Depth Control for Blind Water Jet Drilling in Bone

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Depth Control for Blind Water Jet Drilling in Bone
Analysis and Design of a Probe-Based Depth Controlled Arthroscopic Water Jet

By

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Depth Control for Blind Water Jet Drilling in Bone
Design and Evaluation of a Probe-Based Depth Control System for Arthroscopic Water Jets

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Abstract – When surgically drilling blind holes in bone using a Water Jet (WJ), control over the resulting depth is a challenging issue of paramount concern. This thesis was part of a project aimed at replacing the awl and mallet technique used in traditional microfracture procedures with an arthroscopic high-pressure WJ instrument is capable of accurately drilling 2–4 mm deep holes in subchondral bone. The focus of this paper was to develop, analyze and evaluate concepts for ensuring the depthwise accuracy of a microfracturing WJ.

Research was performed on both WJ systems and the microfracture procedure, and a thorough problem analysis detailing all concerning requirements and parameters was set up. It was determined that due to the strong non-uniformity of human bone, both spatially and between subjects, a WJ capable of monitoring the depth and implementing a closed-loop control system was needed to ensure safe and accurate drilling. To measure the depth of the hole and allow for feedback control, a flexible Nickel Titanium probe concept was devised and tested. The concept featured a 3D printed nozzle with built-in WJ orifice and depth probe, which could be extended down the hole made by the WJ by an ex-vivo actuator featuring load and displacement sensors. When the load sensor detected a sudden rise in extension resistance, bottom contact was assumed and the hole depth was calculated based on the displacement of the probe.

A proof-of-concept experiment showed the viability of using a flexible probe to measure the depth. Additionally, the algorithm produced for calculating the depth was shown to be robust against the hysteresis and backlash exhibited by the setup. When probing holes with depths of 0, 1, 2, 3, 4 and 5 mm and bore diameters of 1, 1.5, and 2 mm drilled in solid PMMA, the prototype managed an error mean of 0.00 mm with a SD of 0.19 mm. To test the probe in holes shaped as expected during microfracture surgery, a virtual interference experiment was carried out using mCT scans of WJ-drilled bones and simulated probes of varying diameters. Seven scans were probed from 4 different angles each; the results suggested that a probe with a 0.2–0.3 mm diameter was optimal in terms of traversing the hole without blockages and without risking over-penetration. Moreover, this thesis produced recommendations on carrying the project further, towards a fully integrated system capable of drilling accurate blind holes in human bone, in a closed-loop depth-controlled manner.

Index Terms – water jet, depth control, microfracture, bone drill, blind hole.

1. Introduction
In microfracture surgery, small holes, typically 2–4 mm deep and spaced 3–4 mm apart, are created in subchondral bone. The procedure is carried out by using a surgical awl and, if necessary, striking it with a mallet [1]. This method suffers from drawbacks inherent to the use of rigid and impact-driven tools during arthroscopic surgery; namely, reduced accuracy and limited reach within a joint cavity. This thesis was made as part of a then ongoing venture called the Healing Water project; its aim was to develop an arthroscopic instrument capable of creating microfractures using a Water Jet (WJ) supplied of high-pressure water via a flexible hose. This would allow for increased reach and maneuverability inside the joint cavity, as opposed to with traditional rigid tools. The background and motivation behind the project are elaborated in Appendix A.1.

Machining a workpiece by exposing it to a high-pressure WJ, eitherplain or containing abrasives, is an established technology within in a variety of industrial fields for performing tasks such as cutting, drilling, milling, peening and turning [2]. Systems that only use water, or a saline solution as is customary in clinical applications, are referred to as plain WJs and were what this project focused on. A plain WJ system features a nozzle that ejects a high-pressure jet of water through an orifice directly onto a workpiece [3]. The pressure is generated by a unit referred to as the pump. When drilling blind holes; i.e., holes that do not pierce the workpiece, the crater produced by the WJ in the workpiece is characterized by its hole depth and hole diameter as measured at the surface, see Figure 1. The main advantage of WJ machining is that it operates in a non-thermal manner [4], produces minimal workspace forces [5], can deal with otherwise difficult to machine materials [6] and is not susceptible to cutting tool degradation [5]. These advantages make the technology very attractive for a variety of surgical applications, including microfracture surgery.

This thesis focused on the technical aspects of a WJ-based microfracturing instrument with the objective to accurately control the resulting hole depth. An analysis of the problem and situation was set up and a brainstorming session was then carried out. The produced concepts were then assessed and a final prototype was designed and evaluated.
2. Problem Analysis of Water Jet Microfracturing

Because microfracture surgery formed the original motivation behind the Healing Water project, it was assumed to be the intended application of the WJ instrument. As such, details specific to the procedure were analyzed and incorporated into the design requirements. In preparation for the brainstorming session, the envisioned operating environment of a microfracturing WJ was analyzed to identify all the process parameters. Additionally, the fundamentals of WJ control were examined and evaluated for use in orthopedic blind drilling, with emphasis placed on process monitoring and control implementation.

2.1. Microfracture Surgery and Requirements

The goal of the microfracture procedure is to fix a cartilage lesion by using the body’s own mesenchymal stem cells to regenerate new cartilaginous tissue. The site of the lesion is first prepared by debriding the area and removing the underlying calcified cartilaginous layer, leaving a clean bed on the subchondral bone. Special care is given to the creation of a closed, steep and intact cartilage perimeter surrounding the cleaned site. Small holes are then created in the subchondral bone; this allows bone marrow containing mesenchymal stem cells to flow out from the trabecular bone onto the prepared site and form a regenerative clot, see Figure 2 below.

![Figure 1: A schematic of a typical plain water jet system showing its main components, including cross-sectional views of the nozzle and a hole, not to scale. The relevant process parameters and their units are given in bold.](image)

Figure 2: The microfracturing procedure. Left: holes created on the debrided subchondral bed using an angled awl. Right: the mesenchymal blood clot, which regenerates into cartilaginous tissue [9].

The physiology of subchondral bone causes that our workpiece is non-uniform, strongly heterogeneous and difficult to predict; it varies considerably between patients, as well as spatially within a patient’s bone [7]. Therefore, using a WJ to drill blind holes in bone is a substantial departure from industrial blind WJ machining techniques, where workpieces properties are predictable [8].

The developers of the microfracture technique, Steadman et al., state that the microfractures should be approximately 2–4 mm deep to allow for bone marrow bleed-through without overly compromising the structural integrity of the bone. [1]. However, Mithoefer et al. refrain from explicitly mentioning specific depth targets, stating instead that: “The release of fatty droplets from the microfracture holes indicate that the adequate depth of the microfracture has been achieved” [9]. Therefore, two acceptable approaches to drilling blind holes can be identified; holes can be drilled until either a target depth or an effect criterion is reached. In the former case, a 2–4 mm deep hole is desired, and in the latter, bone marrow bleed-through.

