A tissue tensioner to limit water injection during high pressure water jet debridement

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by

Colette P. Abah

Submitted to the Department of Mechanical Engineering
in partial fulfillment of the requirements for the degree of

Bachelor of Science in Mechanical Engineering

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A Tissue Tensioner to Limit Water Injection During High Pressure Water Jet Debridement

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Abstract

Removing necrotic tissue and foreign materials from wounds is a critical step in the management and treatment of chronic wounds. MIT's BioInstrumentation Laboratory developed a novel debridement technology that uses two high-speed impinging water jets to excise necrotic tissue. However, this device potentially causes accidental injection of water into healthy tissue beneath the wound bed, which can cause injury and necrosis in the healthy tissue. The purpose of this thesis is to explore tissue tension as a solution to reduce the required cutting power and consequently reduce water injection to acceptable levels. After validating the positive effect of tissue tension on the cutting efficiency of the water jet debridement device, we developed a technology that uses angled rolling wheels to tension tissue prior to debridement. This novel tensioner was qualitatively tested and successfully applied local tension at the site of cutting. Suggestions for further testing to improve this device are given. This tissue tensioner shows promise as a complementary appendage to the water jet debridement device.

Thesis Supervisor: Ian Hunter
Title: Professor of Mechanical Engineering

Acknowledgments

I would like to thank my faculty supervisor, Professor Ian Hunter, for the opportunity to work in the BioInstrumentation laboratory this semester. It was an incredible learning experience and I came out a better scientist and engineer.

I would like to thank my graduate adviser, Ashley Brown, for her guidance and mentorship throughout this project. She is a great teacher and a brilliant engineer. I am grateful for the knowledge she has imparted to me.

To the members of the BioInstrumentation lab, it was a pleasure to work with you and learn from your expertise.

Rachel and Marie, thank you for helping me with testing. Maxine, thank you for regularly checking up on me (and my sanity). Abir and Jerop, thank you for providing food, entertainment and hugs. To my family and to the friends I now call family, thank you for your unconditional love and support. Your kind words of encouragement kept me strong in the most challenging times.

To my brother, Alain, I dedicate my MIT degree to you. Thank you for teaching me that I can achieve anything I want, if I want it badly enough.

To my Heavenly Father, thank you for the amazing grace to survive and thrive at MIT.

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Chapter 1

Introduction

Chronic wounds represent a significant burden to patients, health care professionals and the US health care system, costing about $25 billion annually [3][4]. Approximately 3 to 6 million Americans are affected by chronic wounds, especially due to venous ulcers, pressure ulcers and diabetic ulcers [5][6]. Most chronic wounds are non-healing; of all cases of venous and diabetic ulcers, only 25 to 50% heal after twenty weeks of treatment [7].

Debridement, the removal of necrotic tissue and foreign materials from a wound, is an essential step in the treatment of chronic wounds [8]. There currently exist many debridement techniques, but the search for novel and more effective techniques is ongoing [9]. MIT's BioInstrumentation laboratory developed a novel debridement device that uses two high-speed impinging water jets to excise necrotic tissue [1]. The current alpha prototype of this device was successful in debriding a surface with side-by-side cuts, implementing a suction technique to remove waste and reducing water injection through pre-scoring the tissue.

The use of the water jets on soft tissue caused water injection into healthy tissue underneath the wound bed. The lowest injection level achieved by the water jet debridement device is $4.3\,\mathrm{L\,m^{-2}}$, which is higher than the $3\,\mathrm{L\,m^{-2}}$ maximum acceptable injection value [10].

Tensioning tissue prior to cutting with the water jet device is a potential solution to reduce water injection in the tissue, as less force is required to cut tissue under tension

[11]. Applying tension to the tissue prior to cutting will reduce the required cutting pressure and consequently, the water injection[1]. This thesis describes the design a novel technology to tension tissue surface and prevent excessive water injection, in order to increase patient outcome post water jet debridement.

Chapter II provides background information on the treatment of chronic wounds and MIT's BioInstrumentation Laboratory's novel water jet debridement device. Chapter III investigates the effect of tissue tensioning on the cutting efficiency of the water jet debridement device. Chapter IV presents the design and performance of a novel tissue tensioner. Finally, Chapter V evaluates the device capabilities and discusses future work.

Chapter 2

Background

2.1 Management of Chronic Wounds

A wound is a breach of the skin's outer protective layer, epidermis, that can lead to infection and sepsis [12]. There are two types of wounds: chronic wounds and acute wounds. Acute wounds are caused by trauma or through surgery and heal in four overlapping stages[12] [13]. Chronic wounds are any interruption in the continuity of the body's surface that requires a prolonged time to heal, does not heal, or recurs [6][14]. Chronic wounds are especially common in patients with diabetic, venous and pressure ulcers.

The healing process for acute wounds follows a well-defined healing process, with four overlapping stages, that can last for months [12]. **Coagulation** initiates the wound healing process by releasing clot of platelets embedded in a mesh of cross-linked fibrin fibers that act as a temporary shield for the denuded wound tissues [15]. At the **inflammation** stage, inflammatory cells are recruited from circulating blood to the wound site through chemotactic signals. Neurophils clears the initial rush of bacteria and macrophages clear the remaining pathogenic cells and matrix debris. At the **cell proliferation and matrix repair** stage, capillaries penetrate the cloth and form granulation tissue. Fibroblasts then fill the wound site with interim wound matrix, while epithelial cells multiply at the wound edge before migrating across the granulation tissue and forming a new epidermis. This stage can last for several weeks.

The final stage of wound healing is **epithelialization and remodeling of the scar tissue**. This stage can last up to several months and is characterized by the synthesis of a new extra-cellular matrix and the apoptosis of unneeded cells [12] [1].

Chronic wounds do not follow the same well-sequenced healing stages as acute wounds. The healing of chronic wounds get disrupted at one or many stages. In order to transform the molecular and cellular environment of a wound bed from chronic into acute, the barrier to healing must be identified and removed using adequate methods [12]. Wound bed preparation is a chronic wound management technique that converts non-healing wounds into acute wounds through debridement, management of exudate and resolution of bacterial imbalance [12].

2.2 Debridement Techniques

Debridement is an essential step in both acute and chronic wound management. It is the technique used to clear wounds of necrotic tissue and bacteria in order to promote healing [12]. In chronic wounds, necrotic tissue provides a focus for infection, prolongs the inflammatory phase, obstructs contraction and prevents re-epithelialization [16].

2.2.1 Excising Debridement Techniques

There are five different types of the debridement techniques, each with its advantages and limitations [17] [12]:

Autolytic debridement is the process by which the wound bed clears itself of debris by utilizing phagocytic cells and proteolytic enzymes[18]. This debridement technique is easy to perform, natural, selective, painless and most appropriate for wounds with minimal debris. Unfortunately, this technique is prohibitively slow [17].

Enzymatic debridement describes the application to the wound bed of protolytic enzymes such as collagenase able to chemically digest and breakdown cellular debris [19]. This debridement technique is easy to perform, selective and painless. However, this process is slow and the enzymes may be inactivated by the wound's pH level [17].

Table 2.1: Comparison of debridement techniques. 1 = most appropriate; 4 = least appropriate. Adapted from [2]

	Autolytic	Surgical	Enzymatic	Mechanical
Speed	4	1	2	3
Tissue selectivity	3	2	1	4
Painful wound	1	4	2	3
Exudate	3	1	4	2
Infection	4	1	3	2
Cost	1	4	2	3

Mechanical debridement describes the process of physically removing debris from a wound bed. This debridement method includes procedures such as wet-to-dry dressings, hydrosurgery, irrigation and dextranomers [20] [21]. Mechanical debridement is easy to perform, faster than both autolytic and enzymatic debridements,and useful for wounds with necrotic materials and moderate to large amounts of exudate. However, this method is non selective and may damage or remove viable tissue in the process [17].

Surgical and sharp debridement is the excision of non-viable tissue using sharp instruments such as scalpels, curettes, or scissors[17]. Surgical debridement is the fastest and most effective way to remove debris and necrotic tissue [12]. This method is commonly use with widespread infections or with septic patients [12]. However, surgeons are taught to debride until bleeding occurs [22], which make this debridement method extremely painful and risky for the patient's immune system. This technique is also very costly [2] and requires the presence of a trained clinician [17].

Larval Therapy involves the dissolution of necrotic tissue by using the enzymes present in green bottle fly saliva. This method is efficient, safe and simple to perform [23] but is only applicable to specific wound characteristics [17].

Table 2.1 summarizes the advantages and drawbacks of each debridement technique [2].

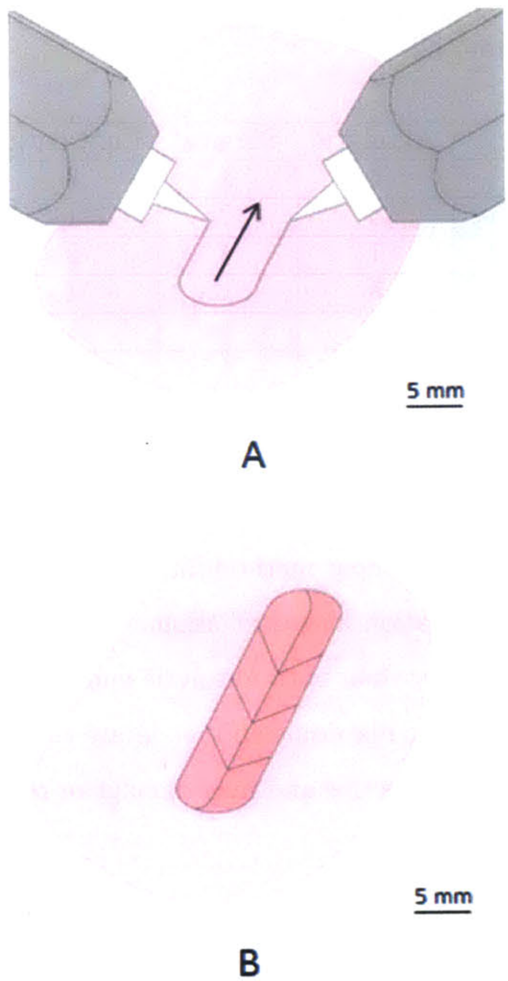

Figure 2-1: Method for excising tissue with two nozzles. In (A), the nozzles each simultaneously make a cut. Because the nozzles are angled towards each other, their cuts separate a section of tissue, which has been removed in (B). Reproduced from [1]

2.2.2 Novel Debridement Method

MIT's BioInstrumentation laboratory developed a novel device that employs two simultaneous high pressure water jets to debride necrotic tissue from wounds [1]. The water jets are impinging, such that most of their kinetic energy is dissipated into atomization and the device is able to excise sample strips of the epidermis without perforating deeper skin layers. As illustrated in Figure 4-9, the two jets make simultaneous parallel cuts. Because the nozzles are angled to intersect at the subsurface, their motion excises a sample of the tissue [1].

