Enhancing the Design of Arthroscopic Shaver to Reduce Stresses Experienced

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Abstract. In light of the scarcity of design data for arthroscopic surgery equipment due to manufacturers’ non-disclosure of research and patents, the aim of the presented work is to study the mechanical stresses experienced by the arthroscopic shaver during soft tissue resection, thus reaching a new design that enhances performance and tool life. The finite element analysis method was used to determine the effect of changing either the tooth angle or rotational speed on stresses experienced by the shaver by creating a model on ANSYS Explicit Dynamics Module. Results were analysed to find that a tooth angle in the range of 55° to 62° would achieve less stresses on the blades, as well as verifying that cutting at 1500 rpm is the most suitable speed for a longer tool life. This research is a part of a project implemented by the NRC and is planned to be verified by experimental work.

1. Introduction

While the number of orthopaedic surgeries has been growing rapidly over the past few decades, most of the competing medical equipment companies operating in Egypt are working extensively on importing the newest and most advanced tools used in surgeries. As these tools are all imported from European manufacturers, it became necessary for the Egyptian research community to start exploring orthopaedic equipment development and technologies. This research is concerned specifically with studying the arthroscopic shaver (Figure 1) as a cutting tool for human soft tissue, with the objective of setting a new design that performs better and experiences less stresses on blades during operation. The greatest advantage of arthroscopic surgery over traditional surgery is that it is less invasive (minimally invasive surgery). As opposed to a typical knee joint operation for example, where the joint has to be fully opened, arthroscopic surgery would only require two very small incisions on both sides of the joint. This minimally invasive procedure increases the success rate due to less trauma to the connective tissue, reduces recovery time which is of a great importance to athletes who usually suffer joint injuries and are required to get back to their full physical fitness as soon as possible. Also because of the smaller incisions, the probability of infection is less than that of conventional joint surgery, and it results in much less scarring.
The shavers have become one of the most widely used orthopedic instruments[1]. They are often consisted of a hand piece with the motor and control buttons, a control unit, and a resection tool which enables continuous cutting and debris removal simultaneously. Shavers are manufactured and sold in different shapes and sizes, diameters usually ranging from 1.9 to 6.5 mm, and lengths from 120 to 180 mm[2]. More importantly, the cutting blades of the shavers come in various shapes, designs, and levels of sharpness, where the number of teeth usually range from just a single curved cutting blade to 4 teeth on the outer tube, while the inner tube's blade was found to have more teeth than the outer tube in some cases, with a limit of 5 teeth on the inner tube observed in manufacturers catalogues. Teeth heights ranges from 60% to 70% of their width between the roots and 15% to 22% of the outer diameter of the inner tube, the tooth angle ranges from 66° to 77°[3].

Despite the increasing usage of shavers globally, manufacturer-independent data of the characteristics and performances of different shavers’ designs are unavailable, as a result of the competition between companies they secure their design data with patents[3-5]. While reviewing previous research work in the field of this study, rarity of such work made it challenging to collect reliable and useful data for our study. Future work in the areas of testing mechanical properties of soft tissue and stress analysis on surgical tools is recommended to enable access to manufacturers-independent data for researchers in the mentioned fields.

The use of the shaver as a cutting tool depending mainly on shearing the soft tissue necessitates the knowledge of the mechanical properties of soft tissue, several researches have conducted tests on soft tissue to estimate its mechanical properties focusing mainly on tensile strength, elasticity, shear modulus, and creep resistance[6, 7]. Furthermore, trials have been made to model the soft tissue using the finite element method and the results were useful for modeling its behavior under the studied stresses, recent works in this field attempted integrating the finite element model into an optimization algorithm to allow fit the unknown parameters of the nearly incompressible material behavior of the soft tissue which were modelled as isotropic, viscoelastic, and non-linear. These models were verified using experiments on synthetic materials where good agreement were found between the results and the models developed[8-10].

Therefore, the objective of this research is to study the effect of changing various design parameters of the shavers’ cutting blades on their performances from the perspectives of material removal rate, and blades sharpness throughout its lifecycle, using modeling and simulation of the tool and the
reseccion process of the soft tissue using ANSYS, moreover setting, manufacturing, and testing a new shaver blades design that experiences lower stresses and performs better throughout its lifetime, while performing a proper cut.

