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Review Article

Applying Waterjet Technology in Surgical Procedures

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Abstract

The main objective of the paper is to predict the optimal waterjet pressure required to cut, drill or debride the skin layers without causing any damages to the organs. A relationship between the waterjet pressure and skin thickness has been established. It also includes the modulus of elasticity of the skin, the diameter of nozzle orifice, the nozzle standoff distance and the traverse speed of the waterjet as well as the duration of applying the waterjet pressure. Thus, practical relationship between waterjet operating parameters and the physical properties of the skin has been formulated. A real Caesarean section procedure data has been applied to the formulation. Given the Ultimate Tensile Strength of the skin at the abdomen to be 20 MPa, incision parameters of 18 mm deep, 12 cm long and 0.4 mm wide, applying a traverse speed of 0.5 mm/s and stand-off distance of 5 mm, the resulted waterjet pressure is 17.89 MPa using a 0.4 mm orifice diameter.

Keywords: Waterjet; Surgery; Skin; Incision

Introduction

Waterjet technology has been used in several applications such as industrial cutting, drilling and cleaning. Furthermore, waterjet technology can also be used in the medical field; applications of this include dentistry, wound cleaning and other surgical operations. Over the years, waterjet techniques have been developed into a revolutionary cutting tool in variety types of surgery [1]. It can be used in precision cutting of skin for any type of surgery. The tool would simply be moved in a line to apply the pressure and the cut. The main advantage of waterjet incision is its precision; it is as effective as a laser cutter. However, the waterjet incision does not cause any thermal damage to the separated tissue due to its coolant ability. Additionally, the waterjet also washes away blood which eliminates any extra tools to do this which would be required in a regular cut [2].

In vivo and in vitro experiments on patients and animals have been conducted with continuous waterjet at different low pressures. However, few studies have focused on the skin. Further analyses on the relationship among the operating parameters of waterjet, structure, and mechanical properties of the skin must be conducted.

Literature Review

The waterjet technology is currently used for cutting a wide range of materials. The main advantages of this technology include the lack of thermal effect on the material being cut. While waterjet is applied to all kinds of industries, only the medical field will be highlighted. Table 1 summarizes some of the applications of waterjet cutting in the medical field.

The performance of waterjet machining process is dependent on the water pressure of the jet and the elastic properties of the skin. The initial impact is considered to be the highest impact; it can be achieved when the waterjet hits the tissue. After that, the water starts flowing radially and the impact of the jet decreases [4].

Type of Surgery	Operation Description	Benefits
Orthopedic	Cutting endoprosthesis and bone	Below the critical temperature by cutting
Dental	Cutting and grinding of dental materials	Reduces the risk of jagged teeth and reduces the need for anesthesia
General	Resection of soft tissues: liver, gall bladder, brain, kidney, prostate, cleaning wounds	Blood vessels and nerve fibers remain in the defined pressure maintained, minimal bleeding, intact edges and precise cuts, lack of necrotic edge, reduce the duration of myocardial ischemia
Plastic	Cleaning skin graft, removal of tattoos, liposuction	Separation of the layers of tissue, higher accuracy of results without edema and contour changes
Dermatology	Removing dead skin	Possibility of direct dose medications in a water jet

Table 1: Overview of using waterjet in medicine [3].

Waterjet in surgical wound debridement

Waterjet technology can be used for surgical wound debridement and surgical interventions where selective cutting is necessary. Surgical wound debridement uses devices on the market such as Versa Jet and Debrito while surgical interventions use devices on the market such as Jet Cutter 4, Helix HydroJet and ErbeJet2 [4].

A study in 2006 introduced Versa jet waterjet as an alternative to standard surgical excisional techniques for burn wounds. In the study, the Versa jet waterjet was able to sufficiently debride superficial partial thickness and mid-dermal partial thickness wounds for the subsequent placement of Biobrane. Additionally, the study has demonstrated that the Versa jet waterjet has the advantage in the surgical treatment of superficial to mid-partial thickness burns in the face, hand and foot [5].

Another study conducted in 2007 reviewed the versatility of the Versa jet waterjet surgical tool in treating the deep and indeterminate depth face and neck burns. With ex-vivo histologic analysis of depth of debridement on human skin, the study confirmed that predictable and controlled depth of debridement could be obtained by adjusting the apparatus settings [6].

The use of waterjet incision in other surgical procedures

Waterjet technology in surgical procedures was first reported in 1982 for liver resection. Throughout the years, waterjet machining process has become a recognized technique in different surgical areas. Clinically, waterjet technique is used for cutting softs tissues like liver tissues. Experimentally, waterjet technique is used for dissecting spleen, kidney tissue and brain tissues. While these tissues can be cut at low water pressures, waterjet techniques can also cut bone and bone cement at much higher water pressures [7].

