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A feasibility study of laser-assisted titanium implant drilling for periprosthetic fracture repair

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Abstract

This paper studies the feasibility of hand drilling through a titanium implant located in the femur. This is hypothesized to be achievable via laser-assisted drilling with carbide tools. A series of tests were conducted to measure the thrust force and torque with different shaped drill bits under dry- and laser-assisted drilling (using a 200-watt fiber laser), respectively. These drill bits included 2-flute and 3-flute twist drills and a straight flute drill that is clinically available. Results showed that the 2-flute drill outperformed the other two in both thrust force and torque. The laser can further reduce the forces of 2- and 3-flute drill bits by over 10%, but has a negative impact on the straight-flute one. This paper also discusses results from a clinical perspective, current limitations, and future work.

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1. Introduction

Bone fractures located near implants, known as periprosthetic fractures, are some of the most difficult to repair. If the fracture is not near an implant then its repair is straightforward; a metal rod is inserted into the femur to stabilize the fracture and, if necessary, additional plates are attached to further stabilize the displacement. If there is already an implant, this method is not possible; the implant occupies the space where the rod would be inserted. Under these conditions, only metal locking plates can be used with attachment screws being inserted into the cortical bone at an angle [1-5]. This leads to a high chance of mechanical failure due to poor anchoring characteristics of the surrounding tissues [6]. With an increase in life expectancy, as our population ages and remains active longer this raises several issues: an increase in both total hip and knee replacements (THR and TKR, respectively) and an increase in osteoporosis [7-9]. The need for simpler solutions to address periprosthetic fractures are becoming increasingly necessary. Furthermore, as the surgical process for THR and TKR matures, it is becoming a more viable solution for younger patients [10], who have a higher risk of periprosthetic fractures resulting from increased activity levels. Current fracture repairs are accomplished via setting screws angled into the cortical bone around the implant, locking the plates into place. An ideal solution would be drilling and anchoring directly into the implant, thereby addressing the issues of weak bone structure (found in elderly and osteoporotic patients) and reducing complications from current anchoring techniques. However, this is not possible with a regular surgical hand drill and stainless steel drill bit because the implant material is titanium and/or cobalt chromium alloys, which are typically difficult to machine. To make this solution feasible, this study aims to explore a laser-assisted drilling process along with different drill geometry designs adapted from the manufacturing industry.

Lasers are increasingly deployed in the supporting roles of machining difficult materials. They are used to heat the material, such as Inconel or titanium alloys, immediately preceding the cutting edge of the tooling. The localized energy input reduces the strength of the material, allowing for a force reduction of at least ten percent on the cutting edge while significantly extending the life of the tooling, and thus

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decreasing manufacturing costs. The high-powered laser typically heats the material in excess of 1000 ˚C during turning applications on a lathe, though research has also been done to examine the possibility of laser-aided machining using a lower powered laser for milling [11].

Dry machining of titanium alloys is well-documented, as it is a ubiquitous industrial application [12-19]. This includes not only turning and milling, but dry drilling of titanium [20]. Current research on laser-assisted machining is oriented towards improving the overall machinability of difficult-to-machine materials and thereby increasing productivity. For example, Chang and Kuo observed higher material removal rates when a ceramic was treated via laser while machining [21]. In addition, there has been research demonstrating a reduction in cutting force when treated by a laser [22, 23]. When the system was optimized for the distance of the laser projection and feed rate, a significant force reduction was observed by Ayed et al. [24]. Shun confirmed this in a reduction of feed force when milling Ti-6Al-4V after laser treatment [25]. Furthermore, the heat propagation of laser machining has also been extensively studied: Suthar et al. [26] considered laser intensity cutting speed, depth of cut, etc. on the effectiveness of laser-assisted machining (LAM). Both Yang etc. [27] and Joshi et al. [28] conducted numerical analysis on the effects of 3D heat propagation through titanium [28]. Finally, the effects of more power resulting from different strengths of lasers have also been studied (Rashid et al. [29]), with Rashid et al. recommending a range of 800 to 1200 W following an observational study on varying powers of lasers in the assistance of machining titanium [30]. This research demonstrates that the machining of titanium with lasers in an industrial setting has been well-documented with most laser powers having been in the 1 kW or greater range, purposed for heavy-duty machinery. However, little, or probably none, research has been conducted using low-powered lasers (*e.g.*, several hundred watts) as methods of arresting heat propagation during surgery on live bodies.