The preliminary requirement for the accuracy of the WJ device in terms of depth was set in line with Steadman et al. and is quantitatively defined as a maximum deviation of ±1 mm from the target. Alternatively, if bleed-through is desired, the bottom of the resulting holes should be 0–1 mm deeper than where the subchondral bed ends; i.e., the WJ should pierce the subchondral bed, but by no more than 1 mm. In both cases, a confidence interval 95% was sought.

Further surgical considerations specific to the arthroscopic microfracture procedure include limited working space and instrument diameter restrictions [8]. In consultation with experts involved with the Healing Water project, a maximum height of 5 mm was determined to be adequate. This reflects the maximum height achievable inside the joint cavity by separation of the bones. Additionally, the procedure requires that the nozzle be maneuverable inside the joint cavity. Therefore, any connections it may have to its ex-vivo ancillaries need to be flexible.

2.2. Surgical WJ Parameters and Erosion Control

A schematic overview of the envisioned WJ in its operating environment is given in Figure 3. It shows an outline of the device while drilling in bone, and lists the most important parameters involved with the process. All the parameters identified as part of the WJ microfracturing process were considered during the brainstorming session as candidates for influencing the process, or monitoring it. The latter is discussed in section 2.4.

In regards to influencing the process, certain parameters affect the effective kinetic energy of the WJ and can hence be used to control the erosive power of the system. These parameters include the water pressure, jetting duration, jet impingement angle, standoff distance, orifice size and backflow restrictions (discussed in Appendix B.2). Fundamentally, material is only eroded from the workpiece while it is exposed to a WJ of high enough kinetic energy. All else staying equal, the WJ’s kinetic energy at ejection is
a primarily function of the water pressure and the orifice size. Therefore, the resulting hole depth and rate or drilling can be controlled by modulating the water pressure, limiting the jetting duration and/or changing the orifice size. The water pressure and jetting duration can be adjusted directly via the pump and are the most effective at controlling the depth [8].

Figure 3: The features and parameters of the microfracturing WJ environment, in addition to those presented in Figure 1. The BV/TV value is the ratio between the bone volume (BV) and the total volume (TV), and is a strong determinant of the drill rate and resulting hole depth when the bone is exposed to a WJ. As with subsequent images, the WJ emitted from the nozzle Is visualized as a dark blue stroke.

2.3. Approaches for implementing Feedback Control

Open-loop predictive control is the most used control method for blind machining in the WJ industry; the process consists of predefining a jetting strategy based on information about the system and workpiece, and subsequently operating the WJ without any information regarding the real-time state of the workpiece. Real-time being defined as the period when the WJ is actively jetting. As found in a previously conducted literature study, an open-loop control system is inadequate at dealing with the perturbations and uncertainties present when using a WJ to drill blind holes in human bone [8]. Therefore, a closed-loop system that uses feedback from the workpiece state to adapt the WJ strategy is warranted. A workflow schematic showing the possible implementations of feedback in regards to WJ-based blind drilling is given Figure 4.

The feedback can occur either in real-time or iteratively. In iterative control, the desired result is approached stepwise by measuring the workpiece state during a jetting session and adjusting the subsequent jetting strategy accordingly, mitigating the need to measure the workpiece while the WJ is active. The main challenge with real-time feedback is that the measuring apparatus needs to operate in an erosive and turbulent jetting environment, and without excessively reducing the WJ’s effectiveness.

2.4. Approaches for Monitoring the Process

Any type of closed-loop control system will need to monitor the workpiece state and feed it back into a controller that adjusts the process accordingly. Ideally, a closed-loop control system would monitor the desired target-criterions directly; i.e. the hole depth or bone-marrow bleed-through.

However, in cases where this is not feasible, monitoring a strongly correlated proxy-parameter may suffice. This is the most pursued method in industrial WJ milling; here, the acoustic signal caused by the WJ on the workpiece is measured away from the jetting site, and used to estimate the depth [2;10;11].

The brainstorming session took into account all the parameters identified in Figures 1 and 3, and devised ways of using them to monitor the process. In regards to measuring the depth, it was deemed most feasible to do so directly rather than estimate it using a correlated proxy-parameter. Initial proposals using the latter approach included estimating the hole depth by measuring its width or by tracking the removed bone material. The main disadvantage of indirect approaches was that it introduced inaccuracies due to uncertainties and weakness in the proxy-parameters’ correlations to the actual depth. However, directly measuring the depth during a jetting session may prove extremely difficult and/or infeasible, which is why it is not commonplace in the WJ industry [11].

In terms of using marrow bleed-through as the target-criterion, when the assumption is made that subchondral bed penetration necessarily leads to bone marrow bleeding, indirect monitoring approaches were envisioned; when the WJ penetrates the subchondral bed, the characteristics of the backflow and the intraosseous pressure may be influenced. As such, these phenomena may lend themselves to be used as proxy-parameters to determine whether bone-marrow bleed-through has occurred, refer to Appendix B.1 for additional discussion. Methods for monitoring the workpiece state can be subdivided into two fundamental approaches; namely, continuous and binary tracking. In the former approach, the state of the workpiece is continuously measured, whereas in the latter, the system only tracks whether or not the workpiece has surpassed a predetermined threshold. Continuous feedback allows the control-
ler to constantly adjust the WJ parameters based on the depth and its derivative, i.e. the drill-rate. Although it may introduce additional complexity, a continuous tracking system allows for better controllability compared to binary systems, which can only shutoff the water jet after a certain condition is triggered.

### 3. Brainstorming Session: Depth Control Concepts and Concept Selection

A brainstorming session was carried out to produce concepts for a depth control system. All previously identified requirements, process parameters, and WJ control factors were incorporated into session to maximize the exhaustiveness of the devised concepts. Concepts for both the marrow bleed-through and hole-depth target criteria were entertained; those most meriting mention are discussed in Appendix C.

In regards to marrow bleed-through, the concepts either attempted to directly detect bone marrow in the backflow or irrigation fluid, or indirectly assume bleed-through by detecting if the WJ had pierced the subchondral bed. The latter approach relies on the assumption that the marrow pressure; i.e., the pressure inside the trabecular structure, would feature a sudden pressure spike when the WJ penetrates it. The idea was then to monitor the marrow pressure and stop the WJ when a pressure spike was detected.

Methods for determining the hole depth included using mechanical probing or optical triangulation. In the latter, a light was diffracted into the hole and the depth was determined by the characteristic of the reflected light. An visualization of the optical triangulation concept is given in Figure 5. White light is brought to the nozzle via an optical cable (not pictured) and is then diffracted into the hole by means of a prism or diffraction grating. The WJ orifice and nozzle cavity function as a collimator, only allowing vertical light into optical fiber opening on the top part of the nozzle cavity. This output optical fiber than transmits the light to a ex-vivo detector, which calculates the depth based on the color of the reflected light. The optical fiber concept is further discussed in Appendix D.1.

The mechanical probing method relied on the assumption that a probe can be lowered into the hole and is impeded when it reaches the bottom; the depth of the hole can then be calculated based on the displacement of the probe. The advantage of the probing concept was that it measured the depth directly without needing a proxy-parameter, and was mechanically simple. However, to ensure suitable efficacy when used in irregular and porous holes, as is the case for microfracture surgery, the probing concept had to overcome challenges in terms of probe placement, shape, rigidity and thickness. Several probe-based concepts featuring a variety of mechanisms and control methods were devised and evaluated. Rigid, flexible, vertical and tilted probes, and continuous and binary systems, were all entertained, producing several novel and promising concepts; discussed in Appendices D.2 and D.3.