Studies have been done using waterjet technology to drill or cut bone or bone cement. A study in 2014 has shown that such cut requires water pressure that ranges between 30 MPa to 50 MPa; which depends on the diameter of the nozzle. The study also summarized different materials that were tested in previous analyses, the required waterjet pressure to cut them as well as the nozzle diameter (Table 2).

Material Tested	Dnozzle (mm)	Required Pressure (MPa)
Human calcanei	0.6	30
Human femora	0.3	40
Bone cement		40
Human femora	0.2	50
Bone cement		30
Human interface tissue	0.2	12
	0.6	10

Table 2: Overview of required waterjet pressures to cut bone and bone cement [7].

A comparison between the existing systems and the proposed algorithm is illustrated in the following table 3.

Author	Year	Type of Study	Method	Apparatus	Water Purity	Pressure	Width of Cut	Cutting Velocity	Orifice Diameter	Stand-off Distance	Angle	Feed Rate
Arif (8)	1997	Skin Incision	FEA	Theoretical	100%	Predetermined	Varying	NA	Predetermined	NA	NA	NA
Vichyavichien (9)	1999	Skin Incision	FEA	Theoretical	100%	Predetermined	Varying	NA	Predetermined	Constant	Constant	NA
Wanner., *et al*. (10)	2002	Fat Tissue Incision	Ex Vivo	Commercial	0.9%	Predetermined	NA	Constant	Predetermined	Predetermined	Constant	NA
Hans-Oliver (5)	2006	Debridement Of burn Wounds	Ex Vivo	Commercial	Sterile Saline	Predetermined	NA	Predetermined	Constant	NA	Constant	NA
Cubison., *et al.* (11)	2006	Debridement Of burns	Ex Vivo	Commercial	NA	Predetermined	NA	Predetermined	Predetermined	NA	NA	NA
Tenenhaus., *et al*. (6)	2007	Wound Debridement	Ex Vivo	Commercial	NA	Predetermined	NA	Predetermined	Predetermined	NA	NA	NA
Keiner., *et al.* (12)	2010	Brain Tissue Dissection	Ex Vivo	Commercial	0.9% Saline	Predetermined	NA	NA	Constant	NA	NA	NA
Kraaij., *et al.* (7)	2015	Interface Tissue Incision	In Vivo	Custom	100%	Varying	NA	Varying	Predetermined	Constant	Constant	Constant
Bahls., *et al.* (4)	2017	Various Tissue Incision	In Vivo	Commercial	10%	Predetermined	NA	Predetermined	Constant	Predetermined	Constant	NA
Proposed	2019	Skin Incision	Mathematical	Theoretical	100%	Varying	Varying	Varying	Predetermined	Varying	Within Range	Varying

Table 3: Features of previous works and proposed methods.

The methods proposed in this study will provide more flexible and robust solutions for setting up the waterjet apparatus when used in surgical procedures.

Mathematical formulation

The operating parameters of the waterjet machining process are determined several independent variables. Table 4 summarizes these variables based on four system components: Process, skin, nozzle and pump characteristics [8].

Process Characteristics	Skin Characteristics	Nozzle Characteristics	Pump Characteristics
Depth of cut	Thickness	Stand-off distance	Pressure ratio
Width of cut	Hardness	Orifice diameter	Flow rate
Traverse (feed) rate	Consistency	Nozzle structure	Pump efficiency
Waterjet flow rate			Power

Table 4: Waterjet Incision Parameters.

Figure 1 describes how each parameter can control the incision characteristics as well as the illustration of the incision processes.

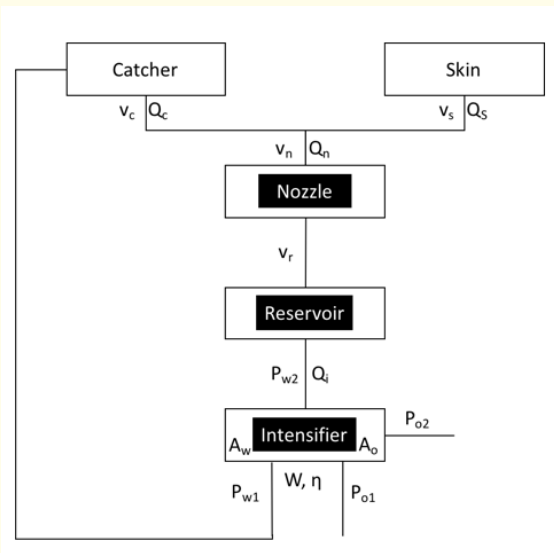

Figure 1: Waterjet parameters and its components.

