Preliminary bone sawing model for a virtual reality-based training simulator of bilateral sagittal split osteotomy

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Abstract. Successful bone sawing requires a high level of skill and experience, which could be gained by the use of Virtual Reality-based simulators. A key aspect of these medical simulators is realistic force feedback. The aim of this paper is to model the bone sawing process in order to develop a valid training simulator for the bilateral sagittal split osteotomy, the most often applied corrective surgery in case of a malposition of the mandible. Bone samples from a human cadaveric mandible were tested using a designed experimental system. Image processing and statistical analysis were used for the selection of four models for the bone sawing process. The results revealed a polynomial dependency between the material removal rate and the applied force. Differences between the three segments of the osteotomy line and between the cortical and cancellous bone were highlighted.

Keywords: Bone sawing, virtual reality, training simulator, bilateral sagittal split osteotomy

1 Introduction

Bone sawing is used in many medical procedures, such as: ostectomies, osteotomies, harvesting of bone grafts, arthroplasties and amputations. The success of the surgery and the rate of recovery of the patients are closely related to the precision of the sawing process. The complex structure and the anisotropy of the bone [1] can affect the sawing process. Concerning these, a high level of dexterity is required on part of the surgeon. During sawing procedure, they therefore rely a lot on tactile and force feedback, which leads to the demand of high-fidelity realistic haptic feedback in the training systems. Regardless of the traditional training methods, computer-based simulations have proven to be a valid alternative. In case of Virtual Reality (VR)-based training systems, a virtual environment is created by a computer and the trainee is able to naturally interact with it, e.g. by physical interaction by means of a haptic interface.

For simulation, bone cutting is often related with metal machining due to the strong similarity between the tools used [2, 3]. Besides this, other physics-based approaches were used for cutting force models in VR-based training systems, such as: Hertz's contact theory [4] or impulse theorem and Coulomb's law of dry friction [5]. Several authors have studied the specific cutting energy of the bone in certain processes [6, 7], but no definitive conclusion can be formulated at the present time in the case of bone sawing. Other authors used specific bone properties, e.g. bone mineral density [8], to establish a relation for the drilling forces. While there are numerous studies investigating the bone mechanical properties, there are only a few studies conducted on particular case, such as the human jaw [9–13], due to the difficulty of obtaining bone test samples with the dimensions required by most testing standards.

Concerning the treatment of deformities or malposition of human jaws, unfavourable sawing pattern or insufficient area of contact can lead to procedure-related errors, which can range from aesthetically unpleasant results to malocclusion and even life-threatening bleedings. Among the maxillofacial surgery procedures, bilateral sagittal split osteotomy (BSSO), according to Obwegeser and Dal Pont, is probably the most frequently used technique for total osteotomy of the mandible [14]. It is performed via an intraoral approach and starts with detaching the soft tissue from the mandibular ramus and body. After that, the osteotomy line is marked using a saw or a Lindemann's burr and successively deepened. By reversed twisting of two chisels inserted into the line, the mandible is split apart. After relocation in the desired position, the segments are fixed using an appropriate osteosynthesis. The technical difficulty of the procedure requires a high level of dexterity and experience which can be gained only through training. Currently, the training of the BSSO is limited to human cadavers or to patients. The first alternative is expensive and not readily available; the second alternative entails obvious risks for the patients. Due to these considerations, the aim of this study is to obtain a physics-based model for bone sawing during BSSO in order to implement it into a VR-based training system for the mentioned procedure [17].

The paper is organized in five sections. The next section, Materials and Methods, contains an analysis of a typical sawing process for maxillofacial surgery, in order to determine the process parameters. Furthermore, the conducted experiments, made to gain realistic values for the parameters, and the according methods used for data processing and statistical analysis are described as well. Afterwards, the obtained regression models for bone sawing are presented and discussed.

2 Materials and Methods

2.1 Bone sawing analysis

All material machining processes (turning, milling, drilling, sawing, etc.) can be reduced to the general case of oblique cutting with a single point cutting tool. The tool at a rake angle of α is moved against the workpiece with a velocity v in order to remove a layer of material in the form of a chip. The depth of the layer removed by the tool is known as the undeformed chip thickness s (see Fig. 1).

