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## A Proof of Concept

Van Riet, Tom C.T.; De Graaf, Willem M.; Van Antwerpen, Reinier; Van Frankenhuyzen, Jan; De Lange, Jan; Kober, Jens

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# Robot Technology in Analyzing Tooth Removal - a Proof of Concept

Tom C.T. van Riet[1], Willem M. de Graaf[2], Reinier van Antwerpen[3], Jan van Frankenhuyzen[3], Jan de Lange[1], Jens Kober[2]

***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.**

## I. 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 3 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

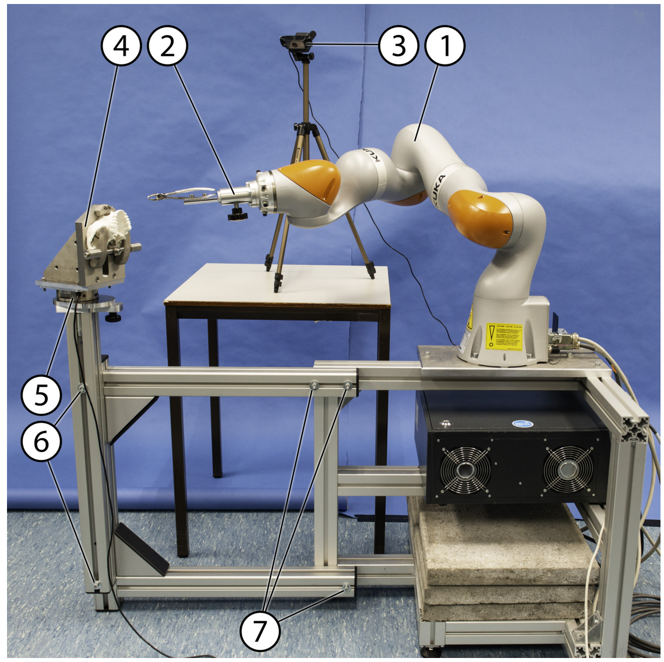


Fig. 1: Overview of the setup. (1) robot arm, (2) forceps holding device, (3) video camera, (4) upper jaw holding device, (5) force torque sensor, (6) bolts to adjust frame vertically, (7) bolts to adjust frame horizontally

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[1]Tom C.T. van Riet and Jan de Lange are with the department of Oral and Maxillofacial Surgery of the Amsterdam University Medical Center and the Academic Centre for Dentistry Amsterdam (ACTA), Meibergdreef 9, 1105 AZ, Amsterdam {t.c.vanriet, j.delange}@amsterdamumc.nl

[2]Willem M. de Graaf and Jens Kober are with the department of Cognitive Robotics of the 3mE faculty of the Delft University of Technology, Mekelweg 2, 2628 CD, Delft w.m.degraaf@student.tudelft.nl and j.kober@tudelft.nl

[3]Reinier van Antwerpen and Jan van Frankenhuyzen are with the Department of Biomechanical Engineering of the 3mE faculty of the Delft University of Technology, Mekelweg 2, 2628 CD, Delft {r.vanantwerpen, j.vanfrankenhuyzen}@tudelft.nl

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.

## II. MATERIAL AND METHODS

### A. 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 3 dimensions and at a high rate to be able to analyze movements in full detail and, for example, enable 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 3 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 compromises 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.

### B. 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)

### C. 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 aluminium 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

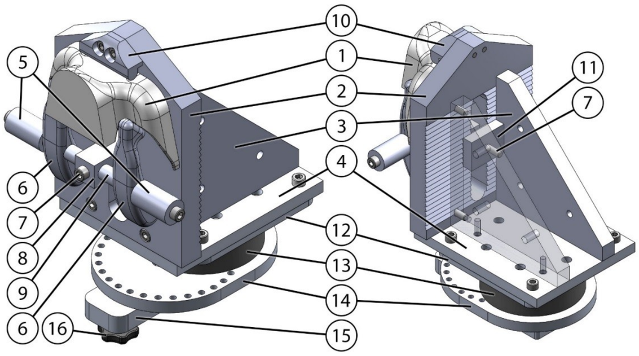



Fig. 2: Holding device for upper jaw: (1) upper jaw, (2) surface plate, (3) support plate, (4) ground plate, (5) axle boxes, (6) clamping arms, (7) clamping bolt, (8) sliding block, (9) clamp axis, (10) front block, (11) clamping nut, (12) top plate of sensor build-up, (13) force/torque sensor, (14)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