As illustrated in Figure 2-2, each nozzle is mounted in a nozzle arm that can swivel, thus changing the angle of the jets. The two arms are mounted in separate blocks and a knob controls the relative distance between the two blocks. By swiveling the nozzle arms and turning the knob, the angle and the distance between the nozzles can be adjusted. Figure 2-3 shows the water path within the device [1].

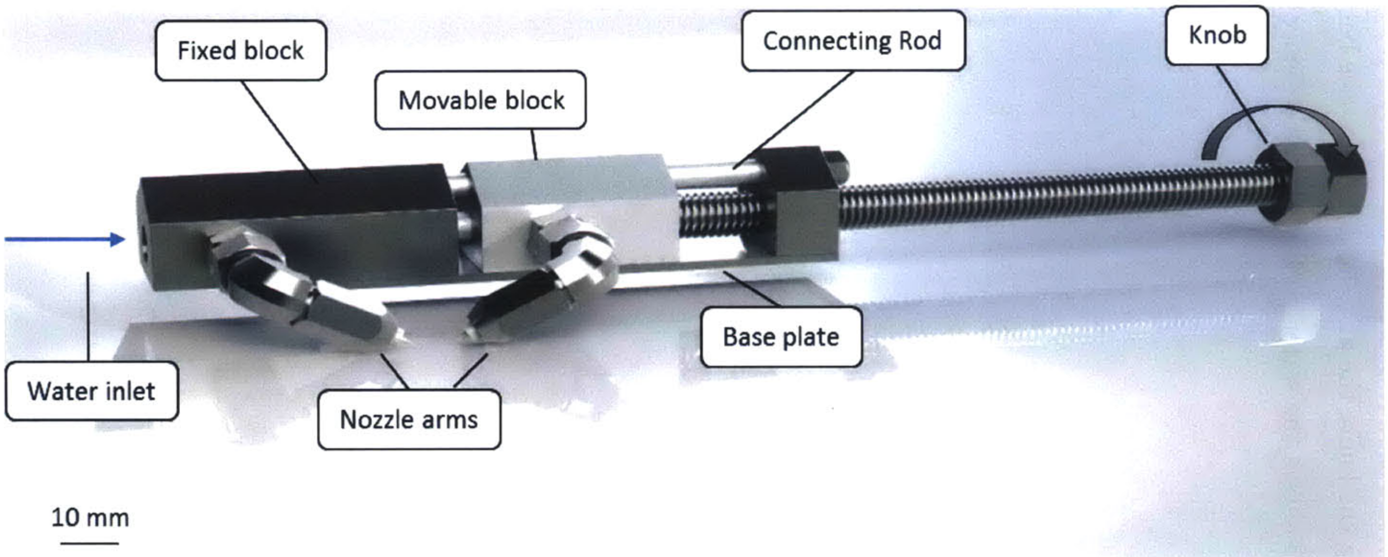

Figure 2-2: Each nozzle is mounted in a nozzle arm that can swivel, thus changing the angle of the jets. The two arms are mounted in separate blocks. A knob controls the relative distance between the two blocks. By swiveling the nozzle arms and turning the knob, the angle and the distance between the nozzles can be adjusted. Reproduced from [1]

The pressure needed to debride tissue depends on both the jet configuration and the properties of the tissue. The device was tested on simulated sloughy tissue at optimum parameters of 75 µm orifices nozzles spaced 2 mm apart at 110° from each other, this device was able to excise soft tissue at 6 MPa of water pressure [1].

However, cuts made in simulated sloughy tissue caused the two-nozzle device caused water to inject into healthy tissue beneath the wound bed. Excessive water injection can cause injury and necrosis in healthy tissue [24], which would make this device counterproductive.

Two methods to reduce the water injection have previously been explored and implemented. Increasing the speed on translation during cutting reduced the water injection but also lead to cuts of unreliable quality and shallower depth. The second method used surgical blades to incise the sample prior to cutting with the water jets. The use of surgical blades in conjunction with the debridement device reduced the water injection. Still, the lowest injection level achieved by the water jet debridement device is $4.3\,\mathrm{L\,m^{-2}}$, which is higher than the $3\,\mathrm{L\,m^{-2}}$ maximum acceptable injection value [10].

Tensioning tissue prior to cutting with the water jet debridement device is a potential solution to reduce water injection in the tissue. Indeed, less force is required to cut tissue under tension [11], and so applying tension to the sample may reduce the required cutting pressure and consequently reduce the water injection [1]

The next chapter explores tension as a solution to reduce the water injection during water jet debridement through an experiment aimed to prove the effect of tissue tension on achieved depth of cut.

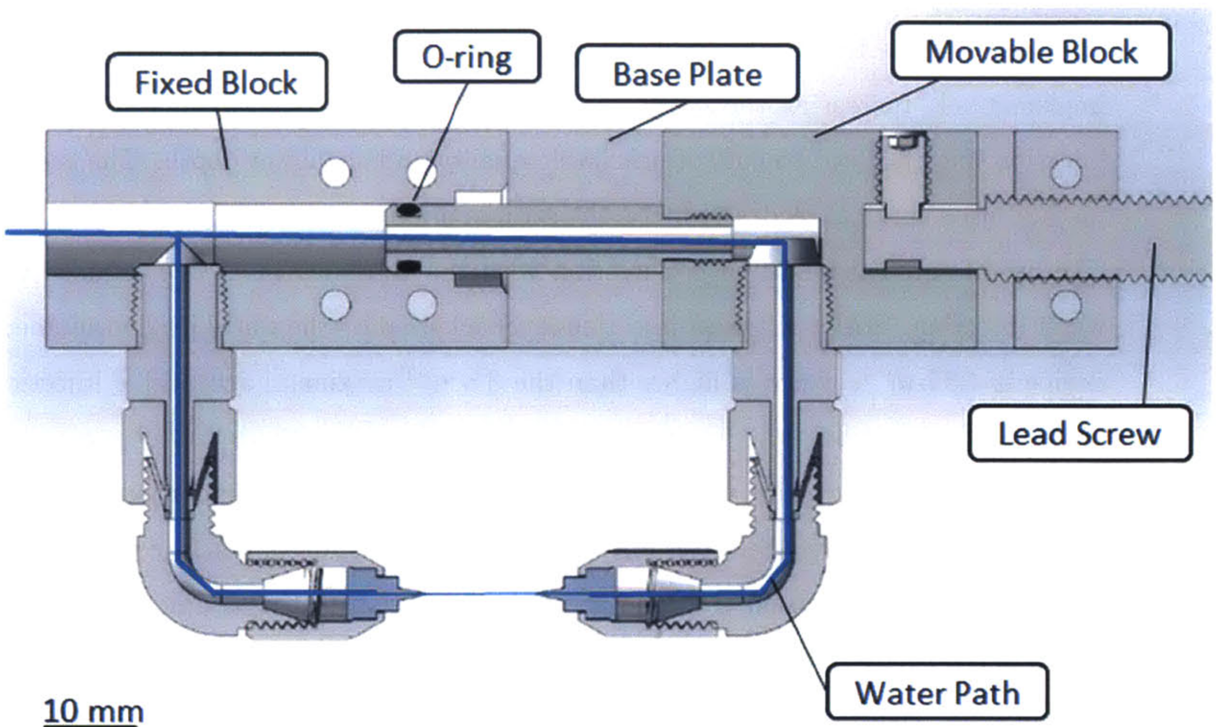

Figure 2-3: A cross section of the water jet cutting device showing the water path. Reproduced from [1]

Chapter 3

Proof of Concept

It was hypothesized that tensioning tissue prior to cutting with a water jet debridement device could increase the cutting efficiency, hence decrease water injection in healthy tissue beneath the wound bed. This Chapter described a proof of concept experiment that measures the effect of tissue tensioning on the depth of cut achieved by the water jet debridement device at constant water pressure.

3.1 Experimental Setup

In this experiment, we put simulated sloughy tissue under varied levels of uniaxial tension while keeping the cutting pressure constant, 15 MPa. We simulated a sloughy wound, supplied high pressure water, optimized flow through nozzle maintenance and performed a debridement test with tissue under uniaxial tension.