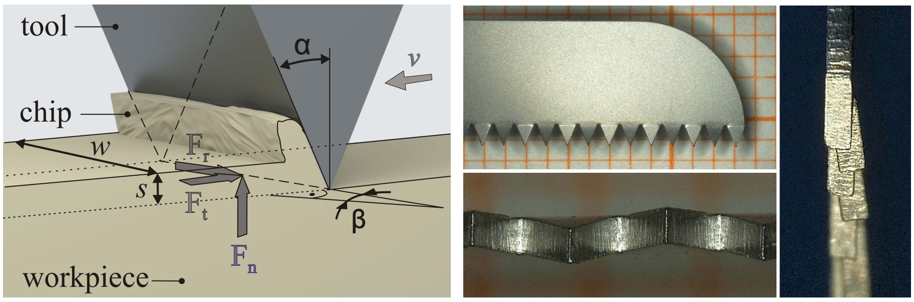

Fig. 1. (Left) Components of the cutting force. (Right) Sawing Blade.

In the general case of oblique cutting (helix angle β different than zero), the force that acts on the tool has three components [15, 16]: the tangential force F_t (in the cutting direction), the normal force F_n (in the feeding direction) and the radial force F_r (perpendicular on both forces F_n and F_t) (see Fig. 1). These forces are proportional to the section area of the undeformed chip A (the product of the chip thickness s times the chip width w [2, 15]:

$$\begin{bmatrix} F_t \\ F_n \\ F_r \end{bmatrix} = \begin{bmatrix} K_t \\ K_n \\ K_r \end{bmatrix} \cdot A \tag{1}$$

where K_t, K_n and K_r $[Nm/m^3]$ are the specific cutting energies along the tangential, normal and radial direction of the cutting. The specific cutting energy can vary considerably for a given material due to the influence of the cutting conditions, e.g. rake angle, helix angle, cutting velocity etc. However, for small changes in the cutting conditions, at a high cutting velocity and large feeds, the specific cutting energy tends to be constant and can be used like a mechanical property of the material [15].

In case of reciprocating sawing, the typically cutting process in maxillofacial surgery, the material removal process is the effect of two motions: (i) an oscillating motion along the workpiece, and (ii) a linear motion, the feed, moving the saw into the workpiece. The process is characterized by small feeds, high sawing speeds and kerf formation. Therefore, the sawing force for one tooth can be better related to the volume of the undeformed chip V_i. The volume can be determined by analysing the saw-tooth movements. The tooth moves in two successive positions during a period of time equal to half of the reciprocating frequency f, along the workpiece (with a distance equal to the reciprocating amplitude, the stroke, a) and along the feeding direction (with a distance equal to the chip thickness s). Therefore, the volume of the undeformed chip is:

$$V_i = w \cdot a \cdot s = w \cdot a \cdot \frac{v}{2 \cdot f} \tag{2}$$

where w is the chip width (equal to the saw blade kerf) and v is the feeding speed. According to the cutting tool classification [16], the saw is considered a multiple cutting edge tool. The saw blades (which are considered to be multiple cutting edge tools [16]) frequently used in surgeries have a constant pitch (see Fig. 1). Therefore, the total forces acting on the saw are proportional with the number of saw-teeth n that are in contact with the workpiece. Another design aspect of the surgical saw blade is that the saw teeth are facing opposite sides (see Fig. 1) in order to cancel the radial forces generated by the neighbouring teeth. Therefore, the cutting force components acting on the saw are then solely the tangential force F_t and the normal force F_n:

$$\begin{bmatrix} F_t \\ F_n \end{bmatrix} = \begin{bmatrix} K_t \\ K_n \end{bmatrix} \cdot V = \begin{bmatrix} K_t \\ K_n \end{bmatrix} \cdot n \cdot V_i \tag{3}$$

where V is the volume removed by the saw, K_t and K_n are the tangential and normal force parameters, respectively. The number of saw-teeth that act on the workpiece can be obtained by dividing the length of the saw part l that is in contact with the workpiece to the saw pitch p. The product of the length of the cut, the incision saw blade width and the cutting speed, is called the removal rate $R_r = l \cdot w \cdot v$. According to these considerations the forces acting on the saw are:

$$\begin{bmatrix} F_t \\ F_n \end{bmatrix} = \begin{bmatrix} K_t \\ K_n \end{bmatrix} \cdot \frac{l}{p} \cdot w \cdot a \cdot \frac{v}{2 \cdot f} = \frac{1}{2} \cdot \begin{bmatrix} K_t \\ K_n \end{bmatrix} \cdot \frac{R_r \cdot a}{p \cdot f} \tag{4}$$

