J. T. P. van den Berg.
Published in: Archives of Ophthalmology, 2009

Correlation of straylight and visual acuity in long-term follow-up of manual descemet stripping endothelial keratoplasty.
Authors: I.J.E. van der Meulen, **T.C.T. van Riet**, R. Lapid-Gortzak, C.P. Nieuwendaal, T.J. van den Berg.
Published in: Cornea, 2012

Validation of the OrthoGnathicAnalyser 2.0—3D accuracy assessment tool for bimaxillary surgery and genioplasty
Authors: F. Baan, J.F. Sabelis, R. Schreurs, G. van de Steeg, T. Xi, **T.C.T. van Riet**, A.G. Becking, T.J.J. Maal
Published in: PLoS One, 2021

Power chains as an alternative to steel-wire ligatures in temporary maxillomandibular fixation: a pilot study
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Published in: International Journal of Oral and Maxillofacial Surgery, 2021

Adverse effects following dental local anesthesia: a literature review
Authors: J.P.T.F. Ho, **T.C.T. van Riet**, Y. Afrian, K.T.H.C.J. Sem, R. Spijker, J. de Lange.
Published in: Journal of Dental Anesthesia and Pain Medicine 2021

Development and testing of a prototype of a dental extraction trainer with real-time feedback on forces, torques, and angular velocity.
Authors: M.G. Beuling, **T.C.T. van Riet**, J. van Frankenhuyzen, R. van Antwerpen, B. de Bloacq van Scheltinga, A.H.H. Dourleijn, D. Ireiz, S. Streefkerk, J. C. van Zanten, J. de Lange, J. Kober, D. Dodou.
Published in: Published in: Proceedings of the 44nd Annual International Conference of the IEEE Engineering in Medicine & Biology Society, 2022

Management of Asymmetry
Authors: **T.C.T. van Riet**, C. Klop, A.G. Becking, J.W. Nolte
Published in: Oral and Maxillofacial Surgery Clinics of North America, 2022

Forces and movements during tooth extraction: A scoping review
Authors: M.G. Beuling, P.C.G. Agterbos, **T.C.T. van Riet**, J.P.T.F. Ho, R. de Vries, J. Kober, J. de Lange
Published in: Advances in Oral and Maxillofacial Surgery, 2023

A review and evaluation of orthodontic brackets, molar bands and orthodontic auxiliaries during orthognathic surgery
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Published in: Journal of Orthodontics 2023

Assessment of Surgical Accuracy in Maxillomandibular Advancement Surgery for Obstructive Sleep Apnea: A Preliminary Analysis
Authors: J.P.T.F. Ho, N. Zhou, **T.C.T. van Riet**, R. Schreurs, A.G. Becking, J. de Lange
Published in: Journal of Personalized Medicine 2023

Other publications in Dutch

Multipele spontane dentogene abcessen bij familiaire hypofosfatemische rachitis
Auteurs: **T.C.T. van Riet**, M. H. Frank, K. A. Hoeben, J. de Lange.
Bron: Nederlands Tijdsschrift voor Tandheelkunde, 2012

Hoog risico op zenuwletsel bij verwijdering van een M3 inferior? Kies voor een coronectomie
Auteurs: **T.C.T. van Riet**, R.J.J. van Es.
Bron: Tandheelkundig Jaar 2013

Trauma van het aangezicht, meer dan tandletsel.
Auteurs: L. Dubois, **T.C.T. van Riet,** F.H.M. Kroon.
Bron: Quality Practice 2014

Alternatieve implantaatsystemen voor de maxilla.
Auteurs: R.C. Apperloo, **T.C.T. van Riet**.
Bron: Quality Practice 2015

Tandheelkundige gevolgen van twee vormen van osteomalacie.
Auteurs: **T.C.T. van Riet**
Bron: Het Tandheelkundig Jaar 2016

Robottechnologie, is er een toekomst voor in de tandheelkunde?
Auteurs: **T.C.T. van Riet**, J. Kober, J. de Lange.
Bron: Quality Practice 2017