3.1.1 Simulating a Sloughy Wound

Slough is a stringy mass of devitalized tissue whose color indicates the level of bacterial colonization [1]. White slough has a low colonization level, while yellow or green slow have higher bacterial counts [25]. Slough was simulated for this experiment to represent soft necrotic tissue. The structure of slough was mimicked by degrading the extracellular matrix (ECM) of bovine tissue samples with acetic acid at 10%

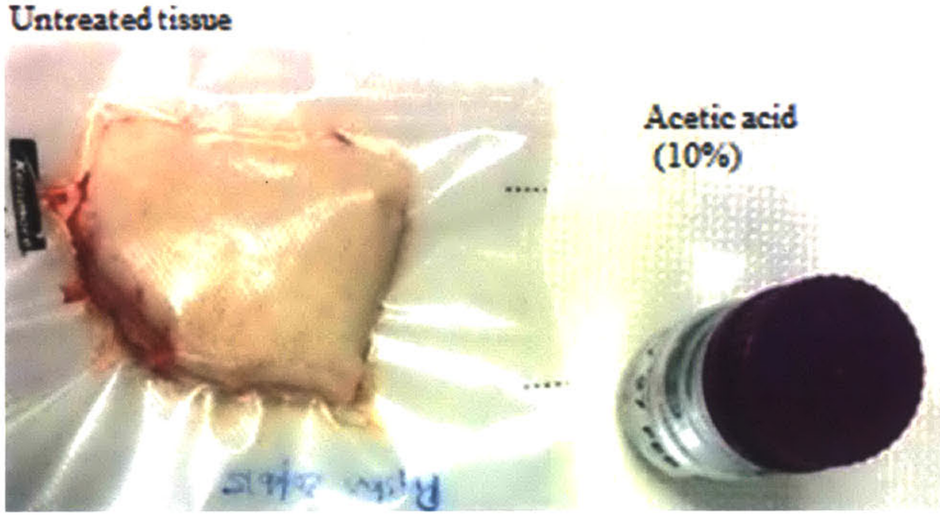

Figure 3-1: Slough was simulated by treating post-mortem porcine abdominal tissue with 10% acetic acid

concentration. In healthy skin, dermal ECM, which is composed of collagen in characteristic triple-helix configuration of three polypeptide chains, serves as a support structure [26]. Dilute acetic acid causes collagen to swell, unfold, and partly dissolve [27]. Concentrations as low as 0.3% for one hour cause a substantial re-arrangement of intermolecular bonds in rat tail tendons [28].

Slough was simulated by applying 10% acetic acid to a sample of post-mortem porcine abdominal tissue, as illustrated in Figure 3-1. The acid was pooled on the surface of the sample, which was then sealed and incubated for at least three hours at room temperature, 25 °C. The sealed sample was then stored at 4 °C. All tests were conducted at room temperature.

Treatment with acetic acid made the tissue dermis stiff and translucent, as shown in Figure 3-2, in contrast to the supple and opaque pre-treated tissue from Figure 3-1, due to broken-down collagen. The acid treated porcine tissue successfully mimicked important characteristics of sloughy wounds [1].

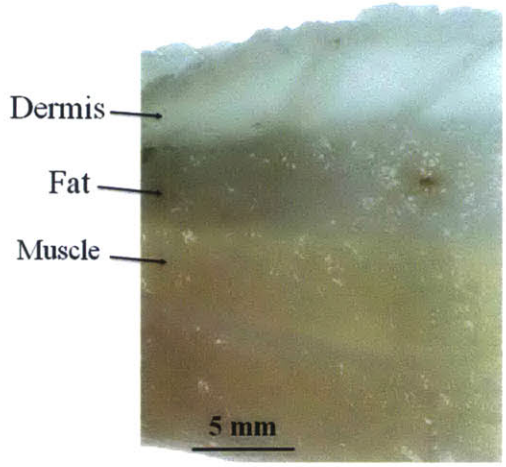

Figure 3-2: Cross section of porcine tissue after treatment with 10 percent acetic acid. Reproduced from [1]

3.1.2 Setup to Supply High Pressure Water

In order to perform debridement with the water jet device, high pressure water was supplied to the system. The pressure setup, illustrated in Figure 3-4, was designed and built by Ashley Brown [1].

A Maxpro Technologies [29] pneumatic piston pump was used and supplied between 2 and 85 MPa. At 20 MPa, the flow rate was $0.011\,\mathrm{L\,s^{-1}}$, comparable to the flow rate used in jet injections. The output pressure oscillated through a range of about 5 MPa. Throughout this experiment, the minimum value of the oscillation was set as the reference cutting pressure.

Figure 3-3 shows a detailed diagram of the auxiliary hardware used to control the water supply. The experiments were performed inside the polycarbonate safety enclosure. Latex globes, a face shield and a lab coat were worn as all time.

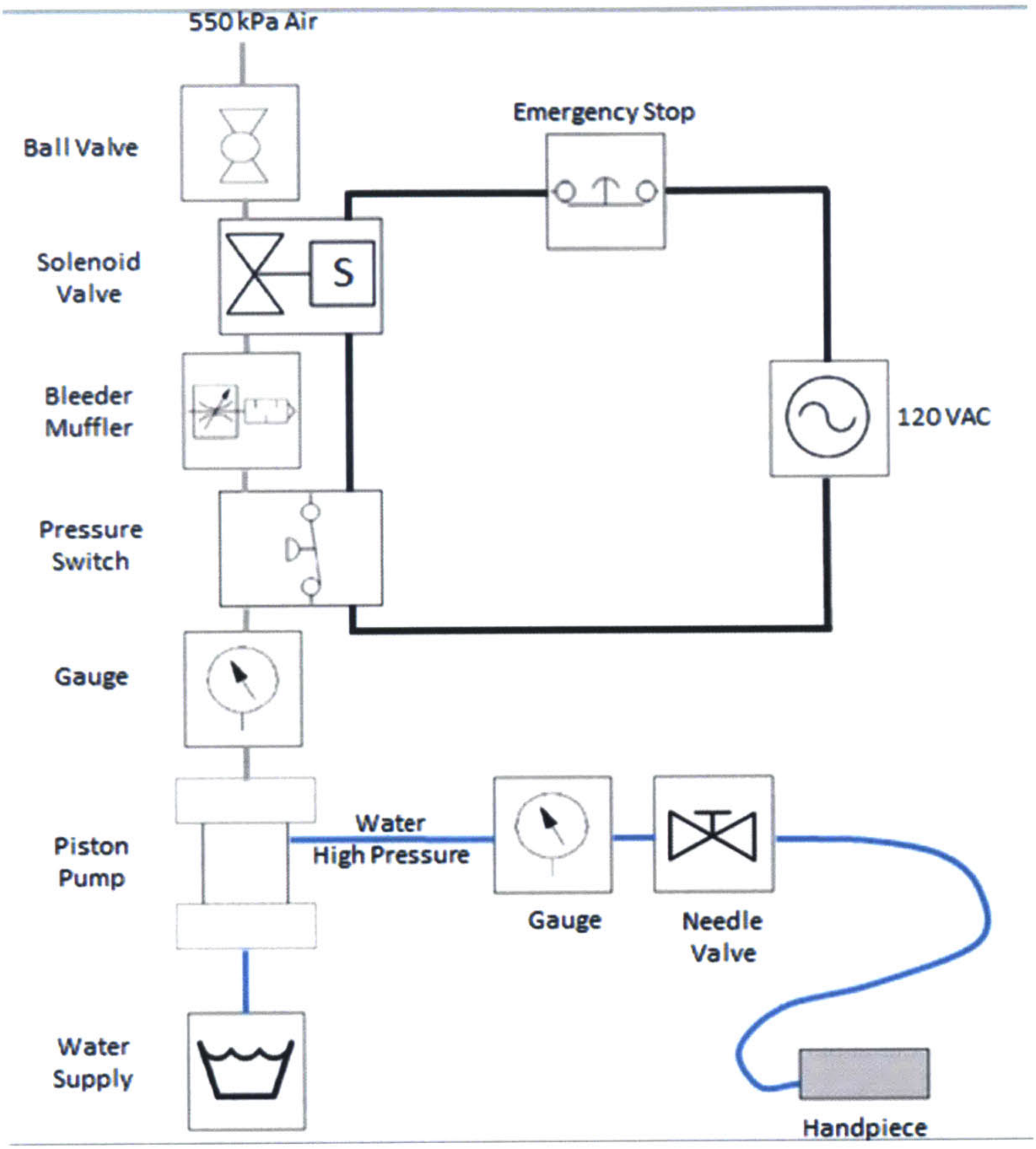

Figure 3-3: Diagram showing setup components. At the input, 550 kPa air is fed through a ball valve to a solenoid valve. On its way to the pump, the air passes through a bleeder muffler, an adjustable pressure switch, and a 400 kPa dial pressure gauge. The air supplied to the pump is controlled coarsely by adjusting the ball valve, and finely by allowing the air to bleed out through a bleeder muffler. Both the pressure switch and the emergency stop are able to cut off power to the solenoid valve, causing the valve to close and isolating the pump from the air supply. The pressure switch is set to activate at 700 kPa, higher than the pressure of the compressed air available, yet still less than 1.4 MPa for which all the air supply fittings are rated. All connections in the air supply fitting are 0.25 NPT. Reproduced from[1]