![Figure 5: The optical triangulation concept. After a short water jetting session (a), white light is introduced into the nozzle head via a fiber optic cable (not shown) and diffracted into the hole, angularly spreading its color spectrum (b). The water jet orifice and nozzle cavity act as a collimator for the reflected light, only allowing vertically reflecting into the optical fiber which leads to an ex-vivo detector. As such, the color reflected from the bottom of the hole varies with its depth (c) and (d), and can be used to calculate the depth.](image)

A WJ’s internal dynamics can be simplified as a three-way relationship between the water pressure, the water flow, and the orifice size [12]. If the pressure is kept constant, increasing the orifice size, increases the water flow, and vice versa. One probe-based concept, henceforth the Flow/Pressure concept, exploited this phenomena and managed to measure the hole depth using a mechanism in the nozzle head that proportionally opened a pressure relief port based on the hole depth. This allowed the ex-vivo system, which featured a flow and pressure sensor, to measure depth, without needing any auxiliary connections to the nozzle head other than the water hose. The concepts feature a pressure operated valve that selects between two modes: probing and jetting. The pump is then set to maintain a pressure which corresponds to those modes. At a low pressure level, the valve leads the water towards the sprung probe, which is then pushed down into the hole while opening a release port. This increases the water flow, which can then be used to calculate the depth. When the pump is set to maintain a high water pressure level, the valve diverts the water away from the probe and towards the WJ orifice, activating the WJ. This causes a pressure drop on the sprung probe, causing it to retract and preventing any interference issues between the probe and the WJ. The concept is visualized in Figure 6, refer to Appendix D.3 for additional details.
A selection process was carried out to choose one final concept to be developed into a prototype. Criteria for the final concept were: functionality, in terms of features or lack thereof; safety, in terms of failure modes and effect; general application, i.e., its applicability for techniques other than microfracture surgery; pragmatism, in terms of realizing a prototype within the project’s timeframe and budget; and, limitations, in regards to potential pitfalls that might prevent the concept from functioning. The flexible pin concept had the highest overall score and was further developed into a prototype, the selection process in detailed in Appendix D.4.

4. Flexible Pin Prototype Design

The flexible probe concept featured a nozzle head with a WJ orifice and integrated probe tunnel, an actuator to move the probe, and load and displacement sensors that detect bottom contact and measure the depth. The system can then be integrated with the pump via a controller, enabling it to drill holes in a closed-loop manner. The complete setup of the flexible probe concept is visualized in Figure 8. The system works as follows:

1. The probe is in a retracted position inside the nozzle head.
2. A short duration WJ is used to drill a small hole.
3. The servo motor extends the probe out of the nozzle body towards the hole.
4. The position of the probe and the force needed to push it are constantly tracked
5. When the load sensor measures a sudden rise in resistance, it assumes the bottom has been contacted by the probe. This is called the trigger event and it occurs when the load exceeds a preset threshold.
6. The position of the probe at the bottom contact event minus the position of the probe when it touches an undrilled surface is the hole depth.
7. The probe is then retracted back into the nozzle body.
8. If necessary, the process is repeated.

One iteration of the abovementioned process was envisioned as occurring rapidly, with each iteration taking less than 4 seconds.

Figure 6: The Pressure/Flow concept. During probing mode, the pump maintains a steady low water pressure, which pushes the sprung probe down into the hole as it opens a release port. The port, which opens proportionally to the depth, increases the water flow (top left and bottom left). An ex-vivo sensor then measures the flow and calculates the hole depth. At high pressure, the valve is pushed so that it redirects water towards the WJ orifice; the jetting mode is then activated and the sprung probe retracts (bottom right). Top right shows a close up schematic of the valve system.

One disadvantage of using a rigid probe is the maximum probing depth is limited to the height of the probe. To address this, a concept featuring a flexible probe was devised. In the envisioned device, a flexible probe is guided into the nozzle head via a sleeve adjacent to the water hose. Once in the nozzle head, a tunnel bends the probe towards the hole so that it intrudes into it when extended. A visualization of the concept is given in Figure 7.

The proposal consisted of having the system operate in an iterative manner by quickly alternating between probing and jetting until the desired depth is reached. The main potential pitfalls of the flexible probe concept were identified as buckling and friction; the probe needs to traverse a sharp bending angle which might cause considerable friction and/or deformation. Additionally, a probe that is not rigid enough it may buckle when extended, preventing system form correctly determining the depth.

Figure 7: The iterative flexible probe concept. Left, the probe (thick black line) is retracted inside the nozzle head while the WJ is active. Right: the probe is extended into the hole until it reaches the bottom, the depth is then calculated based on the probe’s displacement. The process is then repeated as necessary.

Figure 8: Schematic visualization of the total Flexible Probe controlled depth WJ system, not to scale. Note that the probe sleeve, the displacement sensor and the linear actuator are connected to the mechatronics housing. The actuator moves the load sensor, which is connected to the probe.
4.1. Preliminary Calculations and Indications

Due to the maximum height requirement of 5 mm for the nozzle head, the probe needs to traverse a bend with a radius of approximately 3–4 mm. The feasibility of this concept relies on the flexible probe’s ability to transmit compressive force back to a sensor while bent. The probe should have high elasticity and resilience; a search for a mechanically adequate and biomedically compatible material yielded super-elastic austenitic Nickel Titanium as the best candidate, henceforth NiTi [13].

Assuming a 1 mm standoff distance and a hole depth of 4 mm, the length that the probe needs to span without buckling is 5 mm. At the cost of gross oversimplification, a preliminary set of calculations was performed to give an indication of the forces involved. The calculations are further elaborated in Appendix D.2. To calculate the buckling force, the probe was modeled as having a 0.3 mm diameter, a Young’s modulus of $E = 80$ GPa [13], a fixed end at the nozzle, and a pinned end at the hole bottom. Using the buckling force equation for an ideal cylindrical column, the maximum compressive force that the probe can transmit while spanning 5 mm was calculated at 25.6 N. This is considerably higher than our intended working range of between 1–5 N, suggesting that buckling may not necessarily be a problem, in and of itself. The elastic probe also needs to be bent approximately 90 degrees by the tunnel; using the formula for distributed load bending, the necessary load was calculated at 13.5 N, which reflects an indicative approximation. Figure 9 (a) and (b) show how the tunnel bending the probe was modeled. The coefficient of friction was assumed to be $\mu = 0.3$, which is a conservative estimate for a lubricated metal probe in a metal tunnel, or metal probe in a plastic tunnel [14]. As a result, the total friction produced by the force needed to bend the elastic probe was calculated at 4.1 N, visualized in Figure 9 (c). This suggests that it takes approximately 4.1 N to push the probe through the tunnel. Additional friction is introduced when opposite force is applied at both probe ends; e.g., when the probe is pushed through the tunnel and comes into contact with a surface. The perpendicular forces acting on the probe cause reaction forces in the tunnel, which then produces friction. The reaction forces and capstan friction are visualized in Figure 9 (d) and (e), respectively. The friction was approximated using the capstan equation for an angle of 90 degrees and again using $\mu = 0.3$. The trigger value was set indicatively at 5 N, just above the expected 4.1 N force that the load cell will read while pushing the probe through the bend. It was assumed that when the load cell read the trigger value, the probe exert a force on the workpiece which is equal to the trigger value minus the sum of bending friction and capstan friction. The capstan equation for a 90 degree bend is:

$$F_{\text{out}} = F_{\text{in}} \times e^{-\mu s} = F_{\text{in}} \times 0.62 \quad \text{(eq.1)}$$