Surgical incisions main components: operation characteristics

The main three components for a surgical incision are: the width of incision, the length of incision and the depth of incision. Before performing the incision, the surgical team must have these three factors defined. The width of incision as well as the length of incision is determined based on the individual surgery and the recommended incision specifications. When performing a skin incision, the depth of incision is determined by the skin thickness. Epidermal thickness differs by age, sex, gender, skin type, pigmentation, blood content, smoking habits, body site geographical location and many other variables. For these reasons, a system which can adapt to the differences must be created.

To develop metrics for skin thickness, high frequency Ultrasound technology is necessary. By applying the ultrasound apparatus on the area to be operated on, skin thickness can instantly be measured and fed into the system which determines the water pressure required for the skin incision. Other skin characteristics can also be determined from the Ultrasound results. Such characteristics include the elastic modulus of each of the skin layers as well as their tensile strength.

The total energy required for the skin incision which is converted to pressure energy is formulated as follows:

$$PE = UTS\ Q_s \qquad \text{.........................(1)}$$

Where UTS is the Ultimate Tensile Strength of the skin, and Qs is the flow rate at which the waterjet removes the skin which is calculated as:

For skin cutting and debridement:

$$Q_{s\_cut} = D_s L_s f \qquad \text{.........................(2)}$$

For skin drilling:

$$Q_{s\_drill} = D_s w_s v_s \qquad \text{.........................(2a)}$$

D_s is the depth of incision, L_s is the length of incision, f is the traverse speed (feed rate), w_s is the width of cut and v_s is the velocity of the waterjet stream at the skin.

Waterjet operating conditions: catcher characteristics

To minimize the process noise, a catcher is necessary. The kinetic energy of the catcher is the remaining energy that is not absorbed by the skin incision process, it is formulated as follows:

$$KE_c = \frac{1}{2} Q_c v_c^2 \rho_w \qquad \text{.........................(3)}$$

Where ρ_w is the density of water. Q_c is the flow rate at which the residue water is going into the catcher; it is the sum of the flow rates of water out of the nozzle Q_n and rate at which the waterjet removes the skin Q_s.

The velocity at which the excess water is going to the catcher (vc) is:

$$v_c = \sqrt{2gx} \qquad \text{(4)}$$

where, g is the gravity.

Waterjet operating conditions: nozzle characteristics

The kinetic energy of the waterjet stream coming out of the nozzle is the sum of the pressure energy required the skin incision and the kinetic energy of the catcher:

$$KE_n = PE + KE_c \qquad \text{(5)}$$

To look at the nozzle characteristic of the waterjet incision, this kinetic energy (5) will be equal to the following:

$$KE_n = \frac{1}{2} Q_n v_n^2 \rho_w k_e \qquad \text{(6)}$$

Where vn is the velocity of the waterjet stream coming out of the nozzle, ke is the loss coefficient. The waterjet nozzle converts high pressure water to a high velocity jet. The performance of waterjet incision is affected by several variables such as nozzle orifice diameter, water pressure, incision feed rate and standoff distance. In the medical field, waterjet incision devices usually use low to medium pressure as well as a small design nozzle that is different from industrial waterjet.

A relationship between the velocity of the waterjet stream coming out of the nozzle (v_n) and the velocity of the waterjet stream at the skin (v_s) can be described as follows:

$$v_n = \frac{v_s}{e^{-ax}} \qquad \text{(7)}$$

Where, a is the taper index and x is the standoff distance of the nozzle. Assuming a straight taper waterjet nozzle design, the flow of the water from the nozzle to the atmosphere is affected by the area and the shape of the orifice. Table 5 represents the different orifice types and the typical values of contraction (C_c) and loss (k_e) coefficients for water orifices.

Orifice	Description	Cc	Ke
SE	Sharp-edged	0.63	0.08
RE	Round-edged	1.0	0.10
TSE	Tube with square-edged	1.0	0.51
TRE	Short tube with rounded entrance	0.55	0.15

Table 5: Types of Orifices and their Coefficients Values [13].