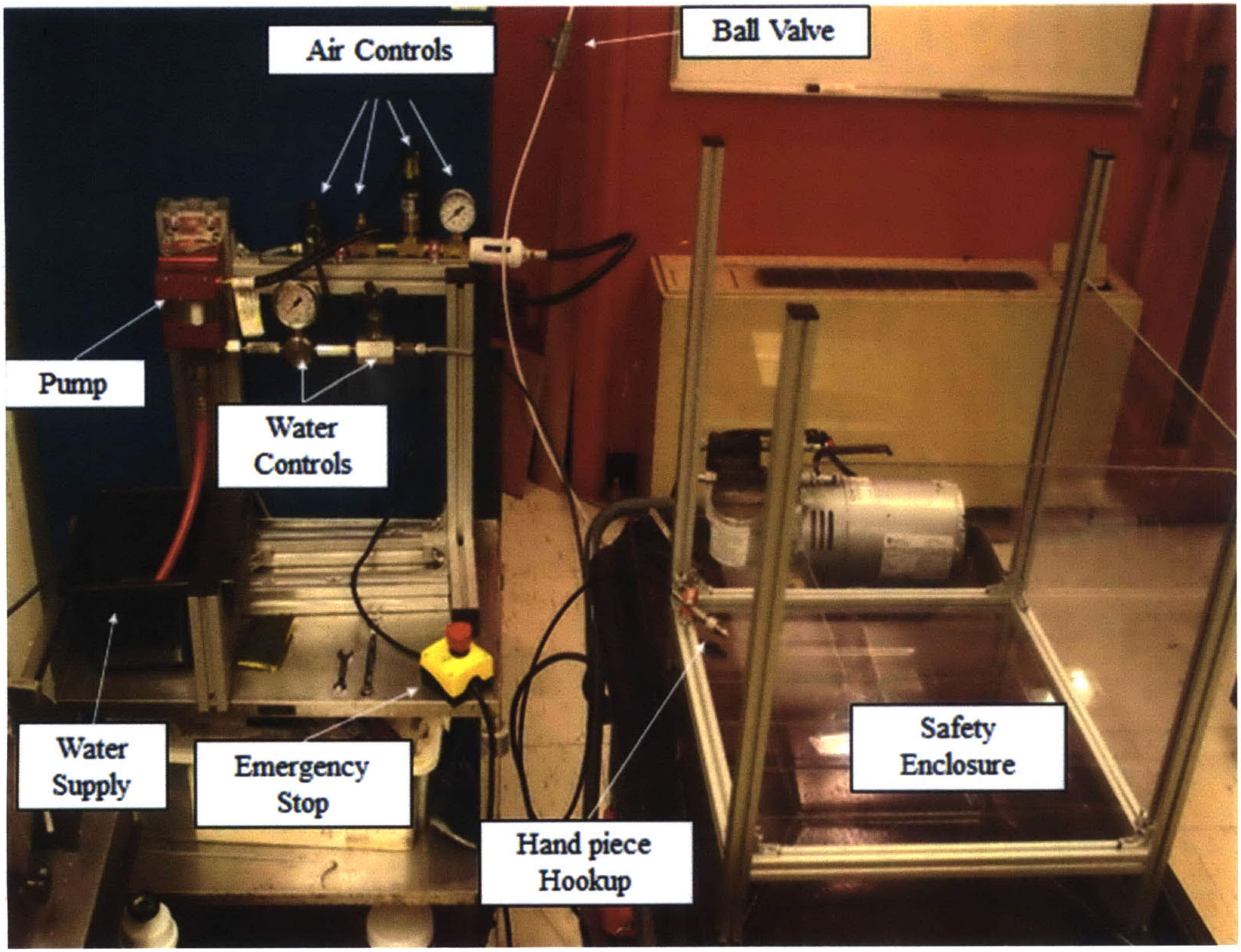

Figure 3-4: Experimental setup to supply high pressure water. Reproduced from [1]

3.1.3 Nozzle Maintenance with Fret Filters

Ceramic nozzles supplied by Small Precision Tool [30] were used in this experiment. At their optimal operational state, the nozzles output a single stream of water at high speed. However, the nozzles were prone to partial and full clogging when left unused for many hours. Partial clog resulted in the output of a diffused mist of water and full clog prohibited all flow out of the debridement device. The nozzles also clogged during use, due to particles from thread sealant tape and other sources.

Fret filters [31] were used in order prevent regular clogging. Two designs were considered and implemented. The first design, shown in Figure 3-5A consists of a square fret filter press-fitted into an acrylic seal. The acrylic seal was used to prevent leaking on the sides of the fret filter during use. This first configuration was unsuccessful due to structural flaws. The fret filter applied force on the acrylic seals, causing stress concentration at the corners of the square hole. The acrylic filters surrounding the fret filter broke regularly during use, causing the debridement device to leak at the nozzle arms.

In the second design, shown in Figure 3-5B, a circular configuration was adopted, eliminating the problem of stress concentration at the corners. This design was successful and significantly reduced the frequency at which the nozzle clogged both during use and in idleness. Figure 3-6 shows an exploded view of the nozzle arm and its internal components, including the fret filter. Acrylic crush washers and an acrylic sealed fret filter are sandwiched between the nozzle and the elbow. The nozzle arm is made watertight through the compressing action of a threaded cap.

3.1.4 Setup for Uniaxial Tensioning

The setup for tensioning of necrotic tissue is illustrated in Figure 3-7. Post mortem porcine abdominal tissue was treated with 10% acetic acid to simulate necrosis, as described in Section 3.1.1. The dermis of the necrotic tissue is held in tension by two steel bulldog clips [31] at two opposite ends, as displayed in Figure 3-8. One of the clip is fixed to a force sensor [32], while the second clip is fastened to an

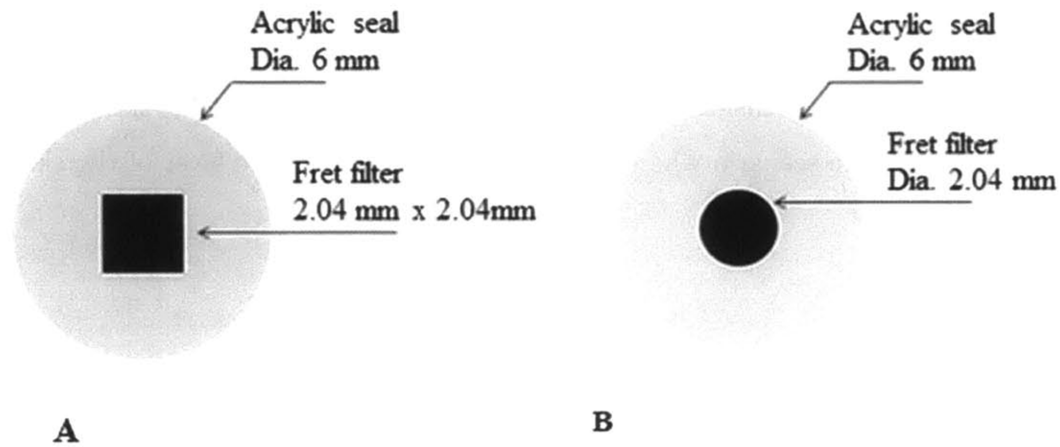

Figure 3-5: Fret filter press-fitted into an acrylic washer. A. The square configuration was structurally weak due to stress concentration at the corners of the square acrylic hole. B. The circular configuration was successful in reducing the frequency of nozzle clogging

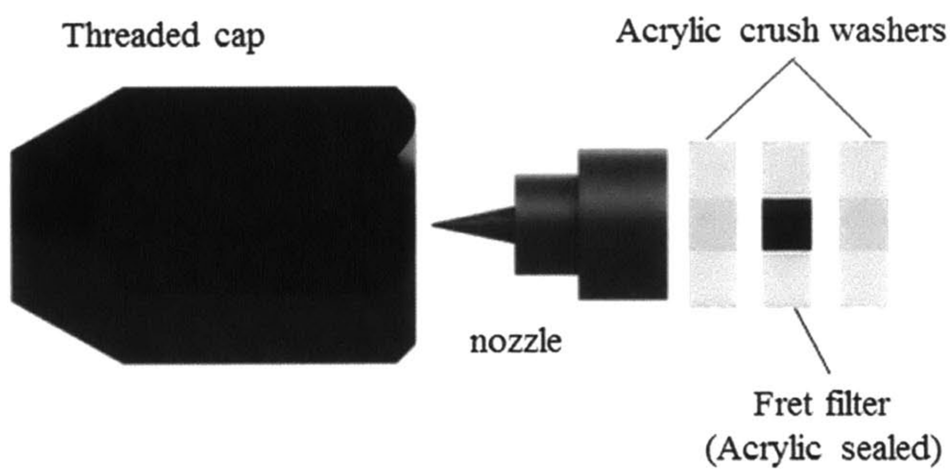

Figure 3-6: Exploded view of a nozzle arm and its internal components. Acrylic crush washers and fret filter are sandwiched between the nozzle and the elbow (not shown). The nozzle arm is made watertight through the compressing action of a threaded cap.

MK 50 mmAluminum profile base [?]. The position of the second clip is variable to a single degree of freedom, making the relative distance between the two clips adjustable. Different gap lengths between the two clips correspond to different levels of tissue tension. The tension is only applied to the dermis layer of the tissue in order to mimic a real life scenario where the dermis is the only visible layer of the skin.

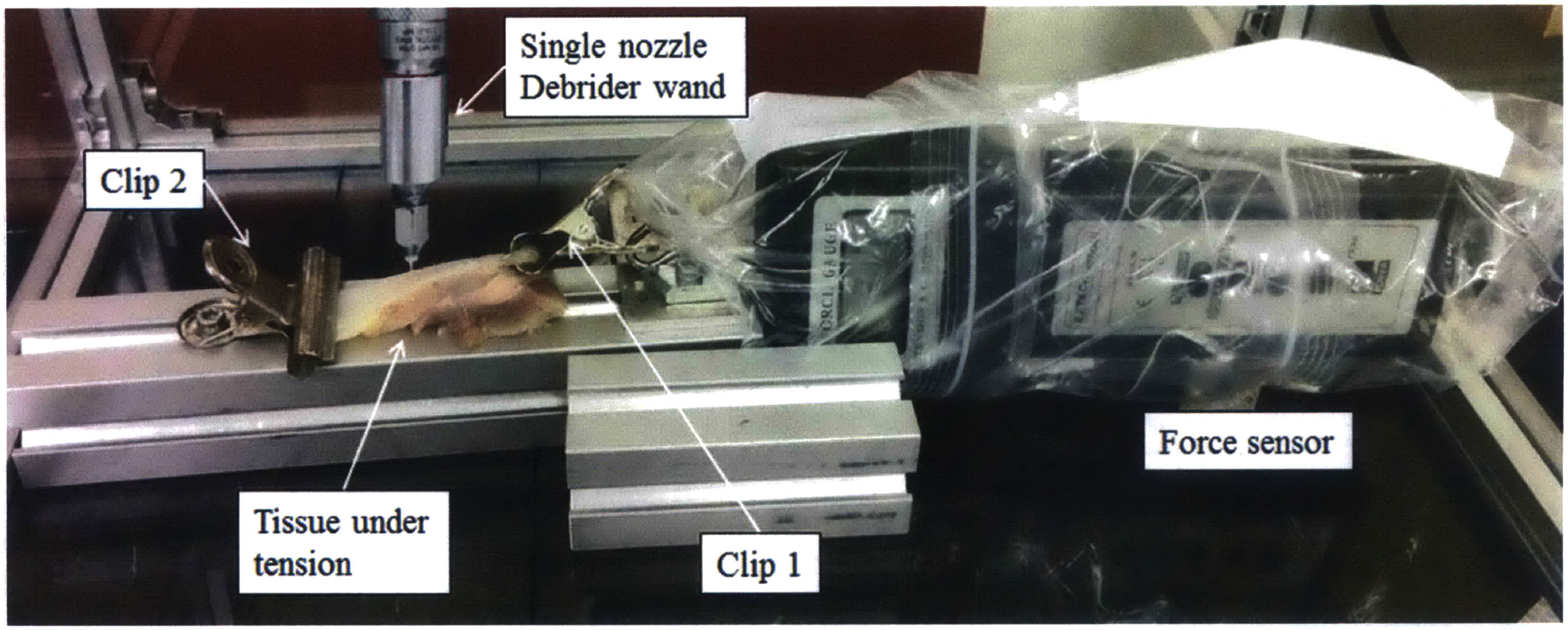

Figure 3-7: The tissue dermis is held in tension by two steel bulldog clips at opposite ends. The first clip is fixed to a force sensor while the second clip is fastened to an MK 50 mmAluminum profile base. The position of the second clip is adjustable. The gap between the two clips determines the level of tension applied to the skin. This tension is measured by the force sensor.

