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Challenges and Advances in Osteotomy

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Abstract

The tools of the osteotomy have been advancing considering the challenges faced by their prior versions. The conventional mechanical tools pose various constraints in the development of osteotomy. This has brought many alternative non-conventional techniques with broad exploration space. Among these techniques, laser stands out as it offers several advantages over conventional osteotomy. These tools integrated with modern automation devices can lead to very efficient osteotomy in the future. The current article succinctly reviews the different approaches, challenges, and advances in the osteotomy since its origin, and its current state of research.

Introduction

Osteotomy is one of the vital orthopedic surgical procedures dealing with the machining of bone. It has been evolving continuously in every aspect for the improved outcome of the surgery. Archeological studies evince the earliest existence of osteotomy in the Neolithic period (3400 BC to 3000 BC) which is believed to be a successful era of surgical techniques. The recent archeological investigation reveals contemporary surgical practices particularly on cow bone to master their techniques before applying it to humans [1]. This practice reflects their awareness about the fact that bovine bone shares similar properties to the human bone that was confirmed in the early decades of the 20th century. Furthermore, they were equipped with a surgical tool made by flint and obsidian stone of which the later tool is still in practice in a few parts of the world. Besides, a sharpened fingernail, a stem of Bamboo, and sharpened shark tooth are some of the reported primitive tools used in early civilizations [2].

Challenges in Conventional Osteotomy

Today's surgical tools are mostly the derivative of the designs of the tools made during ancient Rome and Egypt. These mechanical tools machine the bone with either single or combined fundamental fracturing operations like drilling, sawing, grinding, and milling. Some of the current mechanical tools employed in osteotomy are bone scalpel, saw blade, driller, cutting forceps, bone chisel, and burrs, etc. Usually, the combined fundamental operations involved are ultrasonic, pneumatic, and hydraulic machining. Design of these tools is improved continuously considering the primary goals of high material removal rate with precision and minimal detrimental effects on the surrounding tissue, bone regenerative machined surface, and healing of the osteotomy. However, the complex physical and chemical hierarchical structures of bone render it challenging to control machining parameters for optimization of the machining technique. This can be conceived from Figure 1 that shows the effect of the orientation of osteons in the cortical bone on the mechanical response of the bone while machining. The non-isotropic nature of bone produced by the multi-level physical and chemical composite structure is responsible for differential machining response in a different direction thereby affecting machinability and resultant surface quality [3]. Additionally, the secondary effects of machining like heat evolution lead to necrosis and coagulation, and excessive residual thermal stresses generate surface micro-cracks at the site of surgery. All these effects significantly affect post osteotomy duration of healing of the bone. These secondary effects also hamper the attempts to increase the inherently slow machining rates associated with the conventional (mechanical) machining tools used in the osteotomy. In addition, these slow machining rates contribute to the extension of the thermally affected region around the site of surgery. Furthermore, attempts are made for incorporation of a cooling medium and internally cooled surgical tool design in osteotomy to partly curb these adverse effects [3].

Proposed Non-Conventional Machining Techniques for Osteotomy

In view of the challenges put forth by conventional osteotomy tools, the non-conventional

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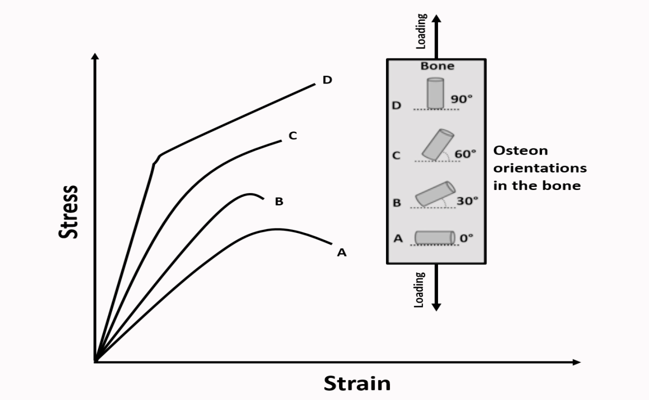

Figure 1: Schematic of stress-strain behavior with varying orientation of osteons in the cortical bone (Adapted from reference [3]).

