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Colliding jets provide depth control for water jetting in bone tissue

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ABSTRACT

In orthopaedic surgery, water jet drilling provides several advantages over classic drilling with rigid drilling bits, such as the always sharp cut, absence of thermal damage and increased manoeuvrability. Previous research showed that the heterogeneity of bone tissue can cause variation in drilling depth whilst water jet drilling.

To improve control over the drilling depth, a new method is tested consisting of two water jets that collide directly below the bone surface. The expected working principle is that after collision the jets will disintegrate, with the result of eliminating the destructive power of the coherent jets and leaving the bone tissue underneath the focal point intact. To assess the working principle of colliding water jets (CWJ), the influence of inhomogeneity of the bone tissue on the *variation* of the drilling depth and the impact of jet time (t_{wj}) on the *drilling depth* were compared to a single water jet (SWJ) with a similar power.

98 holes were drilled in 14 submerged porcine tali with two conditions CWJ (impact angle of 30° and 90°) and SWJ. The water pressure was 70 MPa for all conditions. The water jet diameter was 0.3 mm for CWJ and 0.4 mm for SWJ. t_{wj} was set at 1, 3, 5 and 8 s. Drilling depth and hole diameter were measured using microCT scans. A non-parametric Levene's test was performed to assess a significant difference in variance between conditions SWJ and CWJ. A regression analysis was used to determine differences in influence of t_{wj} on the drilling depth. Hole diameter differences were assessed using a one way Anova. A significance level of $p < 0.05$ was set.

Condition CWJ significantly decreases the drilling depth variance caused by the heterogeneity of the bone when compared to SWJ. The mean depth for CWJ was 0.9 mm (SD 0.3 mm) versus 4.8 mm (SD 2.0) for SWJ. t_{wj} affects the drilling depth less for condition CWJ ($p < 0.01$, $R^2=0.30$) than for SWJ ($p < 0.01$, $R^2=0.46$). The impact angle (30° or 90°) of the CWJ does not influence the drilling depth nor the variation in depth. The diameters of the resulting holes in the direction of the jets is significantly larger for CWJ at 90° than for 30° or a single jet.

This study shows that CWJ provides accurate depth control when water jet drilling in an inhomogeneous material such as bone. The maximum variance measured by using the 95% confidence interval is 0.6 mm opposed to 5.4 mm for SWJ. This variance is smaller than the accuracy required for bone debridement treatments (2–4 mm deep) or drilling pilot holes. This confirms that the use of CWJ is an inherently safe method that can be used to accurately drill in bones.

1. Introduction

Water jet technology has increasingly gained popularity in surgical treatments (Hreha et al., 2010; Oertel et al., 2003; Rau et al., 2008; Yu et al., 2014). Advantages over conventional rigid mechanical instruments are the lack of thermal damage (Basting et al., 2000; Schmolke et al., 2004) and the always sharp cut. Additionally, it allows the design of instruments with increased manoeuvrability, since the water can be provided by a flexible tube (Schurr et al., 1993). Current commercial products are primarily used to treat soft tissue (Basting et al., 2000; Oertel et al., 2003; Rau et al., 2008). Recent developments do show that water jet technology can provide similar advantages for cutting or drilling through bone tissue (den Dunnen et al., 2013a, 2013c; Honl et al., 2000; Kuhlmann et al., 2005). This study focusses on water jet *drilling* for orthopaedic treatments such as drilling pilot holes for screw fixations and bone debridement treatments (Bronzino, 2000; Steadman et al., 2001, 2003).

A challenge for orthopaedic water jet surgery lies in controlling the

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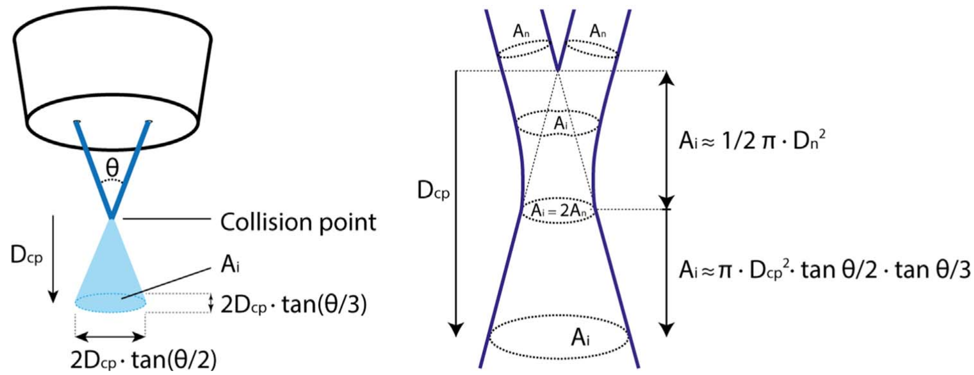

Fig. 1. Left: working principle of colliding water jets. After water jet collision the coherency of the jet is compromised, resulting in spray with an elliptical surface area with a lower energy density than the individual jets. Right: an enlarged view of the colliding water jets. The impact area A_i is nearly constant up to a specific D_{cp} where A_i is equal to $2A_n$. Further increasing D_{cp} will result in quadratic rise in A_i. The dashed areas represent the various shapes and sizes of the impact area (A_i) and the cross sectional area of the water jet (A_n).