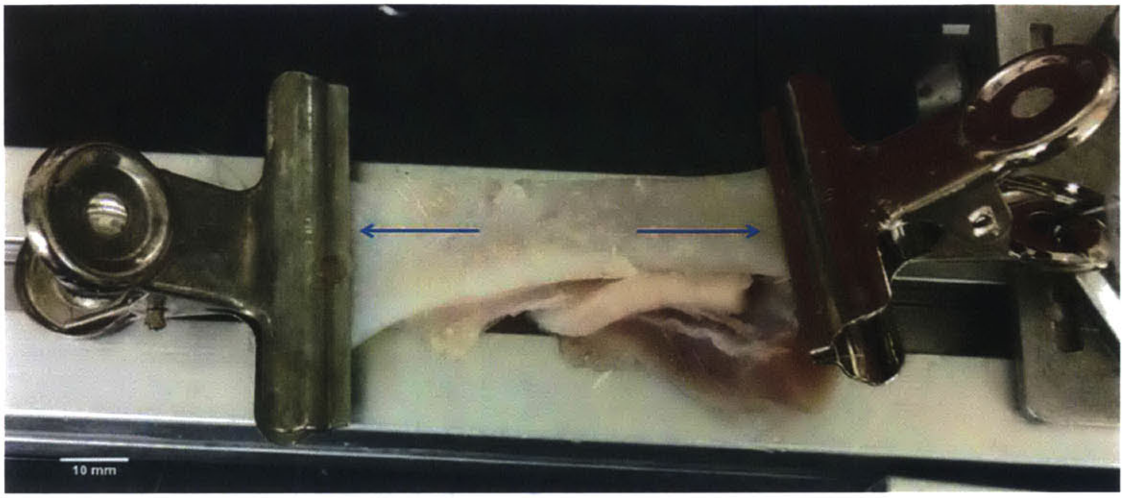

Figure 3-8: Tension applied on the dermis of simulated necrotic tissue. The blue arrows represent the direction of uniaxial tension

3.2 Effect of Tensioning on Cutting Efficiency

In the previous Section, we presented the experimental setup required to perform a debridement test on a tissue under uniaxial tension. In this Section, we investigate the effect of tension on the cutting efficiency of the water jet debridement device.

For the purpose and scope of this test, we used a single nozzle debridement device, shown in 3-9. The single nozzle debridement device operates under the same principles as the double nozzle device presented in Chapter II, but makes a single cut into the tissue.

Throughout this experiment, the water pressure was kept constant. The pressure oscillated by 5 MPa but the minimum oscillation value was kept to 15 MPa. The treated tissue, simulating a sloughy wound, was held at opposite ends of the dermis with two steel bulldog clips, as described in the previous Section. The gap between

Figure 3-9: Single nozzle debridement device. Reproduced from [1]

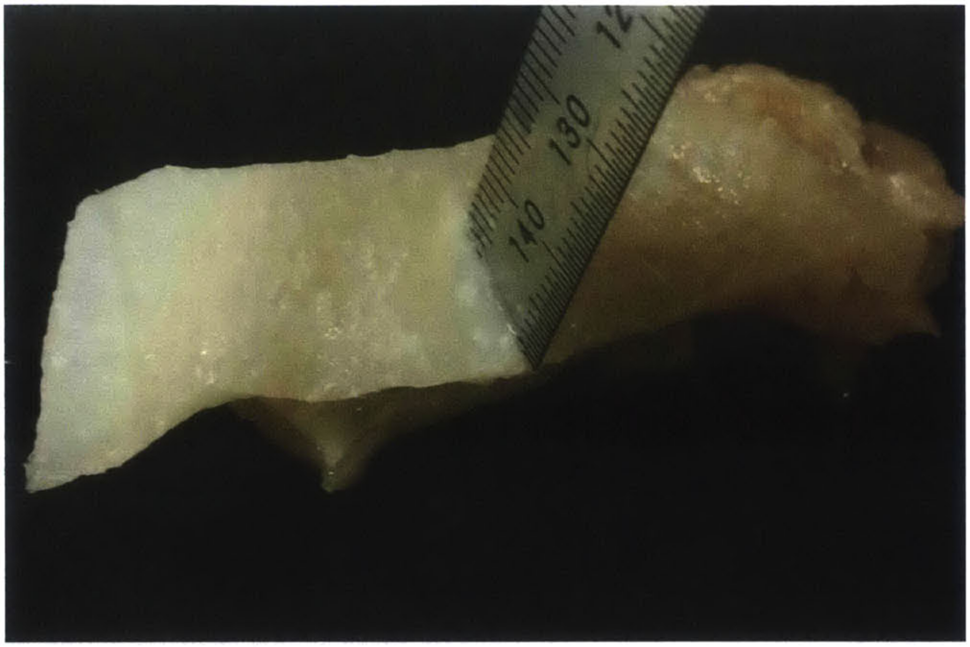

Figure 3-10: The depth of cut achieved by the water jet debridement device was measured using a ruler. The depth of cut value was accurate to 0.5 mm uncertainty

the two clips was adjusted by changing the position of clip 2. Clip 2 was fastened into position using a hex key and the tension value was recorded from the force sensor. A single cut was made in the middle of the tissue, perpendicular to the direction of skin tension, using the single nozzle debridement device.

The depth of cut achieved by the water jet debridement device was measured using a ruler, as displayed in Figure 3-10, to 0.5 mm uncertainty.

The procedure was repeated for ten different levels of tension. The tissue samples used for each case were of comparative sizes.

Figure 3-11 is the graph of the depth of cut versus applied uniaxial tension. The graph shows that as we increase the value of skin tension, the depth of cut achieved when cutting at constant pressure also increases. We can conclude that there is indeed a correlation between the tension force and the cutting efficiency of the water jet debridement device.

This experiment confirms the concept that using a skin tensioner, in conjunction with the water jet debridement device, reduces the amount of water pressure needed to achieve cuts. Less cutting pressure corresponds to less water injection into viable tissue, and consequently a better patient outcome after debridement.

The next Chapter presents the design of a tissue tensioner to be appended to the waterjet debridement device.

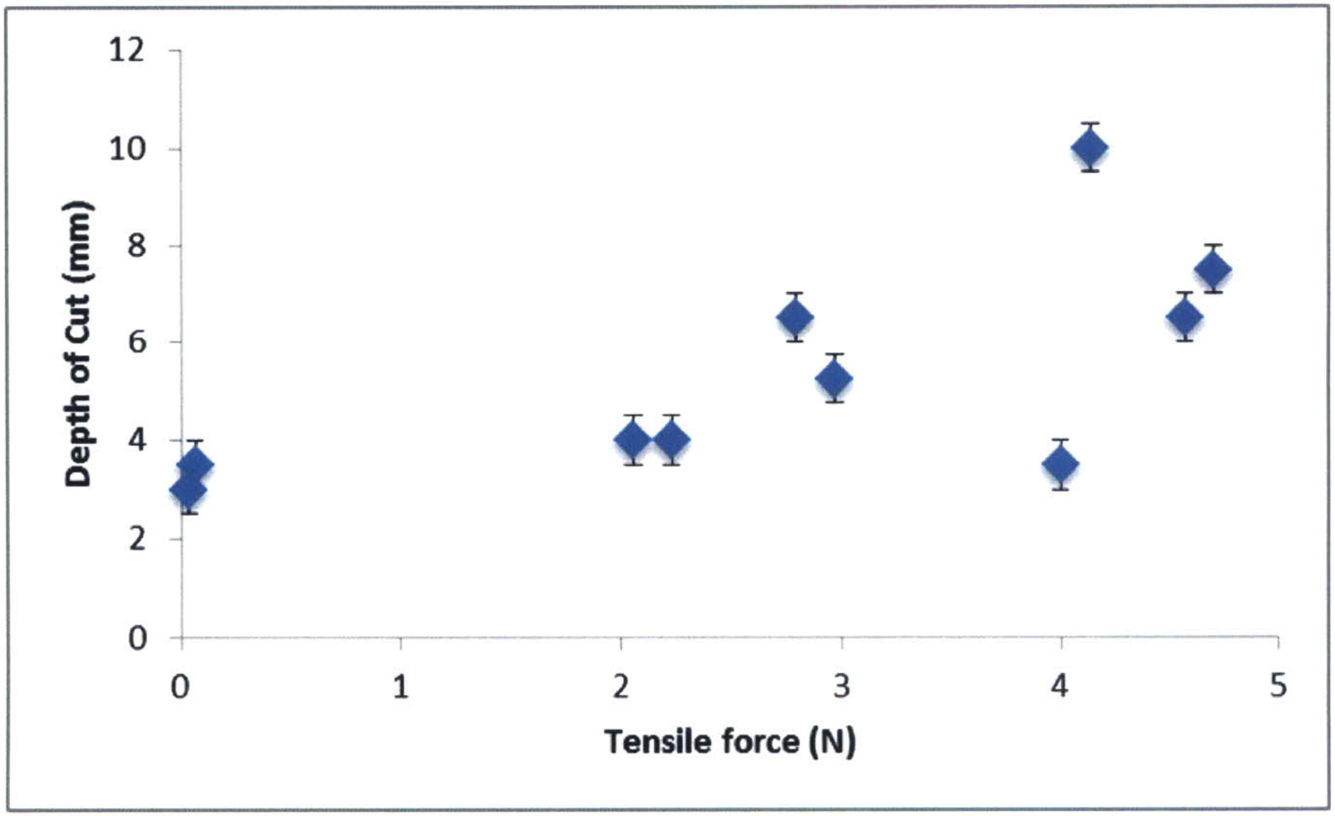

Figure 3-11: Graph of depth of cut versus applied uniaxial tension at constant water pressure P = 15 MPa

Chapter 4

Tissue Tensioner Design

This Chapter describes the design, implementation and testing of novel technology that locally tensions tissue surface prior to water jet debridement. The functional requirements driving the design of this tensioner were: providing a local tensile force, interfacing with the dual nozzle device, easy maneuverability and minimum size.

