2013 WJTA-IMCA Conference and Expo

September 9-11, 2013 ● Houston, Texas

Paper

ROBOT-ASSISTED DISPLACEMENT OSTEOTOMY BY THE ABRASIVE WATERJET – CONCEPT AND TECHNICAL REALIZATION

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ABSTRACT

Displacement osteotomy is an operative method for the load relieving of pre-damaged joints through the correction of skeletally-based abnormal displacement of the leg axes. For this purpose, the tibial or femoral bone is cut and fixed in a mechanically and physiologically reasonable position. Conventional cutting techniques used in osteotomy today cause physiological disadvantages, such as the denaturation of bone caused by heat transmission from the tool. Due to a short healing time and an exact positioning of the cutting contour, the use of an automatable cold cutting process is preferable to conventional methods.

In preparation for clinical application, an experimental operating room was set up. For physiological reasons, the AWIJ process was adapted to include a magnesium suspension. The tool was guided by an industrial robot, controlled through an optical navigation system. The soft tissue was protected by a jet absorber developed specifically for this application. Finally, a realistic focal dome osteotomy cut could be carried out.

1. INTRODUCTION

Displacement osteotomy is an operative method for the load relieving of pre-damaged joints through the correction of skeletally-based abnormal displacement of the leg axes. For this purpose, the tibial or femoral bone is cut and fixed in a mechanically and physiologically reasonable position (Figure 1). Preoperatively, the malposition is determined through radiographs. Based on these radiographs, a correction cut is defined. Next, the desired cutting path is made with saws, drill machines and surgical chisels. These conventional cutting techniques used in osteotomy today cause physiological disadvantages. The application of tools with a geometrically defined cutting edge generates heat, which subsequently leads to a denaturation of bone and thus an extended recovery time. Additionally, treatment with a manual cut is suboptimal for accuracy reasons. A further disadvantageous aspect of manual osteotomy forms (with straight cuts) is leg elongation caused by open wedge osteotomy (Figure 1, A) or a leg shortening caused by closed wedge osteotomy. A physiologically more reasonable technique is focal dome osteotomy (Figure 1, B-C), where the leg length remains unmodified and the correction cut conforms to a cylindrical segment. Conventionally, this osteotomy form is rarely used due to manual impracticality. If carried out manually, drill templates with the above disadvantages have to be used to achieve the circle-segment cut.

Modern manufacturing methods allow the production of work pieces with low tolerances in real-time operation. Abrasive water injection jet (AWIJ) cutting is a production technique with a geometrically undefined cutting edge, which makes it possible to create cuts without forming appreciable heat-affected zones. Modern guiding machines, such as industrial robots, allow repeat accuracies in the micrometer range. The use of a robot-controlled abrasive water jet in displacement osteotomy would result in better accuracy, a shorter healing time, and a more exact positioning of the cutting contour.

2. STATE OF SCIENTIFIC AND TECHNICAL KNOWLEDGE

The adaptation of abrasive water injection jet for clinical displacement osteotomy requires several process modifications. Preliminary investigations revealed the appearance of embolisms with hemodynamically inefficient consequences when using a 3-phase jet. The process was modified with the objective of an air-free abrasive jet. Though it is impracticable to use an abrasive water suspension jet for technical reasons, the AWIJ process was adapted with an ingested suspension of soluble abrasives. Dangerous hemodynamic and thromboembolic effects could be avoided through the technical exclusion of air [Kuh05]. Investigated abrasives were initially different salts and sugars [Pud05]. Higher cutting performances were later achieved using biodegradable metals. Good performances for the in-vitro cutting of femoral and tibial bones as well as excellent biodegradability could finally be reached through the use of different magnesium alloys [Bis11].

A second important factor for an appropriate surgical tool is the heat generation alongside the osseous cutting edge. During the conventional saw osteotomy, local temperatures rise up to

150°C (approx. 300°F) depending on the cutting parameters (how long the saw is used, heat conductivity) [Klo11]. Multiple authors report delayed healing processes after osteotomies with oscillating saws [Bau97, Fri94]. So-called heat-caused necrosis formations, which develop based on tool temperature and exposure time, can be avoided when the tool temperature impact remains underneath a characteristic curve for bone necrosis (Figure 2). Biskup et al. carried out cutting experiments with bovine bones and mounted thermocouples at different levels of the work piece. As a result, it could be shown that it is generally possible to avoid heat-inflicted damage of the bone tissue when cutting with the AWIJ. The use of the AWIJ with an ingested suspension resulted in even lower cumulative temperatures, proving that it is possible to remain underneath the characteristic curve for bone necrosis using adequate cutting parameters [Bis06, Bis11].