As the probe is pushed through the tunnel, it was assumed when the trigger event occurs, the friction associated with the tunnel bending the rigid probe can be subtracted from the trigger value force, and the remaining force is subject to capstan friction. As such, the force exerted on the workpiece was calculated at 0.56 N:

$$F_{\text{out}} = (5 - 4.1) \times 0.62 = 0.56 \text{ N} \quad \text{(eq.2)}$$

This corresponds to a pressure of 7.9 MPa for a probe with a diameter of 0.3 mm. This pressure is substantially within the allowable limits for the solid subchondral bone and the trabecular bone underneath, both of which can withstand indentation pressures upwards of 1 GPa [15].

![Figure 9: An overview of the assumptions made to model the forces of the tunnel on the probe. The thick black line represents the probe and the tunnel is visualized by the light blue figure with dotted outline. The tunnel exerts a distributed normal force (a) on the elastic probe to bend it (b), modeled as a cantilever beam. When the probe is pushed through the tunnel, the normal force causes friction (c). When both the probed surface and the actuator exert perpendicular forces on the probe, a reaction force is applied to the probe by the tunnel (d). This creates an additional friction (e).](image-url)

A preliminary test supported earlier suspicions that repeatedly pushing a NiTi probe through a bent tunnel will cause it to curve. A 0.4 mm NiTi probe was repeatedly pushed through a bend with a radius of 3 mm until the acquired curvature remained stable. As expected, deformation occurs only at the section that traversed the bend, with the strongest deformation occurring in the middle of that section. The acquired curve had a radius of approximately 15 mm, at the sharpest section. The acquired curvature was approximately the same when the test was repeated for using 0.2 and 0.3 mm diameter NiTi probes. It was noted that once curved, the probe cannot be un-curved by simply turning it 180 degrees and again sliding it through the bend. Instead, the elastic probe tended to twist to facilitate the acquired curve; i.e. it “snapped” back to the angle where the acquired curvature best fit into that of the tunnel. Figure 10 shows a 0.4 mm probe after curving. This acquired curvature was taken into account in the subsequent stages of the prototype design. In addition, the concept of rotating the probe about its own axis while extending it through the bent tunnel to prevent it from curving merits mention.
4.2. Final Design for the Flexible Probe Concept

As detailed in Appendix E, two design iterations led to the final prototype, which featured two separate high- and low-pressure sections for the WJ and probe, respectively. This would allow the low-pressure section, which also functions as the housing, to be printed in 3D using materials unsuitable for dealing with high pressures. This facilitates production and permits the inclusion of complex internal features, such as the probe tunnel with a complex 3-dimensional bend.

The coupling between the high-pressure nozzle and water hose is based on a design produced and tested by another Healing Water projects. The nozzle features a rigid and hollow “plug” that is inserted into the hose and clamped in. The prototype is designed to incorporate this rigid plug into the dimensions of the nozzle head, allowing for the water hose protruding from the nozzle head to be fully flexible. A hollow probe sleeve with an internal diameter slightly larger than the flexible probe, and running alongside the water hose, functions to guide the probe between the in-vivo nozzle head and ex-vivo ancillaries. The sleeve prevents the probe from buckling when transmitting compressive forces and, along with the water hose, provides reaction forces to the nozzle head when needed; i.e., they hold it so that it doesn’t get pushed away when the probe is forced through the bend and vice versa for probe retraction. The nozzle head has a height of 5 mm and a width of 6 mm, mainly due to the dimensioning of the coupling. The dimensions of the coupling and nozzle are given in Figure 11 and a schematic overview of the dimensions is presented in Figure 13.

The high-pressure nozzle and plug were made from turned stainless steel and featured an internal waterway with a bore diameter of 1.1 mm. To maximize the proximity between the WJ and the probe, the WJ orifice was positioned as off-center as possible in the nozzle, visualized in Figure 12. In addition, the bottom of the nozzle cylinder was flattened to maintain a symmetrical exit orifice.

In the design, the high-pressure nozzle sits inside a nozzle head housing that features a tunnel that guides the probe towards the hole. The flexible probe enters the nozzle head adjacent to the water hose and out-of-plane with the WJ. Therefore, aiming it down the hole requires a tunnel with a non-planar three dimensional curve. This bend was designed by approximately projecting two \( r = 3 \text{ mm} \) curves onto each other. It was previously determined that a NiTi probe acquires a planar curvature of 15 mm when repeatedly pushed through a planar bend of 3 mm. This curvatures is incorporated into the placement of the probe tunnel. It was assumed that each time the probe exits the nozzle head, it reacquires a three dimensional \( r = 15 \text{ mm} \) curve. Similarly to the probe tunnel, this acquired curve was modeled by projecting two \( r = 15 \text{ mm} \) onto each other. Figure 14 illustrates the desired dimensions of the probe and visualizes its curvatures when inside and outside of the nozzle head. The final design of the nozzle head, including its main dimensions and a visual rendering, is shown in Figure 15.
The final prototype design features a probe that curves with an angle of \( r = 15 \text{ mm} \) as it exits the tunnel. As such, a small error is introduced when measuring the depth, visualized in Figure 17 (left). The expected error caused by the probe curve, as dimensioned in the prototype design, is plotted against the hole depth in Figure 17 (right). The error is a function that, for holes 0–5 mm deep, satisfies the third order equitation:

\[
y = 0.0008x^3 - 0.0065x^2 + 0.0188x \\
\text{(eq. 3)}
\]

Therefore, a third order correction function is needed to correct the error associated with the probe curvature.