4.1 Design Concept

A wheel rolling on a soft surface applies a contact friction force. In order to maintain physical contact during the rolling motion, the wheel exerts a pull on the soft surface [33].

This concept was the governing principle behind the tensioner design. Two wheels of the same size, at an angle with each other, exert a pulling force of the same magnitude $\boldsymbol{F}$ the soft surface, as illustrated in Figure 4-1. The y-components of the forces are in opposite directions for the two wheels, hence creating a local surface tension between the wheels. A cut made with the waterjet debridement device in the area between the wheels, in the x-direction, would be facilitated by the local skin tension and hence require less cutting power.

This concept was implemented into the design shown in Figure 4-2. Two wheels, of diameter 25.4 mm, are linked together such that they are non-parallel. A compass-like component enables angular adjustment. The tensioner also includes a handle for

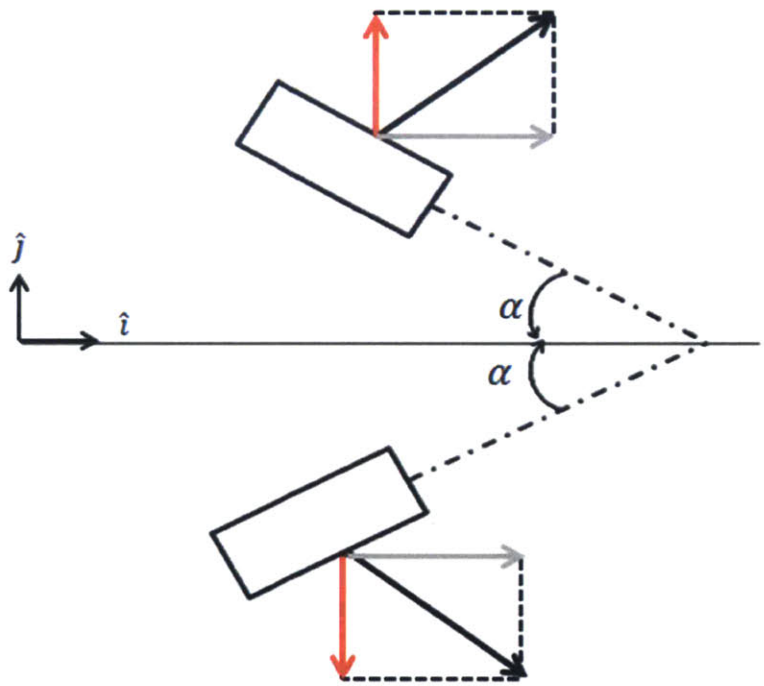

Figure 4-1: Contact force exerted by two angled rolling wheels. The black rectangles represent the two wheels. The gray arrows are the x-components of the force and the red arrows are the y-components. The y-components of the contact force are in opposite directions, hence creating local surface in the y-direction tension between the wheels in the y-direction. Note that the direction of propagation is in the positive x-direction.

maneuverability.

The initial design was able to meet all the functional requirements but one: size. In the future, the dual nozzle debridement device will be used to debride body parts that may not have much surface areas. A smaller tensioner provides flexibility and reach.

The second tensioner design, shown in Figure 4-3 is a scaled down model of the first tensioner design. The wheels dimensions were kept the same. An extruded trapezoid serves as both a chassis for the angled wheels (Figure 4-4) and a handle for maneuverability purposes (Figure 4-5). The angle between the wheels was set as 45°. This design met all the design requirements and was successfully integrated in with the dual nozzle debridement device, as discussed in the next Section.

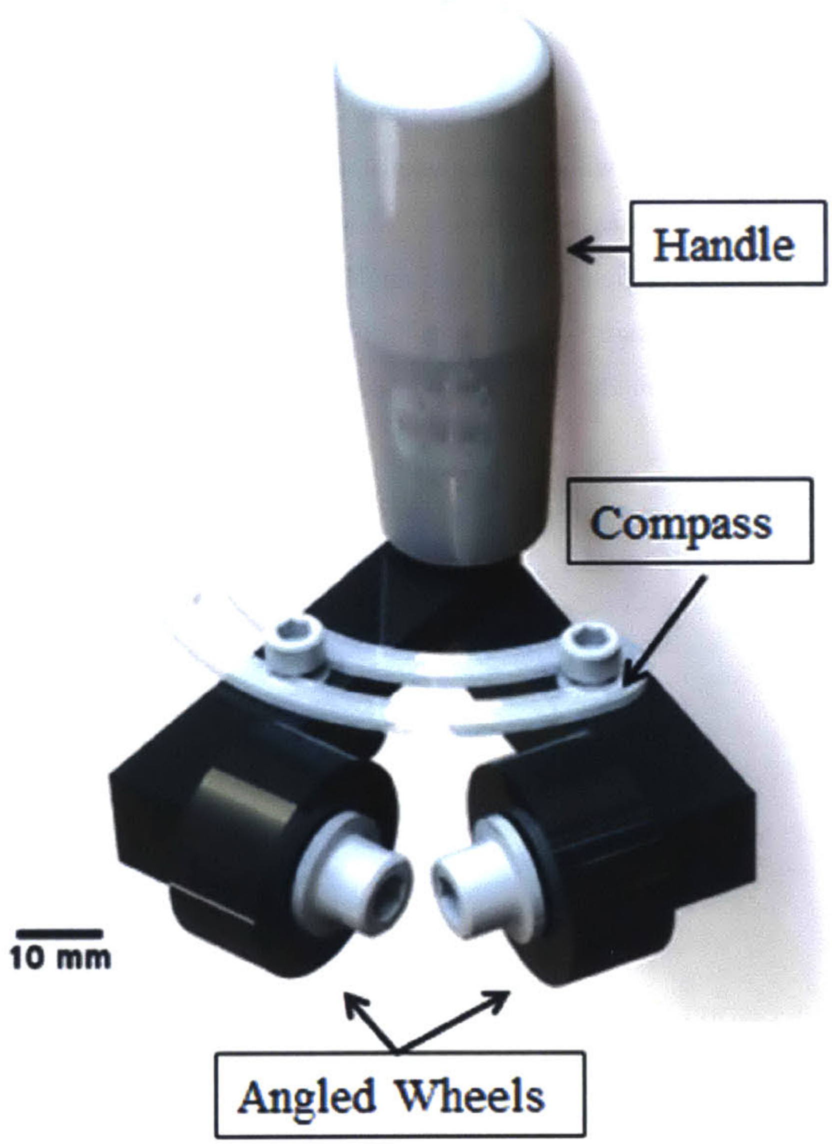

Figure 4-2: Angled wheels tensioner. Two wheels, 25.4 mm in diameter, are linked together such that their are at angle from each other. A compass-like component enables angular adjustment. The tensioner also includes a handle for maneuverability.

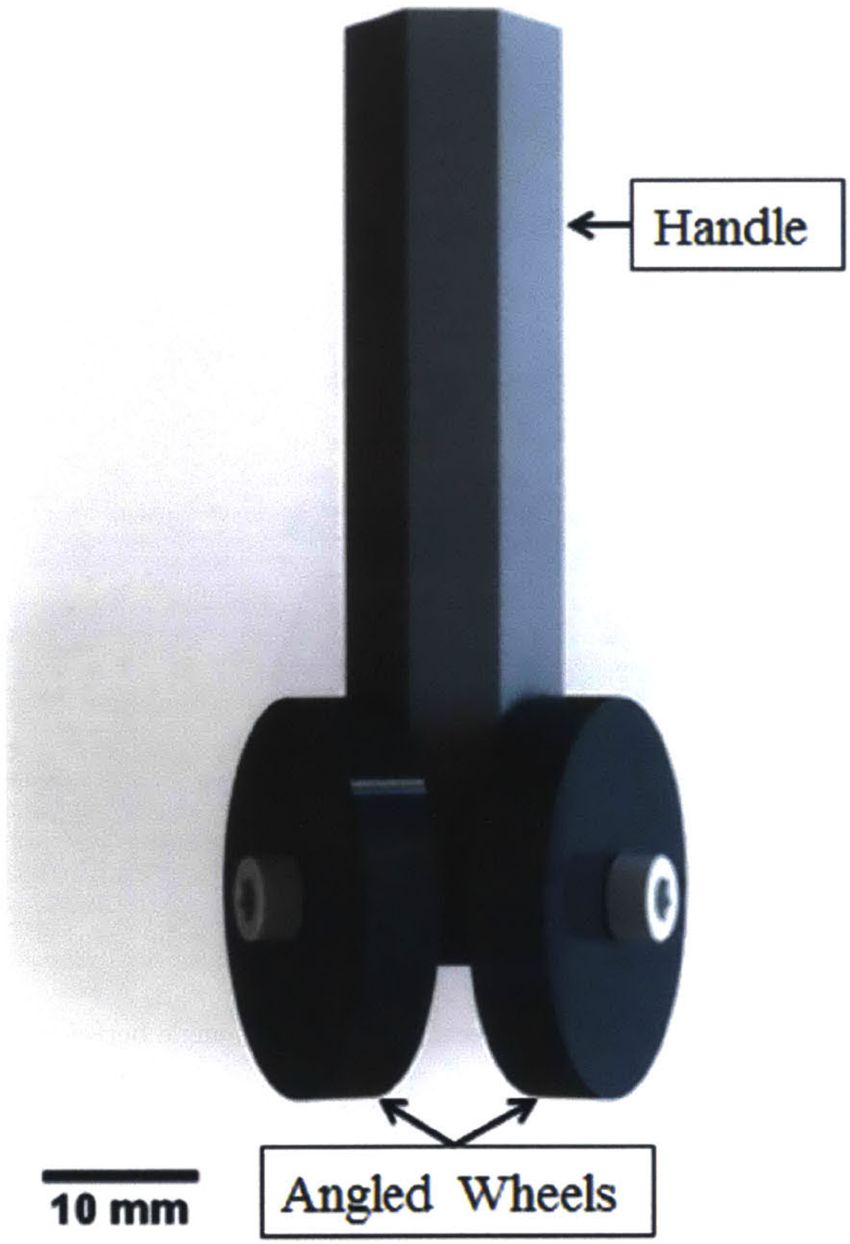

Figure 4-3: Compact Angled wheels tensioner(front view). The wheels are 25.4 mm in diameter. An extruded trapezoid serves as both a chassis for the angled wheels and a handle for maneuverability purposes