Due to the reciprocating saw design, the tangential force is reduced, in the user hand, to a high-frequency vibration. In conclusion, the force perceived by the user for a small reciprocating saw typically used in maxillofacial surgery depends on the material removal rate and the saw parameters (saw pitch, frequency and amplitude of the saw reciprocating motion):

$$F_n = K_n \cdot \frac{R_r \cdot a}{p \cdot f} \tag{5}$$

2.2 Testing system

In order to establish a quantitative relation for bone sawing, a testing system was designed (see Fig. 2). A bone sample fixed on the carriage of a guidance system was pulled into the saw by the use of a pulley system. The forces exerted on the bone sample were acquired using a K3D120 three-dimensional force sensor from ME-Messsysteme GmbH (range 50 N, resolution 0.01 N, eigenfrequency 1000 Hz). The relative distance between the bone sample and the saw was measured by the PMI80-F90-IU-V1 inductive distance sensor from Pepperl and Fuchs (range 80mm, resolution 125 µm). The measurements were collected and stored at a frequency of 500 Hz using the GSV-3USBx2 2mV/V data acquisition system from ME-Messsysteme GmbH. A program for data acquisition was developed using LabVIEWiew 8.5.1 from National Instruments. The sawing system used in the experiments was the Bran Aesculap Microspeed Artho system composed of: a GD678 motor, a GB130R small reciprocating saw (frequency 20000 rpm, stroke 3 mm) and a GC909R saw blade (cutting length 33 mm, width 0.4 mm and kerf 0.6 mm).

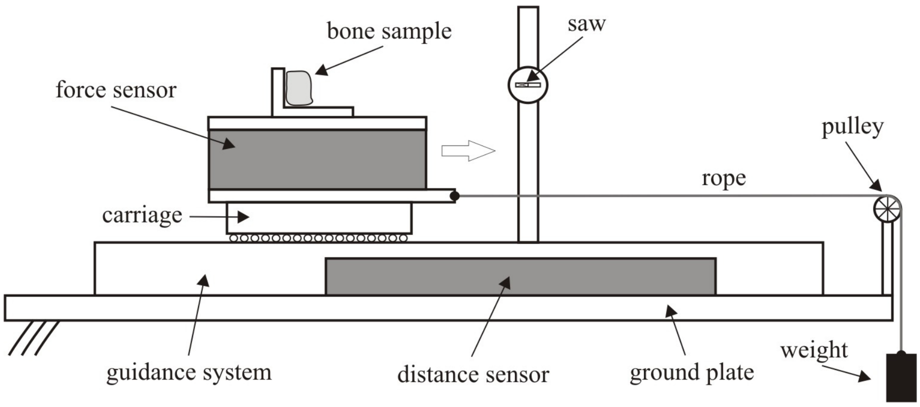

Fig. 2. The testing system

2.3 Bone sample preparation

A human cadaver mandible (male cadaver, 58 years old) was used for the experiments. The mandible was sectioned in six samples: two samples for each of the three typical osteotomy line segments (see Fig. 3). The bone samples were fixed with glue and screws on the force sensor through a mechanical connector, in order to obtain the same cutting directions such as the ones of the BSSO (see Fig. 3).

2.4 Testing conditions

Due to the fact that only one mandible was used for testing, we used the same reciprocating motion parameters (constant reciprocating frequency and amplitude) and the same saw blade (constant saw pitch). In order to select the force for pulling the bone into the saw, we determined typical sawing forces in pre-measurements with an expert surgeon. For each of the bone samples a number

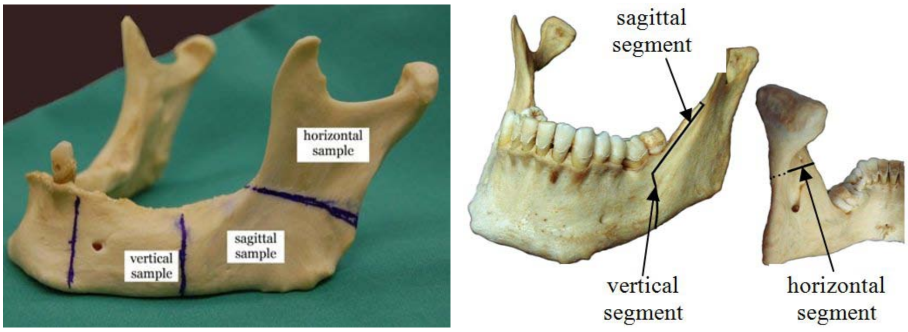

Fig. 3. Bone sample preparation according to the osteotomy line. (Left) The location of the samples. (Right) The segments of the osteotomy line.

of cuts (2...3 cuts) were made according to the procedure specifications and the available space.