4.3. Back-end Design

The mechatronic section of the system was to be controlled by a LabView program that reads the sensors, performs calibrations, calculates the depth and operates the probe. The design of the process required that before the depth can be measured, a calibration procedure has to take place. First, the zero position needs to be determined; i.e., the probe position which corresponds to the probe touching the undrilled surface of the workpiece. Once the probe is in contact with the workpiece surface, it is extended further until the load cell measures a force which exceeds the preset threshold, activating the trigger event. The probe position corresponding to the trigger event minus the zero position is the probe play; i.e., the extra distance the probe needs to be pushed to generate the trigger force after it has contacted a surface. The reasoning behind determining a probe play prior to measuring the depth is to account for possible elasticity and hysteresis in the system. During a WJ-microfracture procedure, the nozzle head is fixated in the joint cavity by being sandwiched between the debrided subchondral bed and the opposing articular cartilage, which features compressive elastic properties [16]. When the probe extends down and out of the nozzle head, it causes the nozzle head to push against the opposing articular cartilage, possibly deforming it before a trigger event can be detected. Additionally, the probe, sleeve, and mechatronics section may feature elasticity, hysteresis and backlash. The magnitude of the play caused by these parameters is a function of the state of the system, its operating environment, and the shape in which the flexible sleeve.
is held. Therefore, calibrating the probe before each use may be warranted when a high degree of accuracy is required. When measuring the depth, the probe is extended into the hole until the load cell measures a force which exceeds the preset threshold. The corresponding probe position minus the sum of the zero position and the probe play is the hole depth.

For the subsequent experiments, a LabView (version 11.0.1, National Instruments) console was created to control the probe extension and calculate the depth. Because the probe was advanced manually in the setup described in section 5.1, the program featured a manual mode which alerted the user when to stop turning the manual extension wheel. This was done via a text display, a visual signal and an auditory signal.

5. Proof of Concept Experiments

As proof of concept for the probing system and the LabView controller, three experiments were carried out: (a) Pilot Experiment, to assess the system and produce preliminary data; (b) Experiment 1, to produce data on the system’s accuracy and precision when probing in a solid workpiece; and (c) Experiment 2, to produce data when probing in a porous workpiece that mimics trabecular bone.

5.1. Flexible Probe Testing Set-up

To expedite the experiment, the decision was made to use an existing desktop universal testing machine as the concept’s mechatronic section. The testing machine featured all necessary sensors but lacked a suitable servo motor. Instead, the probe was advanced manually. The total setup featured the testing machine, a 15 cm probe sleeve and a stainless steel probe tunnel curved in accordance to the prototype dimensions. The probe was connected to a load cell (Model: FLB3G-C3-50kg-6B, by Zemic) and linear displacement meter (Model: LCTF 2000, by Schaevitz). The set up is pictured in Figure 19 and Figure 20. The probe sleeve featured a $r = 15$ mm bend in the middle. This bend is representative of the approximate maximum bending the sleeve will encounter as a result of the anteroposterior curvature in the human femoral condyle, found on the medial condyle, which has an average radius of 18.71 mm and a SD of 2.2. radius [17].

A clear acrylic workpiece with predrilled holes of known depths was created to test the system under ideal conditions; namely, in a solid workpiece with uniform cylindrical holes. The holes had diameters 1, 1.5 and 2 mm and depths of 1, 2, 3, 4 and 5 mm, making a total of 15 holes. In addition, surface measurements were performed; i.e., probing ‘holes’ with a depth of 0 mm. The abovementioned hole dimensions were representative of the spread of the dimensions of the holes created during WJ-based microfracture surgery [18]. To produce a clear representation of the accuracy and precision of the system when probing holes of unknown widths, data analysis was performed on the total population of equally distributed holes; i.e., equal amounts of measurements were performed for all hole types, and the all samples were jointly analyzed. In addition, accuracy and precision data was produced for each hole diameter to give an indication of the effect of this parameter on the measurement error.

Figure 18: Top: the user control panel of the LabView program. Bottom: the graph on the control panel, which plots the path of the force/position curve. The shape of the curve is from the pilot experiment and further elaborated in Figure 23. The horizontal axis of the graph shows actuator position, because of the way the system is set up, a decrease in actuator position denotes an extension of the probe. The vertical axis shows the force on the load cell. A green horizontal line shows the trigger force, in this case it is set to 4 N. The graph traces the progression of the position/force curve until the user clicks reset, the current position/force state is given by the white circle. The red vertical line shows the zero position and the teal line shows the position at where the bottom of the hole was calculated.
The clear acrylic workpiece was used in the Pilot Experiment and Experiment 1. For Experiment 2, a second workpiece featuring the same collection of holes was made in porous PMMA, which is a solid foam intended to mimic the structure of trabecular bone. Note that the actual depths of the drilled holes vary slightly from the reference depths due to machining inaccuracies. The actual resulting hole depths are referred to as the true depths, and were measured using a depth caliper with a 1 mm diameter probe. The workpieces and true depths are discussed further in Appendix 0. The proof of concept experiments were all carried out using a probe with a diameter of 0.4 mm.

The existing manual universal testing machine was used as the concept’s mechatronics section. Note the sign convention used for probe displacement; extension is negative and retraction positive. The probe sleeve is 15 cm long and features a r = 15 mm bend in the middle.

5.2. The Pilot Experiment

A pilot experiment was performed to test the system, make necessary tweaks, and determine if the system suffers from a non-linear relationship between the probe extension and hole depth, in addition to the error caused by the probe curvature. To account for the non-linearities, a correction formula as a function of probe extension was devised. The decision was made to model the system as a blackbox and determine the correction formula empirically. This was done by performing 80 measurements; each hole and surface were probed 5 times, and the errors were subsequently calculating by subtracting the probed depths from the true depths. The error cloud appeared to show a bathtub-like distribution and a third order polynomial was fitted to it, as suggested by the curvature error formula. This equation was then used in experiments 1 and 2 to correct the measured depth and its added value in terms of error reduction was assessed. It should be noted that a third order fit produced approximately the same curve as a second order fit, and, as became apparent after experiments 1 and 2, did not enhance the error correction power of equation. Polynomials of forth order and above did not improve the fit in terms of R² and were very sensitive to outliers.

Although the error may correlate to the hole width, the correction formula cannot be a function of the width because the controller does not have access to that information when probing. The depth errors and the fitted curve are given in Figure 21.

![Figure 19: Schematic showing the testing setup (not to scale). An existing manual universal testing machine was used as the concept’s mechatronics section. Note the sign convention used for probe displacement; extension is negative and retraction positive. The probe sleeve is 15 cm long and features a r = 15 mm bend in the middle](image1)

![Figure 20: Top: the testing machine, workpiece and nozzle holding structure not shown. Bottom left: the nozzle head mock-up, which features a probe tunnel embedded in modeling clay; note that the probe is extended. Bottom middle: the nozzle head with retracted probe. Bottom right: the foam (top) and solid (bottom) PMMA workpieces.](image2)

![Figure 21: Results from the Pilot Experiment showing the depth errors plotted against the hole depths and the fitted polynomial curve. For visual indication, the errors are plotted separately for measurements on holes of different widths and undrilled surfaces.](image3)

The pilot experiment depth measurements had an uncorrected error mean of $\mu = -0.02$ mm and a SD of $\sigma = 0.18$ mm, across all measurements. It was observed that the system experiences strong hysteresis and path dependence, but nevertheless achieves a considerable degree of accuracy and precision. A graph showing the progression of the displacement of the probe and the force on the load sensor when probing a hole is given in Figure 23. It was also observed that under normal operation an overshoot occurs in the measured force, with peaks up to 8 N. However, the maximum force on the workpiece during probe contact was approximately only 2.5 N. The overshoot was largely due to the delayed stopping of the probe extension by the human operator. Additional experimentation performed during the Pilot Experiment showed the presence of veloci-
ty dependent stick-slip. Slowly extending the probe introduced jitter in the measure load, graphed in Figure 22. In experiments 1 and 2, care was taken to extend the probe without causing any stick slip and a steady extension and retraction speed of approximately 2 mm/s was maintained.