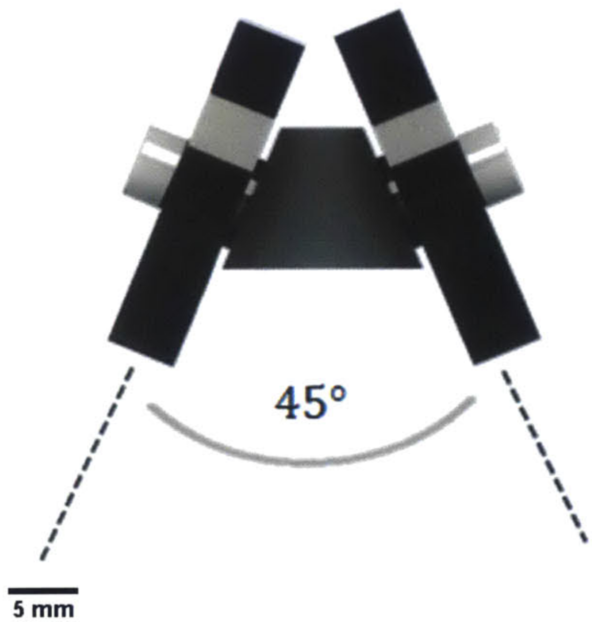

Figure 4-4: Bottom view of the Angled wheels tensioner. The angle between the two wheels is 45°

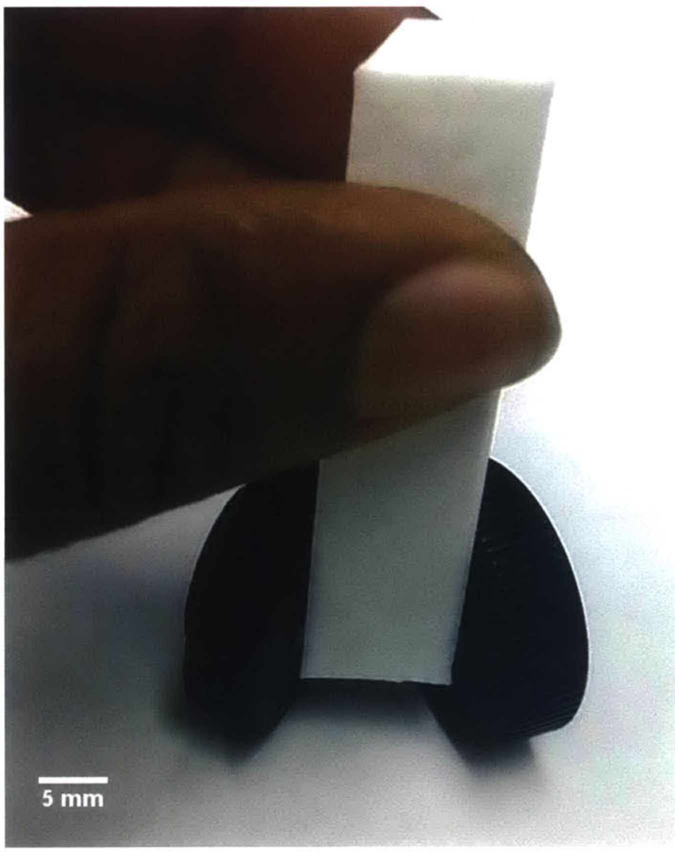

Figure 4-5: The extruded trapezoid handle enables a comfortable three-fingers grip

4.2 Interface with Dual Nozzle Debridement Device

The local tension applied by the angled wheel tensioner is maximum at the area in immediately behind the wheels. The debridement device must be positioned in such a way that the nozzles cut directly behind the wheel. This configuration is illustrated in Figures 4-6 and 4-7.

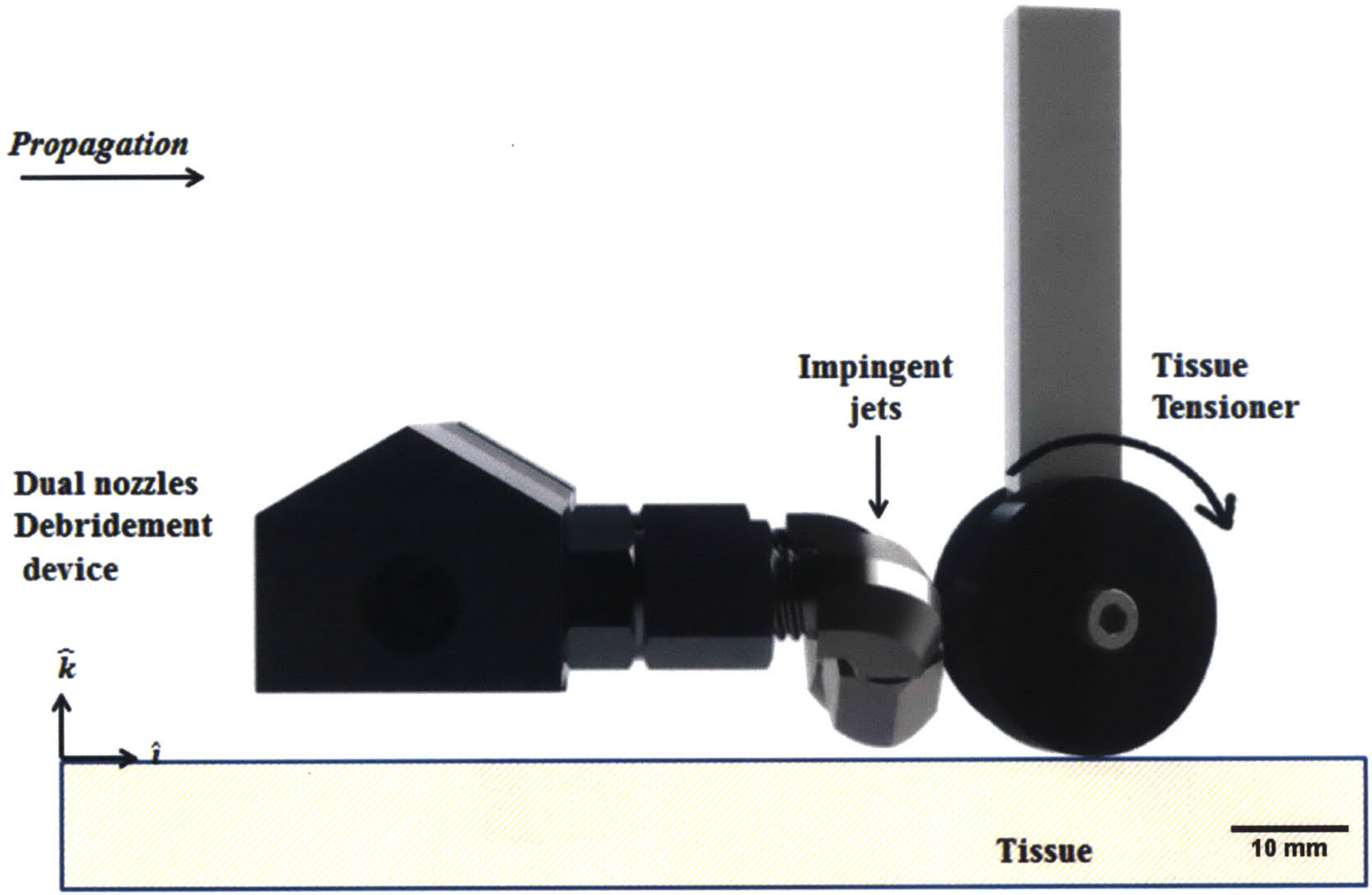

Figure 4-6: Interface of dual nozzle debridement device [1] with angled wheels tensioner(side view)