From (1) through (7) Q_n and v_n are calculated: For cutting and debridement:

$$Q_n = \frac{2\,PE_{cut} + 2gx\rho_w D_s L_s f}{\rho_w (v_n^2 - 2gx)} \qquad \text{(8)}$$

$$v_n = \sqrt{\frac{2\,PE_{cut} + 2gx\rho_w D_s L_s f}{Q_n \rho_w} - 2gx} \qquad \text{(9)}$$

For drilling:

$$Q_n = \frac{2\,PE_{drill} + 2gx\rho_w D_s w_s v_s}{\rho_w (v_n^2 - 2gx)} \qquad \text{(8a)}$$

$$v_n = \sqrt{\frac{2\,PE_{drill} + 2gx\rho_w D_s w_s v_s}{Q_n \rho_w} - 2gx} \qquad \text{(9a)}$$

The relationship between Q_n and v_n can also be represented by:

$$Q_n = C_c A_n v_n \qquad \text{(10)}$$

A_n is the area of the orifice of the nozzle which is represented by:

$$A_n = \pi \frac{d_n^2}{4} \qquad \text{(11)}$$

Where d_n is the orifice diameter of the nozzle.

Waterjet operating conditions: pump and intensifier characteristics

The relationship between the velocity of the waterjet flow coming out of the pump reservoir and the one coming out of the nozzle is calculated as follows:

$$v_r = v_n e^{-2\beta L_n} \qquad \text{(12)}$$

Where L_n is the length of the nozzle and β is the exponential constant which is based on an exponential taper waterjet nozzle design where:

$$\beta = \frac{-\ln(d_n/d_o)}{L_n} \quad \text{.........................(13)}$$

Where d_o is the diameter of the top of the nozzle.

The pressure ratio (r_p) between the water outlet pressure (P_{w2}) and the oil inlet pressure (P_{o1}) and as well as the oil inlet area (A_o) and the water inlet area (A_w) is described as follows:

$$r_p = \frac{P_{w2}}{P_{o1}} = \frac{A_o}{A_w} \quad \text{.........................(14)}$$

The waterjet flow rate out of the intensifier (Q_i) is equal to the waterjet flow rate coming out of the nozzle (Q_n). By design, the hydraulic intensifier increases the pressure of water. Thusly, the water pressure coming out of the intensifier (P_{w2}) is determined by the Power (W), the efficiency of the intensifier (η_i) and the flow rate (Q_i) as follows:

$$P_{w2} = \frac{W\eta_i}{Q_i} \quad \text{.........................(15)}$$

Application example and results

In this example of a caesarean section procedure, Pfannenstiel traverse incision is assumed. This curved incision (Length of incision L_s) is approximately 10 - 15 cm long and 2 cm above the pubic symphysis [9]. Using the waterjet, the skin and rectus sheath are opened transversely. The rectus muscles are not cut and the fascia is dissected along the rectus muscles. The skin thickness at the abdomen for a female is approximately 2.30 mm while the subcutaneous adipose tissue thickness at the abdomen is approximately 15.7 mm [10]. The UTS of the skin at the abdomen ranges between 1 and 24 MPa [11]. The exact thickness of the skin and its characteristics would be measured using high frequency Ultrasound. The width of cut is 0.4 mm; in an traditional incision, a #10 (0.4 mm) blade is used [12,13]. Table 6 summarizes the operation characteristics as follows.

The waterjet velocity coming out of the nozzle (v_n) is 151.05 m/s while the waterjet velocity that reaches the skin (v_s) is 150.86 m/s. The velocity of the excess water that is going to the catcher is very minimal at 0.31 m/s. The calculated power required for the intensifier is 423.52 Watts. Assuming the efficiency of the intensifier (η_i) is 80%, the calculated pressure that is required for the cesarean section operation is 17.89 MPa with a 0.4 mm nozzle orifice diameter.

Parameters	Value
Depth of cut (D_S)	18.00 mm
Length of cut (L_S)	12.00 cm
Width of cut (w_S)	0.40 mm
Ultimate Tensile Strength (UTS)	20.00 MPa
Density of water (ρ)	1.00 g/cm^3
Feed rate (f)	0.50 mm/s
Gravity (g)	9.80 m/s^2
Stand-off distance (x)	5.00 mm
Taper (a)	0.25

Table 6: Caesarean Section Operation Characteristics [14-19].

The results obtained from this study can be summarized as follows:

1. The mathematical formulation for different incision processes has been developed and simulated for the best results.
2. Using the cutting incision, an application example has been demonstrated.
3. The data applied has been extracted from real life application.

Conclusion and Recommendations

Given any surgical operation characteristics, this mathematical model is able to calculate the optimal operating conditions for surgical cutting, debridement or drilling. This will help the surgeon pick the right nozzle size as well as the right waterjet instrument parameters such as pressure, power and velocity. The next step is to use the results of the study to create a comprehensive surgical procedure simulation model such as a Caesarean section procedure or any other surgical procedure that is needed.

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Volume 3 Issue 10 October 2019