This paper presents a preliminary effort to understand potential force reduction in laser-assisted (maximum 200 W) titanium drilling as well as associated temperature propagation. This is the first step towards an integrated laser-drilling system and parameter optimization. The following sections, Material and Methods, will specify the experiments and data analysis, and the Results section will compare different drill bits and laser treatments. The Discussion part of this paper is focused on the clinical aspects of results.

2. Materials and Methods

2.1. Experimental setup

To perform initial verifications, the testing apparatus was constructed as shown in Figure 1. A common hand drill (Chicago Electric Power Tools 61714) capable of accepting various bits was selected. This drill differs from those currently available to surgeons because of the addition of a speed reduction device that increases the available torque and reduces the risk of the drill stalling during the operation. The drill is attached to a linear slider (Moog Animatics L70) to ensure that it is perpendicular to the workpiece and to remove the instability associated with drilling by hand. The titanium sample is a cylindrical shape of 25.4 mm diameter with two flat faces for clamping with the vise (Figure 1). The top surface is faced to be perfectly flat to avoid the drill wandering at the point of contact. The sample is then clamped in axial alignment with the drill bit. Specifically, the titanium used is Ti-6Al-4V alloy, which is the primary composition in a hip prosthesis (the body) in conjunction with cobalt chromium alloy (the head). Torque and force readings are taken via a Kistler piezoelectric dynamometer (Model 9272). A 200-watt continuous fiber laser (IPG 200-watt YLR-SM Ytterbium fiber laser) is mounted in a HAAS VF-1 CNC machine, allowing control of the laser's power and for holding an accurate distance from the workpiece as the laser tip is moved. In experiments, the laser is applied on the workpiece for a period of time and then moved away from the center location as soon as the drill is fed into the workpiece. To monitor the temperature of the heated spot and the entire workpiece, a K-type thermocouple (Omega Engineering 5TC-TT-K-36-36) is placed on the distal edge of the workpiece. It is used to estimate to the center temperature during the heating process, based on a separate calibration test between two thermocouples with one close to the workpiece center and one on the distal edge (shown in Results section).

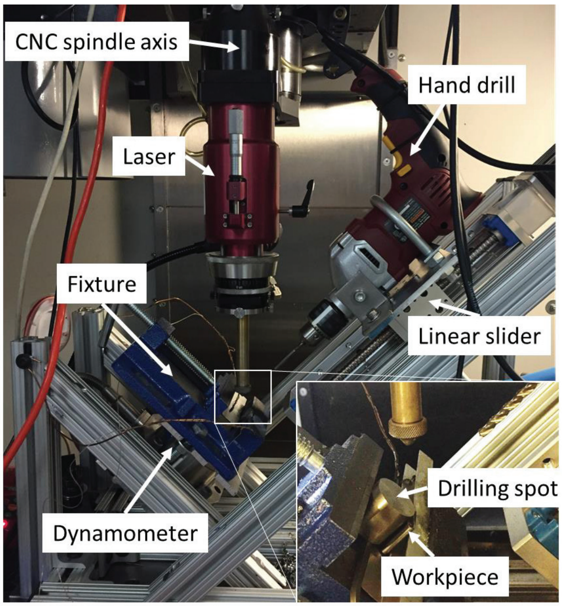

Figure 1 Experimental setup for laser-assisted hand drilling of titanium

2.2. Design of the experiments

Process variables in drilling include drill type, size, feed rate, spindle speed, laser power, and exposure time. In this pilot study, drill feed rate and spindle speed are set constant. The drill is fixed at full speed of 980 RPM; the feed of 0.0153 mm/rev is used to ensure the thrust force below 400 N, which is the linear slider's safety limit. The laser power and exposure time are also controlled at 200 W for 80 s to reach a maximum temperature around 800˚C at the focusing spot. The counterpart comparison is dry drilling without laser