De 3D-geprinte zaag- en repositiemal voor een kinplastiek
Auteurs: M. Parmaksiz, A.C. Verhulst, S. van Heumen, S.W.R. Dalmeijer, F. Baan, J.H.F. Liebregts, C. Klop, T.J.J. Maal, T. Xi, **T.C.T. van Riet**, A.G. Becking
Bron: Nederlands Tijdsschrift voor Tandheelkunde, 2022

Individueel vervaardigde prothesen voor ankylotische kaakgewrichten
Auteurs: T.T. Kramer, J.P.T.F. Ho, S.E.C.M. van de Vijfeijken, M. Koutris, **T.C.T. van Riet**, J. de Lange
Bron: Nederlands Tijdsschrift voor Tandheelkunde, 2022

Acknowledgements (dankwoord)

U, als lezer van dit proefschrift, heeft een lange weg afgelegd om bij het dankwoord aan te komen. Hulde daarvoor! Over het algemeen vindt men in het dankwoord een verkapte klaagzang over een lange periode waarin een promotietraject de 'leuke dingen' in het leven in de weg stond. Helaas, dat gaat u hier niet vinden. Iedereen die er weleens een 'muntje in heeft gestopt' door mij te vragen hoe het ervoor staat met mijn onderzoek, weet dat ik erg (soms iets te) enthousiast kan worden van onderzoek doen. Misschien niet van het schrijven per se, maar wel van de momenten om na te denken over complexe vragen, te werken aan iets wat onontdekt is, de grenzen op te zoeken van mijn eigen kennis en samen te werken met zo veel verschillende mensen. Aangezien dat laatste voor mij het meest belangrijk is, zou ik graag iedereen die een bijdrage heeft geleverd, in welke vorm dan ook, willen bedanken. Een aantal mensen in het bijzonder.

Geachte **Prof. Dr. J. de Lange**, hooggeleerde promotor, beste Jan. Jij zag direct een kans in dit project toen ik voorstelde om met mijn 'robotidee' naar de TU Delft te gaan. Een 'sexy onderwerp' noemde je het in onze eerste meeting. Nu twijfel ik, na al die jaren, of dit eindproduct ook past bij die woordkeus. Desondanks waardeer ik, enorm, de ruimte die jij me hebt geboden om mijn eigen ideeën uit te werken. Daarbij heb je mij op de juiste momenten ondersteund. Ik bewonder hoezeer jij de kunst van het 'vertrouwen geven' als leidinggevende beheerst. Ik wil je ontzettend bedanken voor onze naadloze samenwerking en alle kansen die je mij biedt.

Geachte **Dr. J. Kober**, weledelzeergeleerde promotor, beste Jens. Aan de start van jouw carrière aan de TU Delft koos je ervoor om dit project op te pakken. Het mag duidelijk zijn dat ik daar tot op de dag heel erg dankbaar voor ben. Zonder de samenwerking met jou, was dit boekje er zeker niet gekomen. Ik wil je bedanken voor het delen van je expertise, scherpe blik, razendsnelle feedback en natuurlijk de bizarre smaken KitKat die je meeneemt wanneer je ergens een lezing hebt gehouden. Ik waardeer onze samenwerking en ik hoop dit nog lange tijd te mogen doen.

De leden van de promotiecommissie en oppositie wil ik hartelijk bedanken voor de tijd die zij namen om mijn proefschrift kritisch onder de loep te nemen: **Prof. Dr. R. Babuška, Prof. Dr. J.E. Bergsma, Prof. Dr. T.J.J. Maal, Prof. Dr. S.M. Peerdeman, Prof. Dr. A.G. Becking, Dr. B. van Minnen** en **Dr. Ir. T.H.F. Broens**

Geachte **Prof. Dr. A.G. Becking**, hooggeleerde mentor, beste Eddy. In 2010 kwam ik bij jou in Haarlem, tijdens een 'meekijkweek' in mijn vakantie, voor het eerst in aanraking met de MKA-chirurgie. Het was de eerste keer dat ik een osteotomie van een bovenkaak zag, als co-assistent. Een doorslaggevend moment en daarmee speel je al sinds het begin een belangrijke rol in mijn vorming tot MKA-chirurg. Ik heb ontzettend veel van je geleerd, kansen gekregen, espresso's met je gedronken en ik hoop de gezellige samenwerking nog vele jaren te mogen voortzetten.