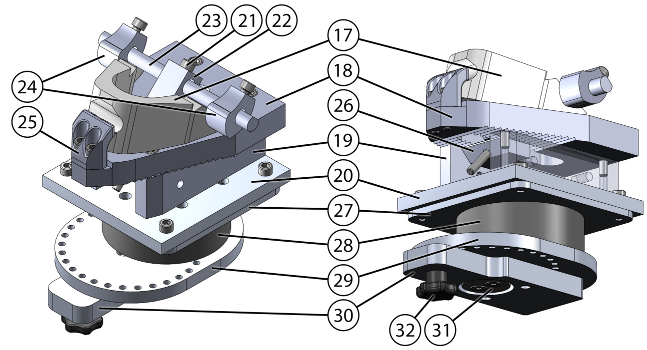



Fig. 3: Holding device for lower jaw: (17) lower jaw, (18) surface plate, (19) supporting plate, (20) ground plate, (21) clamping bolt, (22) sliding block, (23) clamp axis, (24) side blocks, (25) front block, (26) clamping nut, (27) top plate of sensor build-up, (28) force-torque sensor, (29) rotation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

used to facilitate cleaning which is especially necessary when working with (fresh) human material.

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 buttress'). 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 geometrically 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 sidewards. 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.

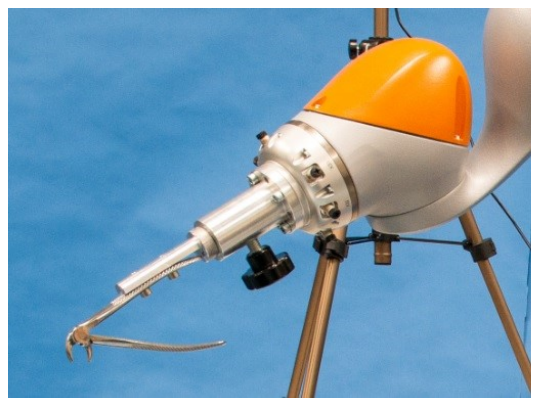


Fig. 4: Holding device for dental forceps.

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.

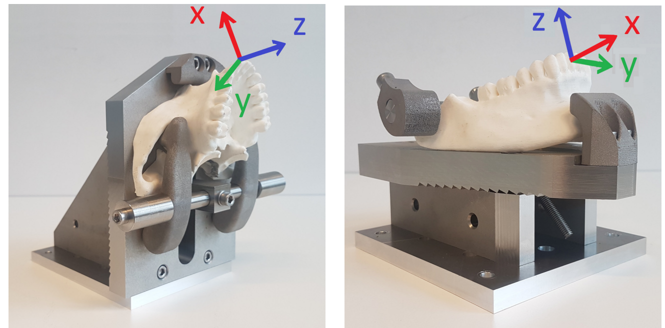
*D. The robot and force-torque measurements*

To obtain sub-millimeter precision and accurate repeatability of movements during the procedure, the KUKA LBR iiwa 7 R800 is used [9]. 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 [10]. 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 [11]. 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.




(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.

*E. 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 for 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 unuseful 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 (Internation Standards Organization number 3950, Fédération Dentaire International).

## III. 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 [12]. 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.

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.