2. Methodology

The need for setting a new design for the arthroscopic shaver arises that considers the effect of changing the cutting parameters on the material removal rate (medically called resection), stresses experienced, and useful lifetime of the tool. The cutting parameters studied included contact pressure, tooth angle, and cutting speed. To study these effects, a valid model is needed where the changes of different parameters combinations and their effect on the stresses experienced by the cutting tool, which will in turn affect its useful lifetime, as well as how the resection rate is affected, and the quality of the cut.

A finite element model was prepared using ANSYS Workbench for the soft tissue material, as well as a model for different suggested designs of the shaver, that allowed the simulation of the cutting process and conditions to study the behavior of each suggested design, leading to a better knowledge of how to improve the cutting process by making variations of the design parameters, therefore setting a new design that will experience less stresses, and be more durable, while achieving the proper resection rate.

This research focus on cutting edges and specifications of cutting speed and contact pressure. One model of each shaver was done using a CAD software by changing a single cutting parameter while keeping other parameters fixed to study its effect on performance, with each variation a model and an ANSYS simulation was carried out. Furthermore, combinations of parameters adjustments are going to be considered in suggested designs to be tested using the method tested before, this design will be an improvement from existing designs, achieving the least experienced stresses on the blades while cutting at the desired resection rate.

While creating a material model for the soft tissue, to simplify the model for processing limitations, it was modeled as isotropic material rather than orthotropic, furthermore the viscoelastic properties were neglected as it would not have a significant effect during cutting the tissue, in addition to the fact that the cartilage which is our focus of study is the least viscoelastic of all soft tissue materials. The ultimate tensile strength for articular cartilage ranges from 15 to 35 MPa according to gender and age[11] Previous data from testing the mechanical properties of soft tissue and articular cartilage [6, 7, 12, 13] resulted in modeling the material as shown in Figure 2.

![Figure 2 Material model for human cartilage.](image-url)
The FEA was done on two phases, static analysis phase and dynamic analysis phase. The static analysis was done to determine the effect of changing the contact pressure on the amount of material removed each stroke (revolution) of cutting by the shaver, the geometry modeled was the cutting blades part only of the inner and outer cylinders of a typical shaver 4 mm diameter, the geometry was straightened to simplify the model for ease of computing.

**Figure 3** Shaver cutting blades straightened model on a block of soft tissue material.

Due to the massively consuming processing requirements for such a complicated model to be done, a simplification was assumed to describe the process, such that one tooth of the shaver’s inner blade was modeled to penetrate and perform a cut on a block of material (Figure 3).

To determine the suitable mesh size to choose for the FE model, mesh analysis was done on a 2N contact pressure problem with varying the mesh size from 0.1 to 0.7 element size, it was found that at mesh sizes between 0.1 to 0.2 the results were not affected by the change of mesh size, as opposed to its change when trying larger mesh sizes (Figure 4). The average aspect ratio for the elements at 0.1 mesh size was 1.95 and average orthogonal quality was 0.84 suggesting acceptable mesh quality, therefore the mesh size selected for the static study was 0.1 element size mesh.

**Figure 4** Maximum deflection at 2N contact pressure for different mesh sizes.

Dynamic analysis of the cutting process was done using ANSYS Explicit Dynamics to simulate the cutting process of soft tissue, a geometrical model was generated to describe the interaction between the blades and the material being cut (Figure 5). Fixation on the bottom part was done on inclined surfaces created to provide support while avoiding sharp corners to be created and interfere with the analysis, a displacement constraint was done on three surfaces of the tooth to prevent it from moving except in the cutting direction. The rotational speeds tested ranged from 1200 rpm to 2400 rpm with an increment of 300 rpm in each trial, this is the typical operating range for an arthroscopic shaver[2]. Due to transforming the model to linear motion rather than rotational, the angular velocities were transformed to linear cutting speeds using the equation.
v = πDN/60
Where, v – Cutting Speed [mm/s]
D – Diameter of shaver’s inner cylinder [mm]
N – Rotational speed [rpm]

Figure 5 Model for dynamic analysis of 1 tooth of the shaver penetrating cartilage material.