2.5 Data processing and statistical analysis

To get the final parameters the collected data was processed in two steps: (i) image processing of the section cuts in order to obtain the dependency between the depth and the length of the cut, and (ii) data processing to relate the measured normal sawing forces via the sawing depth, cut length, and feed rate to a removal rate. Up to three areas were determined for each section cut according to the structure of the bone: cortical bone area, cancellous bone area and mixed cortical-cancellous bone area. Only the areas where one type of bone exists were used in the analysis. Due to the particularities of the osteotomy line, four cases were analysed: cortical bone in the horizontal cut (c-h), cortical bone in the vertical cut (c-v), cortical bone in the sagittal cut (c-s) and cancellous bone in the sagittal cut (s-s).

For each of the four cases, the regression models of the dependency between the removal rate and the normal force were determined. The goodness of the fits was analysed based on the coefficient of determination R^2 . Furthermore, the non-linear correlation coefficient (measure of the strength of a non-linear relation between two variables) was computed for each case in order to illustrate the need of a non-linear fit for the removal rate versus force dependency.

3 Results

The dependencies between the removal rate and the normal sawing force are shown in Figure 4. A non-linear dependency can be observed directly from the graphics in each of the four cases. The non-linear correlation coefficients were: (c-h) 0.981; (c-v) 0.984; (c-s) 0.961; (s-s) 0.975.

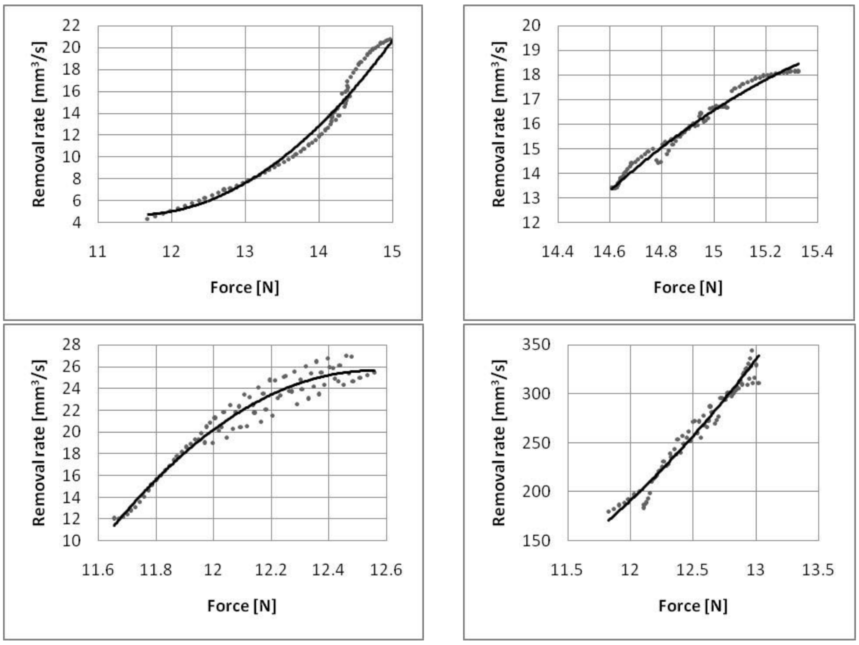

Fig. 4. The bone removal rate versus the force. Legend: (•) the experimental points; (-) the regression model. (Top left) Cortical bone from the horizontal cut. (Top right) Cortical bone from the vertical cut. (Bottom left) Cortical bone from the sagittal cut. (Bottom right) Cancellous bone from the sagittal cut.