Figure 22: Fast and smooth probe extension (left) compared to slow probe extension featuring stick-slip (Right).

Figure 23: The position/force curve traced by the displacement and load sensors when probing a hole once. Note that in the force/position graphs, a positive force denotes the actuator pushing the probe and a negative force denotes the actuator pulling back the probe. At the starting point, the probe is in a retracted position inside the tunnel. When the probe is extended, the previously built up retraction force is alleviated until it becomes a pushing force. This happens at the push/pull transition. After the probe passes the zero position (Figure 23, red line), it enters the hole and is pushed down with a fairly constant force, approximately 3 N. However, when it comes into contact with the bottom, the force rapidly increases. When the force exceeds the trigger force (Figure 23, green line at 4 N) it produces a trigger event and the hole depth is calculated. Note that the depth position (teal line) does not correspond to where the trace passed above the green line, this is due to the "probe play" issue described previously. The depth of the hole is the difference between the red and teal lines.

5.3. Experiment 1: Probing in Solid PMMA

In Experiment 1, each of the fifteen holes in the acrylic workpiece described previously and an undrilled surface were probed five times consecutively. This was repeated three times with a calibration step performed before each round. In total, 230 measurements were done on holes with 0, 1, 2, 3, 5 mm depths and 1, 1.5, 2 mm widths. The goal was to gather comprehensive data on the accuracy and precision of the system and test the correction formula empirically determined in the pilot experiment. Without any compensation or removal of outliers, the system achieved a mean error (µ) of 0.00 mm and a SD (σ) of 0.19 mm, across all measurements. The empirically determined correction formula produced in the Pilot Experiment reduced the SD to 0.15 mm, but increased the mean error to 0.02 mm. The results are tabulated in Table 1. The histograms for the uncorrected and corrected errors, plotted in Figure 24, give a visual indication of how the error correction formula affects the error, showing a reduction in extreme errors and an agglomeration around zero error.

Table 1: The mean error (µ) and standard deviated (σ) of the Experiment 1 results, with and without correction (mm).

<table>
<thead>
<tr>
<th>Measurements on:</th>
<th>Uncorrected:</th>
<th>Corrected:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>µ</td>
<td>σ</td>
</tr>
<tr>
<td>Undrilled surfaces:</td>
<td>0.00</td>
<td>0.11</td>
</tr>
<tr>
<td>1 mm diameter holes:</td>
<td>0.01</td>
<td>0.14</td>
</tr>
<tr>
<td>1.5 mm diameter holes:</td>
<td>-0.03</td>
<td>0.22</td>
</tr>
<tr>
<td>2 mm diameter holes:</td>
<td>0.03</td>
<td>0.20</td>
</tr>
<tr>
<td>All measurements:</td>
<td>0.00</td>
<td>0.19</td>
</tr>
</tbody>
</table>

Both the uncorrected and corrected errors showed negative skew (z-values of -3.8 and -3.1, respectively). In the Kolmogorov-Smirnov normality test, both sets were significantly non-normal, with p < 0.01 and p < 0.03, for the uncorrected and corrected errors, respectively. As such, the data was corrected to allow for parametric statistical analysis. First, all errors were made positive by adding a constant which raised the minimum error to 1. Subsequently, the data was reflected and transformed using log base 10. This reduced the skew z-values to 1.48 and <0.01, for the uncorrected and corrected errors, respective, which is within acceptable limits for clinical research of this sample size [19]. The non-normality in regards to kurtosis was insignificant for all cases. Refer to Appendix F.4 for further details regarding the results.

The corrected data was used to test the significance of the difference between the uncorrected and corrected errors. An F-test and t-test were used to test the differences in variances and means, respectively. Both the increase in precision (p < 0.01) and the reduction in accuracy (p < 0.01) turned out to be significant.

The true depths varied slightly between holes drilled to the same reference depth, preventing proper use of a two factor ANOVA to test significance of the effect of the hole depth and width on the error. In terms of true depth alone, its effect on the error was shown to be significant, for all three widths (three single factor ANOVAs: p < 0.01 in all cases). This significance difference in the error as a result of the depth further supports the use of a correction function.
5.4. Experiment 2: Probing in Trabecular Foam PMMA

Experiment 2 mimicked experiment 1, except for the workpiece material. The results from Experiment 2 are tabulated in Table 2 and show that probing in a porous workpiece has a considerable impact on the accuracy of the device, compared to probing in a solid workpiece, as was the case in experiment 1. This is especially true when probing a 1 mm wide hole, where the error spread was considerably larger than for all the other holes. Across all holes, the measurements had a mean error of 0.26 mm with a SD of 1.31 mm. The correction formula lowered the error to a mean of 0.15 mm with a SD of 1.18 mm. If the results of the 1 mm holes are omitted as outliers, the precision of the system improves considerably; for the 1.5 and 2 mm wide holes, a corrected error mean of 0.29 mm with a SD of 0.61 mm was realized.

The positive mean errors indicate that the 0.4 mm probe extended beyond the hole depth, suggesting that the 0.4 probe penetrated through some of the trabecular pores. Note that the true depths were measured using a 1 mm probe. To test how the pores influence the measurement when using a 0.4 mm probe, 5 sets of 5 measurements were performed on the surface of the workpiece. The resulting uncorrected errors had a mean of 0.37 mm and a SD of 1.44. The experiment 2 results are further tabulated in Appendix F.5.

### Table 2: Results from Experiment 2.

<table>
<thead>
<tr>
<th>Measurements on:</th>
<th>Uncorrected Error (mm):</th>
<th>Corrected Error (mm):</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>µ</td>
<td>σ</td>
</tr>
<tr>
<td>Undrilled surfaces:</td>
<td>0.37</td>
<td>1.44</td>
</tr>
<tr>
<td>1 mm diameter holes:</td>
<td>-0.06</td>
<td>2.01</td>
</tr>
<tr>
<td>1.5 mm diameter holes:</td>
<td>0.44</td>
<td>0.72</td>
</tr>
<tr>
<td>2 mm diameter holes:</td>
<td>0.41</td>
<td>0.66</td>
</tr>
<tr>
<td>All measurements:</td>
<td>0.26</td>
<td>1.31</td>
</tr>
</tbody>
</table>

Figure 24: Histograms for all 230 measurements conducted in Experiment 1, without correction (top) and with correction (bottom).