3. Results

At 0.1 element size meshing, different contact pressure values were tested to determine its effect on increasing the deflection that the material is subjected to, which in turn determines the volume of material removed by each stroke of the shaver, it was found that the relationship is almost linear, and incremental increase in contact pressure results in incremental increase in the amount of material deflected inside the shaver blades, thus no optimum contact pressure (Figures 6 and 7) could be obtained and it is believed that it depends on the surgeon to estimate the required contact pressure while operating using his experience according to the case. It could be observed from the results shown that the maximum deflection happens further from the blade edges as material is compressed and slides to form a volume of material inside the shaver’s cavity ready to be cut.

Figure 6 Analysis of the maximum deflection caused by 2N contact pressure.

Figure 7 Relationship between contact pressure applied and maximum deflection.
Accordingly, five cutting speeds were selected to test for different tooth angles designs, the original design[4] has a tooth angle of 62°, five ANSYS runs were conducted on the developed model using the five selected speeds. Subsequently, five runs were performed on each of the suggested tooth angles, the angles tested were 50°, 55°, 70°, and 75° in addition to the original 62° design. The results would later be analysed and compared to study the effect of changing the parameters of scope.

Figure 8 Simulation of shaver tooth penetrating and cutting through soft tissue.

Figure 9 50° tooth performing a cut at 2400 rpm (modeled as linear cutting speed).

Starting with the design of the typical original shaver, it was studied using the developed ANSYS Explicit Dynamics model on five different cutting speeds and the Von-Mises stresses in each run were compared to acquire the optimal speed of operation that subjects the shaver to the least stress possible while performing an acceptable cut. As observed (Figure 8) maximum stress happens at the last point of material separation while the blade’s tip is exiting the material.

Table 1. Von-Mises stress values at different cutting speeds for original shaver's tooth.

| Rotational Speed [rpm] | Maximum Stress [MPa] |
|------------------------|-----------------------|
| 1200                   | 1.9934                |
| 1500                   | 1.275                 |
| 1800                   | 2.3303                |
| 2100                   | 2.7255                |
| 2400                   | 1.7713                |

Figure 10 Maximum stress during cutting at different speeds for original shaver's tooth.

It was found that 1500 rpm is the speed that results in the least possible stress for the original design, this confirms the experimental work done by researchers before[2]. Stress reaches its peak at 2100 rpm then starts decreasing again at 2400 rpm, but such a high cutting speed is not very common in arthroscopic surgeries, as precision is favoured to speed, resulting in 1500 rpm being the most suitable cutting speed for the tested design from the reduction of stress point of view.
Furthermore, the other four suggested tooth angles were tested and their operation was simulated on the same ANSYS model and results almost followed the same trend as in the original design’s simulation.

Table 2. Maximum stress during cutting at different speeds for 50° shaver's tooth.

| Rotational Speed [rpm] | Maximum Stress [MPa] |
|------------------------|----------------------|
| 1200                   | 2.1078               |
| 1500                   | 2.1841               |
| 1800                   | 1.768                |
| 2100                   | 2.7255               |
| 2400                   | 2.5594               |

Figure 11 Maximum stress during cutting at different speeds for 50° shaver's tooth

For the 50° shaver tooth, it was found that the least stress value occurred at 1800 rpm, also at 1200 and 1500 rpm stresses were not significantly higher. Noticeably, stresses did rise at speeds higher than 1800 rpm, which suggests that the optimal operating range for such design would be 1200-1500 rpm.

Table 3. Maximum stress during cutting at different speeds for 55° shaver's tooth.

| Rotational Speed [rpm] | Maximum Stress [MPa] |
|------------------------|----------------------|
| 1200                   | 2.2216               |
| 1500                   | 1.1574               |
| 1800                   | 2.3211               |
| 2100                   | 2.7837               |
| 2400                   | 2.9514               |

Figure 12 Maximum stress during cutting at different speeds for 55° shaver's tooth

The 55° tooth design clearly shows the expected trend of the 1500 rpm being the optimal speed that corresponds to the least stress on the tooth, as can be seen in Figure 12 stress rises steadily when increasing speed than 1500 rpm.
Table 4. Maximum stress during cutting at different speeds for 70° shaver’s tooth.