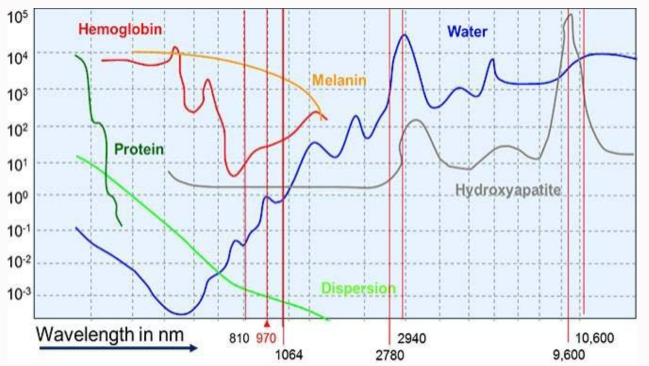

Figure 2: Absorption coefficient of various components of the hard tissue/ bone at various infrared laser wavelength [4].

techniques of osteotomy have been extensively explored in the last few years. Some of the proposed non-conventional techniques are microwave machining, ion beam machining, water jet machining, ultrasonic machining, piezo-electric machining, and laser beam machining [3]. Being non-contact machining techniques, they disclosed most of the conventional machining issues like frequent sterilization of the tool, contamination of the site of surgery with metal particle due to abrasion, and unwanted vibration to the body while machining. Also, these techniques allow reduced bleeding during surgery, reduces scar formation, offers aseptic healing, and lessens post tissue trauma. However, at the same time, they bring new issues, and restrictions. For instance, the ion beam machining is impossible without a vacuum, and the required level of vacuum is difficult to attain in hydrated bone. Nonetheless, this technique holds great potential for micro-machining of bone. For microwave machining technique, the safety of the patient and the operator is a major concern considering the hazardous microwave radiation. This technique still needs to be explored substantially considering its carcinogenic effect and measures to reduce its risk [3].

Additional emerging non-conventional techniques are piezoelectric machining and water jet machining. The former technique is still in its infancy stage and more focused for its viability in dental surgery. Currently, the reported osteotomy rate by this technique is slower than the conventional osteotomy. Nevertheless, this technique can serve with highly precise machining with less collateral damage and could be a potential technique with further research on machining of other hard tissues. Water jet machining has a major advantage of not heating the bone tissues as the water acts as a coolant while machining at the same time. However, the mechanical resistance offered by the bone material to the water jet changes at different depths and thus renders it difficult to optimize its machining parameter. Furthermore, maintaining water jet direction, and striations developed due to the deviation of the water jet trajectory while machining, are still need to be addressed.

Potential of laser assisted osteotomy: Among all the non-conventional technique, laser beam machining technique has been explored extensively since its advent in 1960. It has already firmed its presence in the field of ophthalmology, dermatology, and other disciplines. It is gradually stepping into orthopedic surgery, with its recent implementation in dental surgery. Its promising outcomes for bone machining have increased its potential as a precision tool for osteotomy.

A delicate and fragile bony structure like maxilla and mandible cannot sustain contact pressure produced by mechanical tools and can lead to fracture instantly. Being non-contact, laser osteotomy can be an excellent alternative for such a kind of surgery. However, being a heat-based machining process, it still involves temperature rise in the surrounding tissue that can lead to necrosis, carbonization, and coagulation thereby affecting healing rate. Laser-based machining depends on optical and thermo physical properties of the material unlike their mechanical properties in case of conventional machining. Thus, the absorptivity of the material plays a crucial role in the material removal rate while laser machining. The change in the absorption coefficient of the different components of the hard tissues is presented in Figure 2 [4]. The mechanism of the material removal changes as the absorptivity of the components of bone varies with wavelength. For instance, at a wavelength of 2.94 μm produced by Er:YAG laser, the thermo-mechanical tissue removal mechanism is activated and offers significantly less thermal damages [5]. This mechanism is facilitated by very high absorptive of this laser beam by water that quickly evaporates and exerts high pressure on surrounding mineral crystals leading to violent disruption. This mechanism is only possible if the time to build up a sufficiently high pressure is shorter than the thermal relaxation time of the material to bring out this thermo-mechanical ablation [5]. Such clean material removal eventually led to its implication in dental surgery with approval from the US Food and Drug Administration. Despite this, Er:YAG laser is still experiencing limitations for osteotomy of other hard tissues where bulk removal of bone during surgery is required with higher material removal rate. Furthermore, the low power (fluence) capability limits the material removal rate by this type of laser. Moreover, hemostasis effect produced by this laser, if exposed for a longer duration, severely affects bone healing time.