A prototype jet absorber was developed for the purpose of energy absorption, as well as the avoidance of reflection and accompanying contamination of the wound and operation area. [Bis11]. Through wolfram carbide metal lamellas, the jet could be deflected and then exhausted by an industrial sucker.

3. EXPERIMENTAL SETUP

An experimental operating room was set up for the surgical testing of the cutting technique. (Figure 3). The primary cutting equipment consisted of a Stäubli industrial robot with mounted high pressure valve and AWIJ cutting head. The abrasive used was magnesium powder (99,8%, LNR 40 with a particle size between 140 and 315 µm) which was fed into the cutting head through an ingested suspension with water (ambient pressure). The intensifier pump used was a BHDT Ecotron 38.37. A prototype jet absorber was manufactured with the goal minimum jet reflection and a low construction height (for accessibility reasons.) The absorber was fixed to the operation table though variable stiffness hinged brackets. The jet suspension was moved to a fluid container with an industrial sucker. For safety reasons, the jet absorber was also equipped with a reflecting reference geometry (Figure 4). Thereby, a software based protection mechanism could be installed which only allowed the jet to be switched on while the cutting head was positioned above the approved cutting area.

To permit a physiologically optimal positioning of the correction cut, the cutting contour needs to be fitted to the patients' tibia geometry individually. After completion of a computer tomography scan, it is generally possible to digitally map out this correction cut. The translation of the predefined cutting contour to a practicable traverse path to achieve optimal correction of the malposition is a challenging task in control engineering. Prior to CT scanning, reflecting reference geometries were fixed on both on a proximal and a distal position of the human tibia. Through this arrangement, position and orientation of the scanned bone geometry can later be determined through camera-based op-navigation systems (Figure 5).

The human tibiae were dissected for equipment mounting. A total of three operations were carried out, during which the initial dissection was carried out on a larger area to determine the best position for the jet absorber. After successful surgery planning, three tibial focal dome osteotomies could finally be carried out on cadavers using the abrasive water injection jet with ingested suspension.

4. RESULTS

In order to assure sufficient cutting power using biodegradable abrasives, many preliminary tests were carried out on artificial bones as well as porcine and bovine femora and tibiae. Through the use of magnesium powder as abrasive, the general cutting power of an AWIJ is decreased, especially if a greater volume of water is ingested to avoid air in the jet. For this reason, the hydraulic energy was increased through the use of bigger nozzles (0.35 mm nozzle, 1.2 mm focusing tube). This worked for the preliminary tests with previously defrosted porcine, but has never been tested on human bone before. After consideration of Figure 7 + 8, it becomes apparent that it was possible to generate an all-over smooth cut surface. The jet absorption worked well and no soft tissue was damaged below the bone. The first cut was carried out with a lower cutting speed of about 3 mm/min to ensure a bone transection. This resulted in an operation duration of about 13:30 minutes. After examination of the results, the tool feed rate was raised so that the next correction cuts were carried out in 7:00 and 5:40 minutes, respectively. The wastewater temperature in the fluid tank was about 50 °C (122 °F). Remaining magnesium abrasive could easily be removed from the operation area through irrigation. One aspect with room for improvement is certainly the acoustic emissions, which reach an unpleasant level since the suspension injection and the suction devices both create a lot of noise. For the final surgical application, an enclosure should be designed. Generally speaking, the results of this first human application are very promising.

5. ACKNOWLEDGEMENTS

The authors are members of the Waterjet Laboratory Hannover (WLH, Institut für Werkstoffkunde (Materials Science), Division Underwater Technology Center) and of the German Working Group of Waterjet Technology (AWT). The results presented here were acquired within a research project financed by the German Research Foundation (DFG). The authors would like to thank the DFG for their support.