Heren ingenieurs, **Jan van Frankenhuyzen** en **Reinier van Antwerpen**. Jullie tomeloze inzet en creativiteit voor de bouw van allerhande tafels, klemmen, plaatjes en tangen voor dit project heeft het mede tot een succes gemaakt. Misschien soms wat te laat aanwezig (wie spreekt er dan ook voor 9u af met een ingenieur?) maar altijd met veel humor. Ook wil ik graag **Dr. Dodou**, Dimitra, bedanken voor de constructieve en gezellige samenwerking. Ik hoop ook in de toekomst samen met jullie aan mooie dingen te kunnen bouwen.

Beste paranimfen, **Jean-Pierre Ho** en **Robert Rutgers**, graag wil ik jullie in het bijzonder bedanken. Bassie en Adriaan, Team Dumb en Dumber, de Clowns uit Zuid-Oost, beste JP, jij bent een van de belangrijkste redenen waarom ik het in het AmsterdamUMC zo naar mijn zin heb. We houden samen enorm veel eitjes in de lucht en als een van ons even niet oplet, vangt de ander er eentje op. Meestal ruim voordat deze de grond raakt. Ik waardeer je stille kracht, je duidelijke visie, je grenzeloze motivatie voor de kliniek en je expertise op nagenoeg alle onderdelen van ons vak. Ik kan niet anders dan ook **Krista en Sam** bedanken voor de ruimte die ze jou geven om pijler te zijn in Team Tom en JP. Robert, je eerste e-mail die ik van je heb stamt uit 2009. Je had mijn telefoonnummer niet meer en vroeg je af waar en hoe laat we de dag erna infuuscursus hadden. Het geeft aan hoe zeer wij altijd al verschillen in onze persoonlijkheden, maar desondanks weten we elkaar altijd te vinden. Zowel op persoonlijk vlak als binnen ons aandachtsgebied in de MKA-chirurgie. Je bent al sinds ik je ken een voorbeeld en vriend voor mij. Daarnaast ben je, op zijn minst, medeverantwoordelijk voor mijn carrièrekeuze voor de MKA-chirurgie en daar ben ik je dankbaar voor.

Alle **collega Stafleden** van het AmsterdamUMC en alle **(oud-) AIOS**. Jullie zijn de reden dat ik al zo lang (nagenoeg) iedere dag met veel plezier naar 'het werk' kom. Dank dat jullie (meestal) meelachen met alle flauwe Dumpert-onzin die ik met jullie deel. Ik waardeer de gezellige samenwerking en ik ben trots dat ik deel uit mag maken van een team met zoveel expertise, ambitie en humor. Speciaal dank aan de twee nog-niet-benoemde leden van het osteotomieteam **Jacco Tuk** en **Jitske Nolte.** Jacco, jij bent nét voor mij gepromoveerd. Dank voor het afkijken, je nuttige tips en je openheid over de valkuilen bij de afronding van een proefschrift. Ook bedankt voor de plezierige maandagen in het Amstelland Ziekenhuis. Jitske jij mag zeker niet ontbreken in dit 'gezellige' dankwoord. Je bent een van de drijvende krachten in ons 'gezellige' team, altijd bereid om te helpen, je expertise in ons vakgebied te delen en ik bewonder de betrokkenheid die jij toont in de zorg voor je patiënten.

Alle bachelor- en masterstudenten van de TU en ACTA die ik de afgelopen 5 jaar heb mogen begeleiden wil ik graag bedanken voor hun enthousiasme: **Laszlo, Beerend, Youssef, Juliana, Romee, Lindsey, Pien, Rosanne, Anouk, Edwin, Bram, Bas, Jonathan, Arnout, Sander, Dzan, Bruno, Valentijn, Friso, Josh, Liza, Willem Momma** en **Willem Kolff**. In het bijzonder wil ik **Willem de Graaf** bedanken. Jij hebt het een hele belangrijke rol gespeeld in de kern van dit project, wat goed terug te zien is aan de auteurschappen die je hebt in de 3 belangrijkste hoofdstukken van dit boekje. Dank voor je enthousiasme, de gezellige samenwerking en de hoge kwaliteit van jouw bijdrage aan dit project. Ook **Kevin Chin Jen Sem**, medeauteur van de review hoofdstukken, veel dank voor jouw bijdrage aan dit boekje.