The lasers like CO_2, excimer, Ho:YAG, and Nd:YAG machine the bone *via* vaporization and melt expulsion phenomena. Thermal damages can only be reduced during machining using these lasers by optimizing the machining parameters. Laser osteotomy can be more conveniently and efficiently conducted if the laser beam is transmitted through the optical fibers. However, only a few types of laser beams can be transmitted through the optical fiber at certain maximum power. On the contrary, although the CO_2 laser beam has a high absorptivity for a mineral component in the bone, it can't be transmitted through optical fibers. In a recent patented work, Nd:YAG laser (with fiber delivery), used at higher laser fluence/ energy density has shown a significantly higher material removal rate

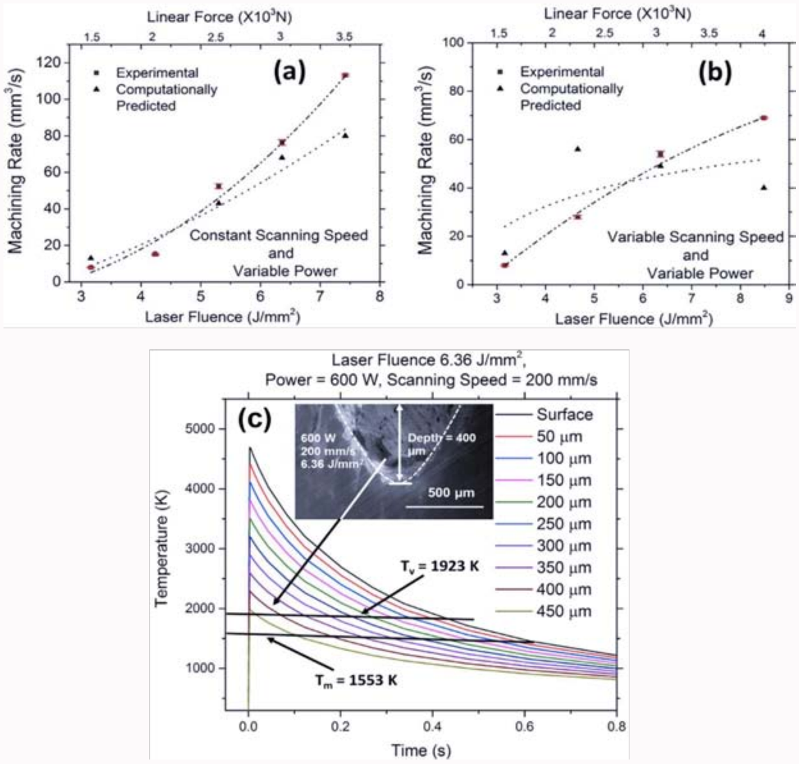

Figure 3: Outcome of Nd: YAG laser machined bone showing (A and B) material removal rate as a function of laser fluence, and (C) corresponding predicted time-temperature relationship (Reprinted from reference with permission from Elsevier) [8].