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7. GRAPHICS

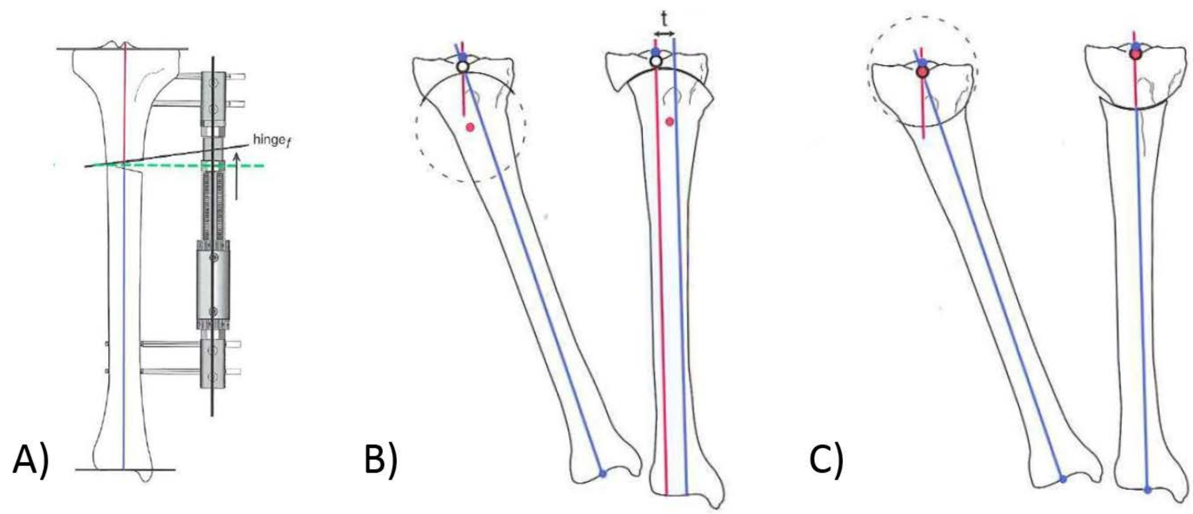

Figure 1. Open-Wedge-Osteotomy with external fixation (A), Focal dome osteotomy of a tibial bone with a distal concave cut (B) and a proximal concave cut (B) [Pal02]

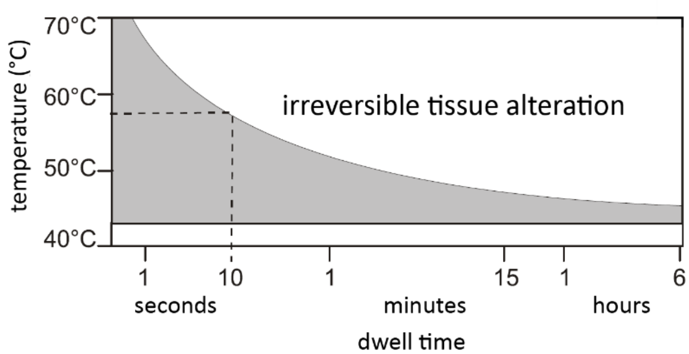

Figure 2. Incidence of head-caused necrosis in dependency of temperature and dwell time [Bis11]

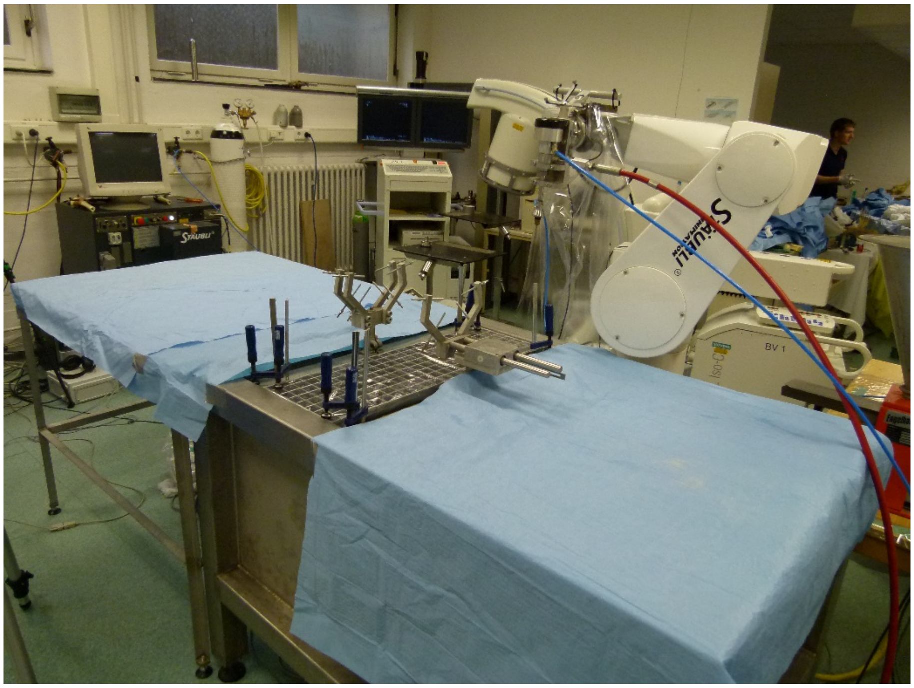

Figure 3. Set-up of the experimental operation room

Figure 4. Prototypic jet absorber for the clinic AWIJ application

Figure 5. Mounted reflecting reference marks on an artificial bone

Figure 6. Mounted equipment for osteotomy execution

Figure 7. Distal concave focal dome osteotomy cut with the abrasive waterjet

Figure 8. Cutting quality after AWIJ osteotomy