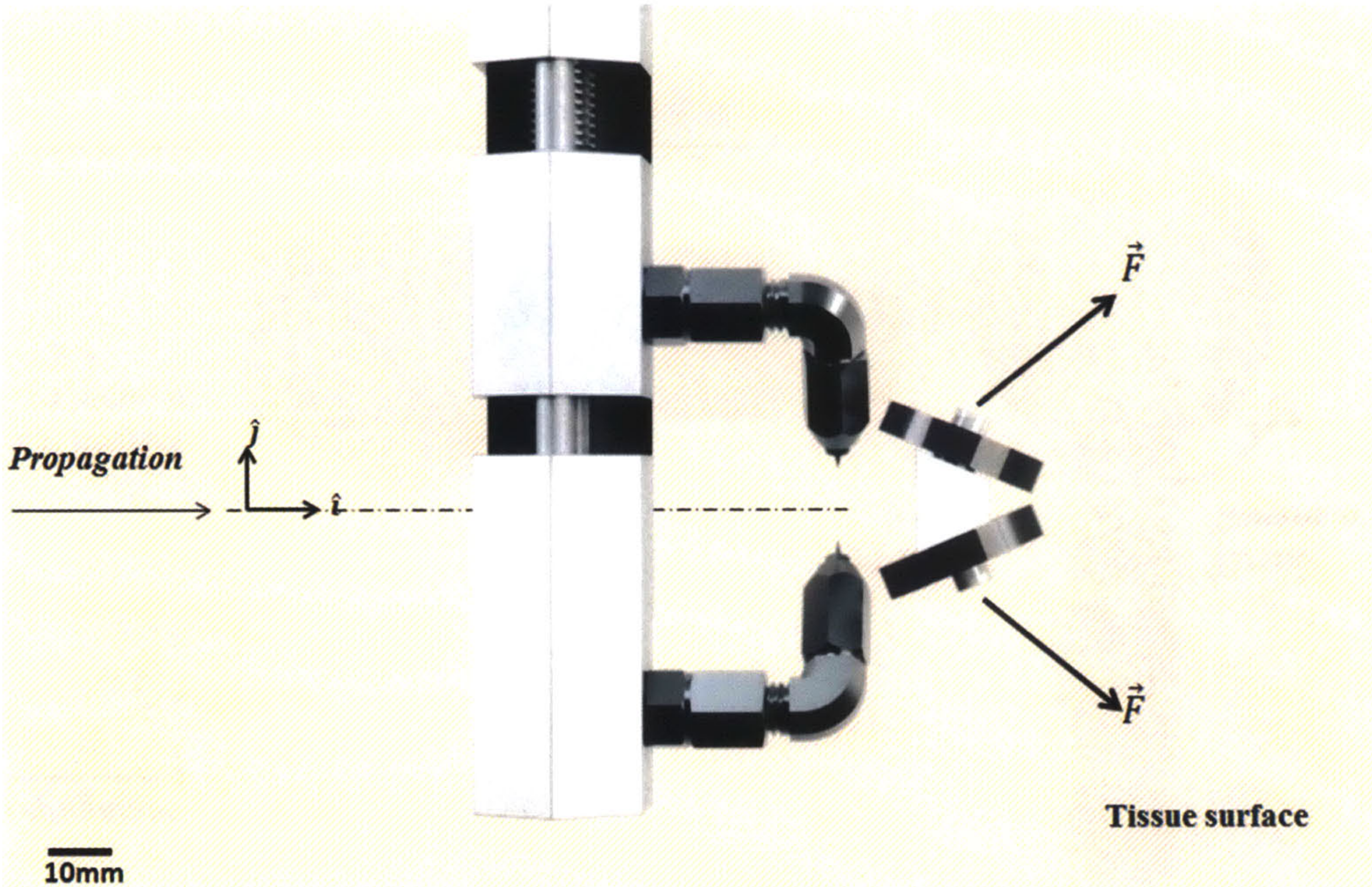

Figure 4-7: Interface of dual nozzle debridement device [1] with angled wheels tensioner(top view)

4.3 Prototype Evaluation

An qualitative evaluation of the first tensioner prototype was performed on human skin. Since both tensioner designs share key parameters such as wheel dimensions and angle, the results acquired from this test are also applicable to the second prototype.

A grid, with squares of dimensions 10 mm by 10 mm was drawn with a marker on flattest area of a subject's forearm. The tensioner was slowly rolled from one end of the grid to the other. Step-by-step photographs of the grid were taken in order the visualize the how the tensioner affects the shape of the grip lines.

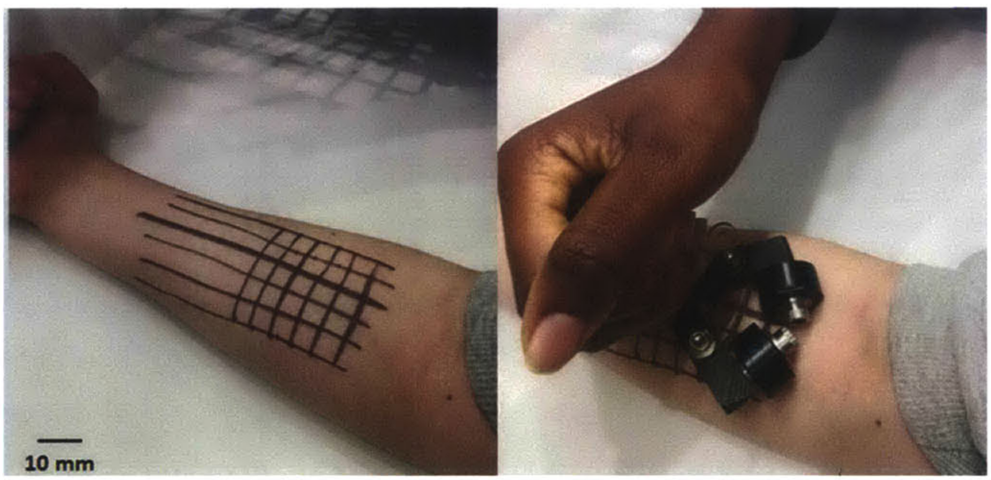

Figure 4-8: Qualitative evaluation of tensioner. A grid, with squares of dimensions 10 mm by 10 mm was drawn on flattest area of a subject's forearm. The tensioner was slowly rolled from one end of the grid to the other. Step-by-step photographs of the grid were taken in order the visualize the how the tensioner affects the shape of the grip lines.

Figure 4-9 shows four frames, right to left, of the grid as the tensioner travels from one end to the next. An observation of the white dotted lines reveals that the grid lines warp away from each other when in contact with the rolling wheels of the tensioner. This phenomenon confirms that the rotation of the angled wheels causes tension skin tension in the direction perpendicular to the direction of travel.

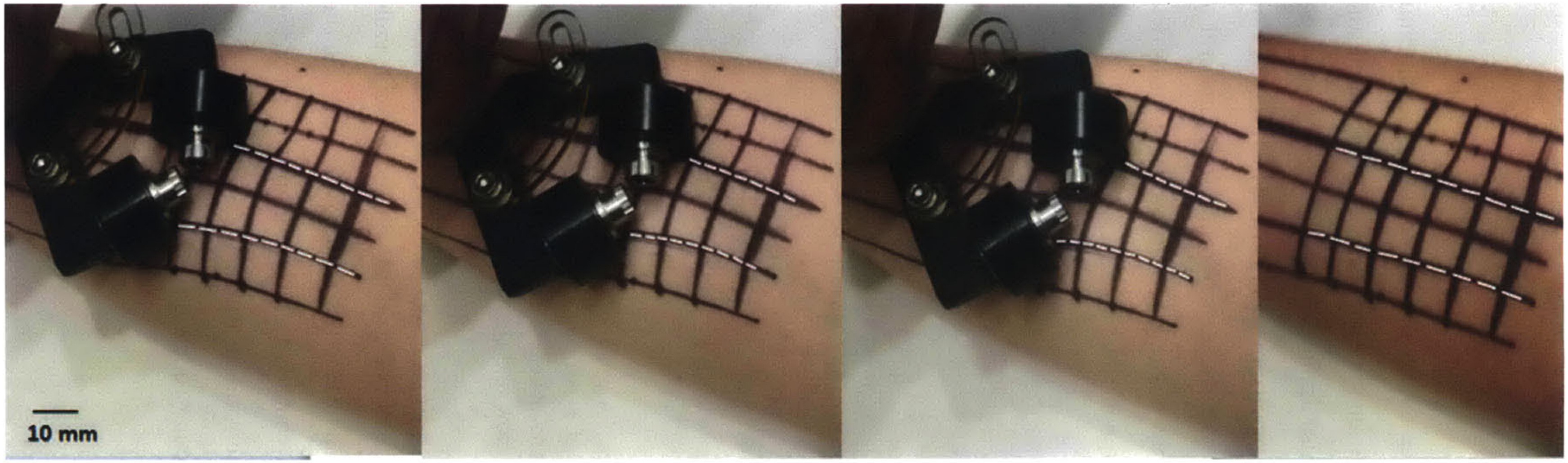

Figure 4-9: Four frames, right to left, show the effect of the rolling wheels on the grid geometry.The white dotted lines reveals that the grid lines warp away from each other when in contact with the rolling wheels of the tensioner. This phenomenon confirms that the rotation of the angled wheels causes tension skin tension in the direction perpendicular to the direction of travel.

Chapter 5

Conclusions and Future Work

In this thesis, we investigated tissue tension as a method to increase the cutting efficiency of a novel water jet debridement device, in order to reduce water injection in to into healthy tissue beneath the wound bed. We proved through experimentation that the depth of cut achieved by the water jet device is correlated with the level of tissue tension at constant cutting pressure. We confirmed the theory that applying tissue tension reduced the cutting power needed for water jet debridement. We designed, implemented and tested a technology that uses the friction from two rolling angled wheels to apply local tension to tissue at the site of cutting. This device met the functional requirements of providing a local tensile force, interfacing with the dual nozzle device, being easy to maneuver and having minimum possible size. Tested on the forearm of a human subject, the tensioner device caused straight grid lines, drawn on the skin with a marker, to warp when in the contact with the rolling wheels of the tensioner, confirming local tension tissue between the wheels. This tissue tensioner shows promise as a complementary appendage to the water jet debridement device.

Further testing is required to improve the performance of the angled wheels tensioner. A quantitative analysis should be conducted to determine the value of the local tension achieved by the rolling angled wheels.

The tensioner was only tested on antemortem human skin. Additional tests should be conducted on simulated necrotic tissue as well as other skin configurations.

The interface between the tensioner and the dual nozzle debridement device should be tested during debridement on a simulated necrotic tissue. This interface could be improved by appending the tensioner directly to the debridement device, instead of operating them as separate entities.

Lastly, debridement test should be conducted with the tensioner, using a low pressure pump. The pump used had a minimum value of 2 MPa, with a 5 MPa oscillation range. Testing with even lower level of water pressure would both quantify the contribution of the tensioner and provide a value for the minimum water pressure needed to achieve a cut.

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