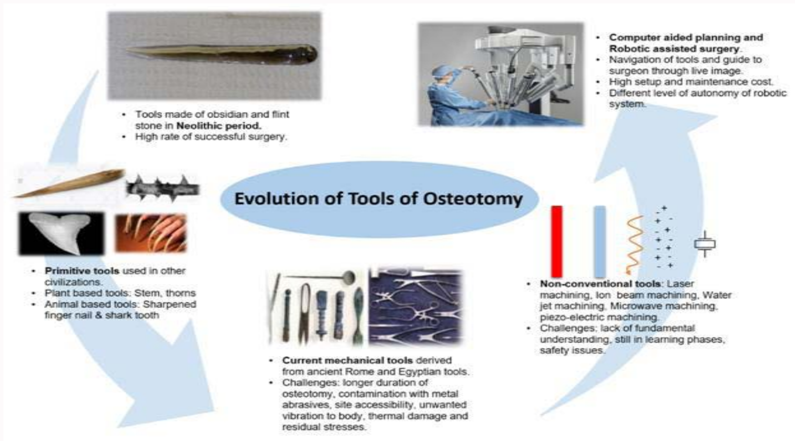

Figure 4: Evolution of osteotomy tools [9].

with low thermal damages in the nearby region as shown in Figure 3A and 3B [6-8]. It addresses the fundamentals of vaporization and melt ejection based material removal mechanisms which could lead to better optimization of machining parameters [8].

Typically, in any machining technique, multiple distinct physical phenomena are associated with the removal of material. The occurrence of these phenomena may be simultaneous or sequential and likely to be affected by the machining parameters. Furthermore, the composite nature of bone structure due to its multiple components with a varied set of physical and chemical characteristic makes the machining process very complex. Therefore, gaining a fundamental understanding of these phenomena is crucial in order to optimize the machining parameters for the desired outcome. As it is very challenging to comprehend these phenomena by *in-situ* probing, several computational models based on heat transfer, fluid dynamics, and stress distribution have been developed [3]. However, most of these models are simulated for the understanding of conventional machining techniques. Considering, the present thrust for the development of advanced manufacturing processes based on non-conventional approaches such as the laser-based technique, recently a unique computational and experimentally integrated approach was reported [8]. Various physical phenomena involved in laser-bone interaction were discerned with the help of predicted thermo-kinetics involved in the process (Figure 3C). Similar extensive efforts are expected in order to gain in-depth insight into other non-conventional machining processes.

Modern Automation in Osteotomy

Other blooming areas which can potentially reduce human efforts in surgery are computer-aided planning and robot-assisted surgery. Manual osteotomy with any machining tool involves a risk of human error. Additionally, the manual operation involves constraints on the geometry of material that can be removed while machining. Various imaging and data collection techniques like computer tomography and intraoperative fluoroscopy of tools assist the surgeon in, accurate detection of the deformity and site of surgery [3]. These surgery planning techniques are adopted in the clinical environment for conventional surgical procedures and can also be easily extended to non-conventional methods. The current demerits like inefficient coupling with new technology, prolonged pre-surgery setup and surgical duration, and excessive cost of maintenance of these tools leaves further scope for advancement in these techniques.

Robot-assisted surgery is another side of automation that has been rapidly evolving since 1987 and now has firmed its presence in neurology, maxifocal, ophthalmic, and orthopedic surgery [3]. Robot-assisted surgery offers many advantages (over conventional surgery) such as improved accuracy and precision during osteotomy, and reliability, accuracy, and tirelessness in repetitive motion of the osteotomes. The different levels of autonomy of the robotic system allow control of tools through active and passive positioning system. So far various robotics systems employed in orthopedics are ROBODOC™, PAKY/RCM™, BRIGIT™, Kawasaki™, and Acrobot™ [3]. Although these integrated robotic systems possess great potential for osteotomy, factors like capital cost, steep learning curve for the operator, significant manual involvement, increased operation time due to additional invasive procedures in certain surgeries, and various other pressing issues are hampering its vast implications. Along with this, considering the advent of non-conventional methods, surgical robotics systems have a long way to cover for their widespread implementation. Realizing the rapid growth of the orthopedics field, the highly expected robotic-assisted osteotomy based on non-conventional methods such as laser-based machining and shaping is likely to develop at an accelerated rate [6-9].

The field of orthopedics and tools for osteotomy has come a long way since the Neolithic period to currently sophisticated, computer-aided and robotic-assisted osteotomy. This evolution of the osteotomy tools is summarized in Figure 4.

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