René Spijker, inmiddels weet ik dat jouw bijdrage als informatie-specialist meer dan bijzonder is geweest. Veel dank voor het meedenken en je actieve begeleiding.

De collega's van die meewerken aan het onderwijsprogramma dat voort is gekomen uit dit onderzoek; beste **Petra, Mara, Jermo, Sem, Inge** en ook **Karl**. Dank voor het meedenken, de flexibiliteit, het enthousiasme en alle hulp binnen deze onderzoekslijn.

Team Rooster, **Peter, Judith, Drikje, Rosita, Birgit** en, in het bijzonder, de steun en toeverlaat van mij en het Team, **Willemijn,** wat ben ik blij dat jullie bereid zijn om gezamenlijk met mij de verantwoordelijkheid te dragen voor die giga roostertaak. Of het op de vrijdagmiddag is, de dinsdagochtend of daarbuiten, ik waardeer het enorm dat jullie iedere keer weer met goede moed de brandjes helpen blussen. Mede dankzij ons teamwork blijft er af en toe nog tijd over voor onderzoek tijdens kantooruren!

De collega's van de technische geneeskunde **Ruud, Juliana, Niels, Edwin en Anouck**, bij jullie kan ik tussendoor altijd terecht met vragen, geklaag, nog meer Dumpert-onzin, een espresso en natuurlijk altijd voor een stevig stukje ***-muziek (thanks Ruud)! De sfeer op jullie kamer is altijd goed.

Aanstormend onderzoektalent, **Maaike, Bas, Naomi en Nina,** ik denk dat ik samenwerken met jullie een van de leukste onderdelen van mijn werk vind. **Maaike**, jij hebt een essentiële rol in het vervolg van dit project; ik zal écht mijn best doen om wat dingen los te laten! Ik zal mijn uiterste best doen om jullie optimaal te ondersteunen bij het uitvoeren van jullie promotieonderzoek.

Geachte **Prof. Dr. T. van den Berg**, **Dr. Franssen**, beste Tom en Luuk. Échte wetenschappers. Jullie hebben mij tijdens mijn stage bij het instituut voor Neurowetenschappen voor het eerst laten zien wat wetenschap inhoud. Die periode heeft een omslag betekent voor mij voor wat betreft mijn ambitie binnen de geneeskunde. Dank voor het overbrengen van jullie enthousiasme, het heeft zeer aanstekelijk gewerkt.

Jason Nak en **Raoul Grasman**, al geruime tijd (!) zijn jullie betrokken bij de 'future perspectives' van dit boekje. De vragenlijstontwikkeling is meer dan een klein puzzelstukje in dit project. Inmiddels besef ik me hoe onwaarschijnlijk complexe de materie is en dat wij absoluut niet zonder jullie hulp kunnen. Dank voor de tijd en energie die jullie hierin stoppen.

Beste **Piet-Hein**, lid van vedienste van **Team B&B.** Ik vond de aanvang, mede dankzij jou, misschien wel het leukste deel van dit project. Zonder jouw enthousiasme was ik zeer waarschijnlijk nooit over de drempel gestapt in Delft.

Alle vrienden en familie, de dubbele Rietberger, Utereg the Sequel, de Coole Gasten, Club Comer, Ma 20u10, 'T Hemeltje en natuurlijk de Boeien Reünisten, dank voor het aanhoren van mijn verschrikkelijke verhalen over tanden en robots, meestal tijdens een diner, borrel of tijdens het sporten. Wees gerust, het houdt niet op, niet vanzelf!

Lieve **dr. Kok**, beste **Madeleine**. Eindelijk een reactie op jouw dankwoord uit 2016 -> ik vind je inderdaad een nerd (net als ik)! Mooie club zijn we met z'n vieren. Dank aan jou en **Joshua**, voor alle adviezen, hyperspontane borrels, avondjes de Villa en beregezellige wintersportvakanties. Ik heb heel veel bewondering jullie

doorzettingsvermogen, zowel op professioneel vlak als daarbuiten. Ik ga jullie zeker missen als jullie niet meer bij ons om de hoek wonen!
Lieve **Mar**k en **Lisette,** ook jullie zou ik graag danken voor de gezellige dinertjes, jullie interesse en aanmoediging.