| Rotational Speed [rpm] | Maximum Stress [MPa] |
|------------------------|-----------------------|
| 1200                   | 2.1264                |
| 1500                   | 2.1264                |
| 1800                   | 2.6167                |
| 2100                   | 2.2984                |
| 2400                   | 2.2097                |

At 70° tooth angle, stresses observed at 1200 and 1500 rpm were surprisingly the same, which might suggest that at larger angles and low cutting speeds the change in speed has insignificant effect on stresses experienced. However, results suggests that 1500 rpm is the most suitable speed to use in order to reduce stresses on the blades.

Table 5. Maximum stress during cutting at different speeds for 75° shaver’s tooth.

| Rotational Speed [rpm] | Maximum Stress [MPa] |
|------------------------|-----------------------|
| 1200                   | 2.1356                |
| 1500                   | 2.1463                |
| 1800                   | 2.8177                |
| 2100                   | 2.3184                |
| 2400                   | 2.3498                |

Behaviour of the curve for the 75° tooth followed the common trend, having the least stresses occurring at 1200-1500 rpm, and rising at higher speeds. As found with the 70° tooth, the effect of speed change at low speeds has no significance.
Table 6. Stresses at 1500 rpm for different tooth angles

| Tooth Angle [Degrees] | Max. Stress [MPa] |
|-----------------------|-------------------|
| 50                    | 2.1841            |
| 55                    | 1.1574            |
| 62                    | 1.275             |
| 70                    | 2.1264            |
| 75                    | 2.1463            |

As observed in Figure 15, the least stress experienced for 1500 rpm operating speed occurred at the 55°, suggesting that teeth angles between 55°-65° experience the least stresses (Approximately 50% reduction in stress) at the given conditions.

4. Discussion

Arthroscopic shavers were rarely studied from a mechanical behavior point of view, the presented research focused on observing the stresses experienced by shaver’s teeth at varying cutting speeds and different teeth angles. A Finite Element model was developed using ANSYS Explicit Dynamics module to describe the cutting process of one stroke of the shaver’s operation on human cartilage material, which in turn was defined in the model using data from previous research work that aimed at testing mechanical behavior of soft tissue materials. Scarcity of such studies made it challenging to collect reliable data about the mechanical properties of soft tissue materials.

Analysis were done on two phases, first, the static study focused on determining the effect of contact pressure on the volume of material being cut each stroke. Mesh size analysis were done to determine the most suitable mesh size for the study, 0.1 element size was chosen and it was found that the amount of material deflected into the shaver blades opening varies linearly with the contact pressure applied.

The second phase was the cutting simulation, it was done using the Explicit Dynamics module, a model was developed to describe the motion of one tooth of the shaver blade to penetrate a block of the material defined earlier for the cartilage. The original tooth with an angle of 62° was modeled and Von-Mises stress experienced during cutting was observed during cutting at five different speeds (1200 to 2400 rpm with 300 rpm increments). Additionally, four new suggested angles (50°, 55°, 70°, and 75°) were modeled and studied at the same five speeds studied with the original designs.

Results were analysed and it verified previous experimental work done by other researches[2] that cutting at around 1500 rpm is optimal from the reduction stress, thus reducing wear, point of view.

Finally, stresses on the different tooth angles were analysed at the same speed of 1500 rpm, it shows a reduction in stresses experienced by the tooth when the angle is less than the original design’s angle, suggestions of an angle in the range of 55° to 62° would be appropriate given the research results.
5. Conclusion

A Finite Element model was created to study the stress experienced by an arthroscopic shaver during soft tissue (cartilage) resection, findings in conformance to previous experimental work suggested that performing at 1500 rpm subjects the shaver to the least stresses possible, while a tooth ranging from 55° to 62° should experience the least stresses.

Computing capabilities of PC’s even with very high processing (up to 32 cores processors were used) were not sufficient to do the Explicit Dynamics work and it was massively time consuming. A single run took an average of approximately 3 hours. We recommend using a high processing cloud host such as ASNYS’s High Performance Computing HPC for future cutting simulation works.

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