Figure 25: Top and middle: histograms for all 230 measurements conducted in Experiment 2, respectively with and without error correction. Bottom: histogram for all measurements except those performed on 1 mm wide holes, note the reduction in error.
5.5. Proof of Concept Experiments: Discussion and Conclusions

The Experiment 1 showed that the flexible probe prototype is capable of measuring the depth under ideal conditions with considerable accuracy and precision. Both experiments showed that a correction formula can improve the precision even further. Experiment 2 showed that the presence of pores in the workpiece considerably reduces the accuracy and precision of the measurements, not just causing the probe to penetrate through the bottom of the hole, but also causing it to snag on the sidewalls, which was evident in the considerably positive and negative errors. It was strongly suspected that the dimensions of the pores in the trabecular foam PMMA did not coincide with those that the probe would encounter during microfracture surgery; to investigate this, a simulation experiment using scans of holes drilled with a WJ in real bone was devised, see next section.

During the experiments, it was observed that the speed with which the probe is extended influences the behaviors of the friction is undergone. This makes manual control of the extension less suitable than an actuator controlled system able to maintain an adequate and steady extension speed. Additionally, manual control required the operator to react to visual and auditory cues in regards to starting and stopping the extension possibly introducing additional non-uniformities into the system.

The tunnel was made from a bent stainless steel tube with an outside diameter of 1 mm and an inside diameter of 0.5 mm. Despite lubrication, the probe experienced considerable fretting when repeatedly sliding through the tunnel. This resulted in considerable increase in friction. During additional experimentation performed after Experiment 2, the trigger force threshold had to be increased to 7 N to avoid false triggers. It should be noted that after Experiment 2, when wear became very noticeable, the probe had already been used for at least 700 extensions and retractions.

6. Visual Simulation Experiment

A simulated virtual experiment was conducted using mCT scans of bones with water jetted holes to investigate the effectiveness of a probe when used in conditions expected during WJ-based microfracture surgery. The holes were produced in porcine talus bones and femoral condyles as part of a previous Healing Water related project. An overview of the holes used is given in Table 3. For the experiment, three dimensional blocks of bone containing the holes were sectioned off from the full scan, which was made at a resolution of 0.037 mm. A visualization of a scanned block containing a hole is given in Figure 27. In the experiment, a simulated probe was lowered into seven holes from 4 different angles each and the resulting simulated measured depth was determined. The deformation of the probe and its interaction with the bone were not modeled. Instead, the clearance between the probe and surrounding bone was measured as the probe was lowered into the hole. The probe was dimensioned and placed in relation to the hole in accordance with the prototype design, see Figure 28.

Figure 26: Histograms showing the errors for the probes. Note that in this virtual simulation experiment, the error is defined as the depth at which the probe first undergoes interference with the hole, minus the true depth of the hole.

Figure 27: LTF: side, top and perspective view of a section of bone used for the experiment (hole 7). The block shown is 3.2 mm in width and depth, and 8 mm in height. The hole has a top diameter of 1.4 mm a is 4 mm deep.

When interference between the probe and the hole was detected; i.e., when the probe model came into contact with the bone model, the probe advancement was stopped and the depth to which the probe was lowered was noted. Interference was categorized as one of the following types:

- **Protrusion/wall contact**: The probe strikes the wall of the hole or a section protruding from it.
- **A choke**: The probe encounters a section of the hole which is open yet too narrow to traverse, or closed, as can be the case for the bottom of a hole.

The holes were probed from 4 different right angles to investigate the effect of their strong angular asymmetry. To simulate the holes the WJ microfracture device is expected to produce, seven holes were chosen that were drilled to a depth of approximately 4 mm using a 0.4 mm
WJ at 700 bar. The experiment was carried out using simulated probes with a diameter of 0.2 mm, 0.3 mm and 0.4 mm, the results are tabulated in Appendix G.

Table 3: Properties of the holes used in the simulation experiment.

<table>
<thead>
<tr>
<th>Hole #:</th>
<th>BV/TV:</th>
<th>Diameter (mm):</th>
<th>Depth (mm):</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.535</td>
<td>1.3</td>
<td>4.4</td>
</tr>
<tr>
<td>2</td>
<td>0.449</td>
<td>1.425</td>
<td>4.0</td>
</tr>
<tr>
<td>3</td>
<td>0.493</td>
<td>1.575</td>
<td>4.0</td>
</tr>
<tr>
<td>4</td>
<td>0.453</td>
<td>1.45</td>
<td>3.4</td>
</tr>
<tr>
<td>5</td>
<td>0.615</td>
<td>1.75</td>
<td>3.7</td>
</tr>
<tr>
<td>6</td>
<td>0.47</td>
<td>1.6</td>
<td>3.9</td>
</tr>
<tr>
<td>7</td>
<td>0.541</td>
<td>1.4</td>
<td>4.0</td>
</tr>
</tbody>
</table>

![Image](51x434 to 289x586)

Figure 28: The above figures show a cross-sectional profile of a water jetted hole in porcine bone (hole 7). LTR: 0.2 mm, 0.3 mm and 0.4 mm probes inserted into a hole. Note the difference in penetration depths. The probe features a $r = 15$ mm bend and is placed in relation to the hole in accordance with the prototype design.

6.1. Visual Simulation Experiment Results

The holes, their respective characteristics and a summary of the results are given in Table 4. The errors means and SDs per hole reflect the four differently angled measurements conducted. The total SDs indicate the spread of error across all measurements. To gauge the error as a result of measuring a hole from different angles, a pooled SD value was calculated. This was 0.67, 0.67 and 0.62 mm for the 0.2, 0.3 and 0.4 mm probes, respectively. In regards to the mean errors, the probe got progressively more inaccurate with thickness. The mean errors were -0.23, -1.18 and -1.72 mm, for the 0.2, 0.3, 0.4 mm probes, respectively. Penetration beyond the true depth occurred in 9 out of the 84 total measurements, with 8 of the 9 occurring with a 0.2 mm probe. The maximum over-penetration had an error of only 0.07 mm. The scans reveal that certain holes appear to have sections which are too narrow for the probe to pass through; i.e. chokes. This is especially the case for the 0.4 mm probe. Table 4 contains the choke depth and choke error parameters. The former is the depth at which a hole is too narrow to allow further probe penetration. Note that for measurements on the same hole but from different angle, the “choke” is not always reached; i.e., the probe may encounter a protrusion before reaching a choke, from certain angles. Similarly, the calculated depth of a choke varies depending on the angle it is probed from. The choke depth was chosen as the deepest of the measurements; the difference in choke depth between angles was at most 0.2 mm. The “choke error” indicates the depth error—i.e. probed depth minus mCT depth—for the corresponding choke. In Table 4, n/a denotes that the probe did not make it to a choke from any of the measurement angles. Instead, all interference were caused by protrusions. In this case, deformation of the probe may cause it to penetrate further.