Lieve **Eef,** grote zus. Jij CGU, ik CGU. Jij geneeskunde, ik geneeskunde. Jij promotie, ik promotie. Jij ouderenzorg, ik uhmmm, kaakchirurgie. We verschillen, gelukkig, nog op genoeg vlakken. Ik bewonder hoe jij en **Jilles** de kunst van het genieten beheersen en het lef hebben om jullie dromen/ideeën waar te maken. En dat alles doorgeven aan mijn lieve nichtjes **Liza en Zoë**. Ik verheug me erop dat de hele bups weer in Nederland komt wonen.

Lieve **MaPa**. Jullie verdienen het om een absoluut zwaargewicht in dit dankwoord te zijn. Aan jullie en het warme nest dat jullie hebben gecreëerd heb ik zó veel te danken. Altijd een luisterend oor. Altijd motiverend. Altijd flexibel. Altijd in voor gezelligheid. Jullie zijn echte ondernemers, zitten nooit stil en jullie arbeidsethos hebben jullie rechtstreeks doorgegeven aan mij. Niet lullen maar poetsen. Heel veel dank voor alles wat jullie mij hebben meegegeven.

Al bijna 20 jaar Mijn Grote Lieverd en sinds 2 jaar "**Claudia** Kok-van Riet". Je geeft me alle ruimte die ik nodig heb om mijn ambities waar te maken. En trekt op tijd aan de bel als je denkt dat het tijd wordt dat ik gelucht moet worden. Ik waardeer alle momenten waarin we tijd maken voor elkaar. Samen hebben we al een groot deel van de wereld ontdekt en er is nog zoveel om naar uit te kijken!

About the author

Tom van Riet was born in Utrecht, the Netherlands in 1986. Growing up alongside his sister, Evelien van Riet and parents Clemens and Jacqueline.

Having completed secondary education at the Christelijk Gymnasium Utrecht in 2004, subsequently, Tom studied medicine at the University of Amsterdam. He graduated with honors in 2011. This was followed by a study dentistry at Radboud University, completing the program in 2015.

He started his training in oral and maxillofacial surgery (OMFS) in 2014 and visited different OMFS-departments during his traineeship, amongst others New York Presbyterian Hospital (Columbia University), Queen Victoria Hospital (East Grinstead, UK), Prince Philip Dental Hospital (Honk Kong University) and Ninth People Hospital (Shanghai Jiao Tong University, China). Since 2019, he works as a consultant in oral maxillofacial surgery at AmsterdamUMC and as an acting oral and maxillofacial surgeon at the Amstelland hospital in Amstelveen.

Tom has been a recipient of various grants to support his research, including NWO's Open Mind Grant in 2018, AmsterdamUMC's Innovation Impulse Grant in 2020, and the University of Amsterdam's Grassroots Grant in 2023.
He lives in Utrecht, together with his wife Claudia.

$$\mathfrak{H} = g^{ik}\Gamma_{\underset{+}{i};k}$$

ein. $\int \mathfrak{H} d\tau$ ist dann ein invarian

identisch
$\delta \int \mathfrak{H} d\tau$ verschwindet dann fü

Variation, die an den Gebietsgrenzen

Die eigentliche Aufgabe ist nun, $\delta \mathfrak{H}$

Zunächst ist

$$\delta \mathfrak{H} = \delta g^{ik} \cdot \Gamma_{\underset{+}{i};k} + g$$

Integriert und partiell umgeform

$$\delta g^{ik} \Gamma_{\underset{+}{i};k} - g^{ik}{}_{,k} \delta \Gamma_i -$$

$$\text{oder } \underbrace{\Gamma_{\underset{+}{i};k}}_{U_{ik}} \delta g^{ik} - \underbrace{\left(g^{ik}{}_{,k} + g\right.}_{U}$$