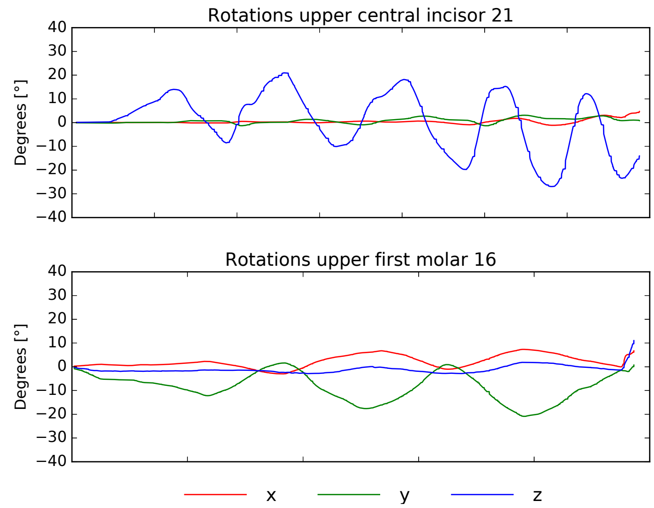


Fig. 6: Comparison of rotations of an upper incisor (21) and upper first molar (16)

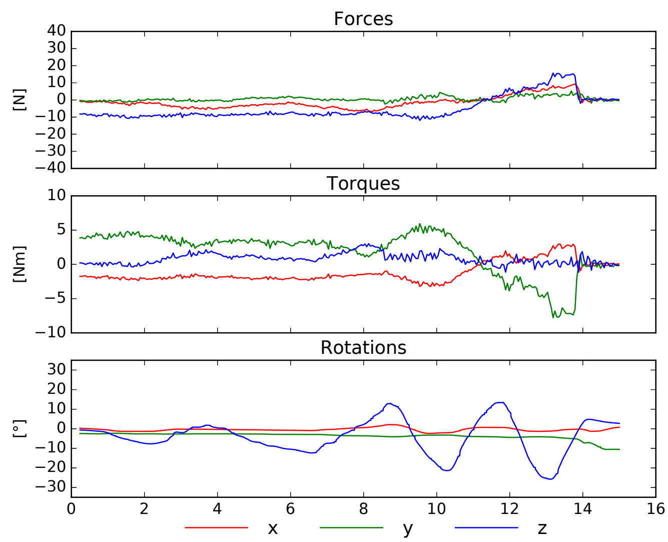


Fig. 7: Removal of a central upper incisor (21) by an experienced surgeon

### A. 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.

### B. 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).

## IV. 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 understanding 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], [13]. The studies that have been performed thus far used either a strain gauge or manometer attached to,

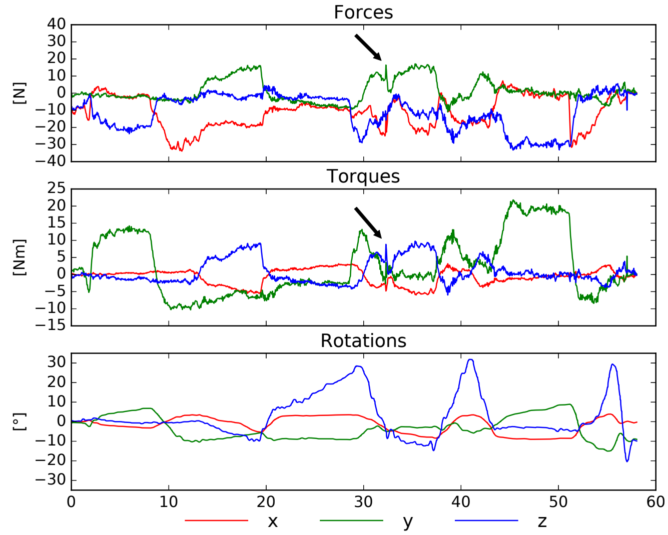



Fig. 8: Removal of a central upper incisor (11) by a dental student. The arrows indicate the spikes that occur at the instance the tooth fractures.

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 (submillimeter) 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.

## V. 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.

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