drilling depth, which is of utmost importance to prevent unintentional damage of healthy tissue during the procedure. The natural inhomogeneity of bone tissue causes local variances in its density, which affect the local mechanical properties. As a result, different hole depths are created when water jet drilling with identical machine settings (den Dunnen et al., 2013a, 2013c, 2016). Though the correlation between the bone density and drilling depth has been thoroughly investigated and can be compensated for to achieve a pre-set hole depth (den Dunnen et al., 2013c, 2016), acquiring the local bone density in a clinical setting can still be difficult due to the absence of proper imaging protocols and prolonged data processing that compromises the workflow in the hospital. Therefore, a novel concept for water jet drilling was investigated: colliding water jets (CWJ). The pursued working principle is as follows: two separate jets are focused to collide just below the surface of the bone tissue (Fig. 1). The energy density of the individual jets exceeds the threshold for machining bone, and will therefore penetrate the bone tissue. At the focal point where the two jets collide just below the surface, the coherency of both jets is compromised causing energy dissipation. As a result, the energy density of the water jets drops below the threshold required to penetrate bone tissue. At this point, no further drilling will occur and depth control is achieved regardless of local bone density.

In this manuscript, this concept of drilling depth control by CWJ is studied and compared to a standard single water jet drilling (SWJ). By determining significant differences between CWJ and SWJ in drilling depth, drilling depth variance and the influence of the drilling jet time (t_{wj}, s) on the drilling depth, the potential of CWJ as inherently safe depth control concept is verified.

2. Materials and methods

2.1. Theoretical overview

A theoretical overview is given that forms the basis for the concept that CWJ improves drilling depth control compared to SWJ. Before actual water jet drilling of a material takes place, a specific threshold needs to be exceeded. This threshold can be expressed in many units, such as the material's compressive strength, yield strength (Mohamed, 2004) and shear stress (Hoogstrate, 2000) in combination with the water jet's pressure (den Dunnen et al., 2013a, 2016), nozzle diameter (den Dunnen et al., 2013c), jet time or transverse speed (Chillman et al., 2010). For this study, the threshold is expressed using a power density P_d ([W/m^2] or [kg/s^3]) model, which can be applied universally for assessing whether a material is being machined. P_d models include the natural disintegration of the water jet to express the diminishing machining capacity of a water jet (Yanaida and Ohashi, 1978, 1980). The decrease in machining capacity can be expressed by an increasing distance from the center axis of the water jet or the distance between water jet initiation and the impact site (Abramovich, 1963; Chillman et al., 2011; Leach and Walker, 1966). When the minimum power density for machining is met, the total energy of the water jet E_{wj} (J or W s) that interacts with the material determines the volume of bone that is removed. P_d is calculated by dividing the power of a jet P_{wj} (W or kg m^2/s^3) by the impact area of the water jet A_i (m^2), as provided in Eq. (1):

$$P_d = \frac{P_{wj}}{A_i} \tag{1}$$

The power and energy of a water jet can be expressed with Eqs. (2) and (3) respectively,

$$P_{wj} = p_{wj} \bullet \dot{q}_{wj} \tag{2}$$

$$E_{wj} = p_{wj} \bullet \dot{q}_{wj} \bullet t_{wj} \tag{3}$$

where p_{wj} is the pressure (Pa or N/m^2), $\dot{q}$ is the volume flow rate (m^3/s) and t_{wj} is the water jet time (s). Using the simplified Bernoulli equation, the volume flow rate can be expressed as

$$\dot{q}_{wj} = c_d \bullet A_n \bullet v_{wj} = c_d \bullet \frac{\pi}{4} \bullet d_n^2 \bullet \sqrt{\frac{2 \bullet p_{wj}}{\rho_w}} \tag{4}$$

where A_n is the surface area of the nozzle (m^2), v_{wj} is the velocity of the water jet (m/s), d_n is the nozzle diameter (m) and ρ_w is the density of the fluid (kg/m^3). c_d is the coefficient of discharge of the nozzle, which compensates for losses in flow due to the shape of the nozzle, compressibility of the water and physical phenomena such as vena contracta. The value of c_d is usually between 0.6 and 0.9 (Anantharamaiah et al., 2006; Annoni et al., 2008; Tafreshi and Pourdeyhimi, 2003). Substitutions of Eqs. (3) and (4) in Eqs. (1) and (2) result in:

$$P_{wj} = p_{wj} \bullet c_d \bullet A_n \bullet v_{wj} = c_d \bullet \frac{\pi}{4} \bullet \sqrt{\frac{2}{\rho_w}} \bullet p_{wj}^{1.5} \bullet d_n^2 \tag{5}$$

$$P_d = \frac{p_{wj} \bullet c_d \bullet A_n \bullet v_{wj}}{A_i} = \frac{c_d \bullet \frac{\pi}{4} \bullet \sqrt{\frac{2}{\rho_w}} \bullet p_{wj}^{1.5} \bullet d_n^2}{A_i} \tag{6}$$

$$E_{wj} = p_{wj} \bullet c_d \bullet A_n \bullet v_{wj} \bullet t_{wj} = c_d \bullet \frac{\pi}{4} \bullet \sqrt{\frac{2}{\rho_w}} \bullet p_{wj}^{1.5} \bullet d_n^2 \bullet t_{wj} \tag{7}$$

P_d can be used to determine whether a material is being machined or not. For a full coherent water jet, A_i is equal to A_n directly after the initiation of the jet. This makes P_d solely dependent on the machine setting p_{wj}, since v_{wj} is also a product of p_{wj} (Eqs. (4) and (5)). This indicates that the size of the nozzle diameter does not influence the capability of machining, which was also concluded in a previous study (den Dunnen and Tuijthof, 2014a). In that experiment, the volume of material removed did increase with an increase in nozzle diameter since