Based on the goodness of the fit, the following regression models of the removal rate R_r[mm^3/s] versus force F_n[N] were chosen to represent the dependencies (6,7,8,9): (c-h) Cortical bone from the horizontal cut ($R^2 = 0.969$):

$$R_r = 1.263 \cdot F_n^2 - 28.859 \cdot F_n + 169.43 \tag{6}$$

(c-v) Cortical bone from the vertical cut($R^2 = 0.978$):

$$R_r = -3.614 \cdot F_n^2 + 115.21 \cdot F_n - 898.47 \tag{7}$$

(c-s) Cortical bone from the sagittal cut ($R^2 = 0.941$):

$$R_r = -17.548 \cdot F_n^2 + 440.72 \cdot F_n - 2741.6 \tag{8}$$

(s-s) cancellous bone from the sagittal cut ($R^2 = 0.954$):

$$R_r = 34.063 \cdot F_n^2 - 706.19 \cdot F_n + 3762.4 \tag{9}$$

The regressions were significantly different between the cortical and the cancellous bone; the values of the cancellous removal rate were much higher than the ones of the cortical bone removal rate. A difference in the regressions for the three segments of the osteotomy line was present, e.g. for the same removal rate of 15...20 mm^3/s the required force was higher for the vertical cut than for the horizontal cut, which was also higher than the force required for the sagittal cut.

4 Discussion

In this study, the cutting process with a small reciprocating saw was analysed in order to establish the process parameters. The analysis results showed that the cutting force depends on the removal rate and on the cutting parameters (saw pitch, frequency and amplitude of the saw reciprocating motion). Experiments conducted on the particular case of the BSSO line sawing proved the dependency between the removal rate and the force.

The removal rate of the cancellous bone was found considerably higher than the one of the cortical bone. This is the consequence of the significant differences between the mechanical properties of these bone structures [9, 11, 12]. Furthermore, variations between the three osteotomy lines were observed. The variations can be attributed to the location sites within the mandible. Schwartz-Dabney et al. [9] reported slightly smaller values for the mechanical properties in the region and on the direction of the horizontal cut than in the one of the vertical cut. Additionally, within a region, the properties vary due to the anisotropy of the bone [9]. It is reported that the mandible is stiffer and stronger in the longitudinal direction than in the radial and tangential direction, mainly due to the orientation of the osteons which are primarily oriented in his direction [12, 13]. However, as the determined removal rates are specific for the cutting conditions used in the experiments, which are dictated by the BSSO use case, it is not possible to directly compare these values to generic mechanical properties of the mandible reported in the literature.

The differences between the theoretical model and the experimentally gained regression models can be attributed to the (i) limitations of the theoretical model (constant specific energy for small changes in the cutting conditions at a high cutting velocity and large feeds [15]), (ii) the heterogeneous properties of the bone, (iii) the smaller feeds and (iv) the chip formation mechanism due to the saw blade kerf. Although, the non-linear model is not based on the theoretical model it is useful to represent an essence of the experimentally gained data in a compact way for the usage in the sawing simulation (see also below).

The limitations of this study are related to the number of sample cuts and mandibles. Due to the fact that only one mandible was used for testing in this stage of the research, only a narrow number of configurations could be taken into consideration (limited force variance and constant sawing parameters). The future work will focus on extending the models by testing a statistically meaningful number of cases and by taking into consideration the neglected parameters. Based on these measurements a more generic model could then be developed which may also consider factors besides sawing conditions like patient age etc.

4.1 Usage in a training simulator

The presented results can be utilized in a virtual reality-based simulator for training of the BSSO with a specific bone scenario. In [17] a simulator prototype is described where a trainee can interact via a haptic input device with a voxel-based sawing simulation. In this, a material removal component takes off bone material depending on the interaction forces between the saw and the bone as well as their collision configuration (for more details, we refer the interested reader to [17]). The configuration specific measurements relating normal forces and bone removal rates presented above, can be integrated into this component to create a realistic sawing behavior. The according removal rate for an interaction force can thereby be determined by searching for a set of appropriate close by measurements and calculating a weighted average. An computationally less expensive alternative is the utilization of the closed-form formulas given by the non-linear models.

5 Conclusion

To enable the development of realistic VR-based simulators which could improve surgeons bone sawing skills a good model of the underlying process is required. This research presents several mathematical models to quantify the material removal rate according to the force applied to the saw in contact with the bone. The proposed models refer to the particular case of a maxillofacial surgery procedure, the BSSO. The presented data reveals differences between the three osteotomy lines and the cortical and cancellous bone, which is consistent with previous findings about the mechanical properties of the human mandible.

Acknowledgments.

This work was funded by the German Research Foundation under grants: KU 1132/6-1, FR 2563/2-1 and GE 2083/1-1. Additionally, it was partially supported by the strategic grant POSDRU/88/1.5 /S/50783, Project ID50783 (2009), cofinanced by the European Social Fund- Investing in People 2007-2013. Furthermore, it received funding from the European Unions Seventh Framework Programme for research, technological development and demonstration under grant agreement no 610425.

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