6.2. Visual Simulation Experiment Discussion and Conclusions

The matter of over-penetration by a probe as identified in the trabecular foam experiment appeared to be a non-issue in the holes examined. All bottom contacts by the thinnest probe were chokes, i.e., the probe could not physically continue traversing downwards. This was visually corroborated by the mCT scans which showed that the pores encountered at 3-5 mm depth do not allow deep intrusion by a 0.2 mm or thicker probe. Consequently the deepest over-
penetration encountered was by just 0.07 mm. Also apparent was that all chokes met by the 0.2 mm probe corresponded approximately with the true bottom of the hole, having a mean error of only -0.2 mm and an SD of 0.13 mm. As expected, thicker probes encountered chokes closer to the hole surface than thinner probes and, consequently, produced significantly larger errors. Immediately noticeable was that hole 2 featured a considerably higher SD. This is due to its strong asymmetry; it features a prominent protrusion impeding all probing done from one, and only one, angle. This outlier in turn affected the total SDs. For comparison, if data from hole 2 is omitted, the SD values become 0.21, 0.82 and 1.08 mm for the 0.2, 0.3 and 0.4 mm probes, respectively. Similarly, the pooled SD values respectively reduce to 0.13, 0.28 and 0.28 mm.

The simulation experiment suggested that, based solely on interferences, the 0.2 mm probe is significantly more accurate than the other two. However, no interactions between the probe and the bone were simulated. In a real setup, interferences caused by protrusions may not trigger a bottom detection. The probe may bend, deform the bone, or break the protrusion and continue traversing downwards without producing a trigger event. If physical chokes are assumed to be impassable, 0.3 and especially 0.4 mm probes can be considered ineffective at probing WJ holes drilled to approximately 4 mm deep in bone. Therefore, it is suggested that subsequent experimentation focus on probes between 0.2 and 0.3 mm in diameter, and investigate how these interact with real bone under the working load.

7. Recommendations and Discussion

The aim of this project was to design and analyze a depth controlled WJ instrument with requirements based on the microfracture surgery. The microfracture procedure was analyzed and a prototype was designed. Due to the limited timeframe of the project, a complete flexible probe prototype able to drill holes using a WJ in a CLC manner could not be built. Nevertheless, several aspects of the concept were researched, built, tested and/or verified.

Firstly, a complete and well substantiated blueprint was created for the nozzle head, the necessary materials, the mechatronic ancillaries, and the overall system integration. The 3d printed nozzle head was designed so that minor alterations, such as a change in probe width or flexibility, can easily be incorporated into the system. It can be rapidly prototyped and tested to optimize its dimensions, without affecting the high pressure section. Likewise, it allows the high pressure section to be easily swapped when needed, e.g. to use a WJ with a different orifice size.

In addition, the complete back-end of the system, a LabView program with user interface, was created and shown to work. The devised method for calculating the depth, including the calibration steps and play inclusion, proved robust against the set ups severe hysteresis and backlash. The simple threshold trigger employed proved to function satisfactorily. However, after continued use, it suffered from the degradation of the probe. As fretting occurred and the friction increased, the threshold value had to be adjusted upwards to avoid false triggers. Note that the probe tunnel used in Experiment 1 was made out of bent lubricated stainless steel, a 3d printed polymer tunnel may function to reduce probe wear.

In accordance with other Healing Water projects, a WJ pressure of 700 bar was assumed and the prototype was designed accordingly. This pressure is based on the maximum pressure obtainable by the project’s industrial WJ setup. The holes measured in the simulation experiment were created using this 700 bar WJ. However, different pressures create differently shaped holes, even if drilled to the same depth. If the 0.2 mm probe proves to be inadequate, subsequent testing could seek to find an optimum pressure which creates holes deep enough yet wider than those used in the simulation experiment, thereby facilitate thicker probes and reducing the chance of wall contact.

8. Conclusion

This project analyzed the issues specific to both WJs and the microfracture procedure and sought to produce an instrument capable of accurately drilling precise blind holes in bone. It was determined that due to the strong non-uniformity of human bone, both spatially and between subjects, a closed loop controlled WJ was needed. Research regarding the control of WJs suggested that modulating the jetting time and WJ pressure are the best way to control the depth. An idea generation and evaluation phase lead to the concept of using a flexible pin probe and a prototype was subsequently designed. This concept proved to be uniquely suited at determining the depth of a hole in a tight cavity and, when iterative control scheme is implemented, can do so without in interfering with the WJ.

Although no fully integrated prototype was produced, several of its fundamental aspects were designed and investigated. Firstly, a proof of concept experiment showed that the probing concept and accompanying depth calculation algorithm both function as required. Experiments 1 showed that under ideal condition, a high degree of accuracy and precision can be achieved; \( \mu = 0.00 \) mm and \( \sigma = 0.19 \) mm, respectively. The precision can be further reduced to \( \sigma = 0.15 \) mm by using a correction function, a significant difference.

A subsequent simulation experiment using scans of real holes drilled in bone using a WJ showed that, based solely on physical interference, a 0.2 mm probe performed significantly better than a 0.3 or 0.4 mm probe. The experiment suggested that probes with a diameter between 0.2 and 0.3 mm are best suitable for the WJ-microfracture application. In addition, this project produced several further recommendations for carrying the project further, towards a fully integrated system capable of drilling accurate blind holes in human bone, in a closed-loop depth-controlled manner.
Appendix A: Healing Water Project

This thesis project was conducted as part of a then ongoing venture named 'Healing Water'. Its aim was to design a high-pressure arthroscopic WJ capable of drilling accurate depth controlled blind holes in bone.

A.1. Motivation

The original motivation behind the project stems from the desire to replace the current awl and mallet technique used in microfracture surgery. The limitations of this surgery were discussed with dr. Gino Kerkhoffs, an orthopedic surgeon familiar with the microfracture procedure and based at the Academisch Medisch Centrum (AMC) in Amsterdam. He mentioned that the current technique of using awls and mallets suffers from several disadvantages; most notably, limited reach inside the knee joint and reduced accuracy in both hole placement and hole depth. It is difficult for the surgeon or nurse operating the mallet to estimate the amount of force needed to achieve the desired depth. They often started with light and ineffective taps and gradually increased the impact force until the pick started penetrating. Additionally, impacting a bent awl in a manner not collinear to its tip can cause it to slip across the surface, rather than immediately penetrate it. This can lead to grooves instead of holes, or holes not placed in their intended position. Dr. Kerkhoffs expressed his wish to see the current microfracture tools replaced with WJ instrument which does not suffer from the abovementioned limitations.

The project was carried out during the 2013 calendar year and the instrument design was carried out at the Minimally Invasive Surgical Interventional Techniques (MISIT) division of the Bio Mechanical department at the Delft University of Technology. The mCT scans were performed by a preceding project at the Eindhoven University of Technology.

Figure 29: Logos of the main institutions involved with the project. LTR: Delft University of Technology, its MISIT Department and the Academisch Medisch Centrum.
A.2. Overview of Preceding Healing Water Projects

The following relevant Healing Water projects preceded this thesis and served as a basis from which the this project was carried forth:

1. Steven den Dunnen’s work:
   - **Nozzle coupling design**
     The miniature connection between the high-pressure water hose and the nozzle needs be able to withstand 700 bars of pressure. A concept for such a coupling, along with the hose type, was created by Steven den Dunnen and is discussed further in Appendix E.3.
   - **Experiment 2**
     This experiment used a 700 bar WJ and varying nozzle sizes to drill blind holes in porcine femoral condyles and talus bones. Scans of holes relevant to this project were used in Appendix G.

2. The author's own work:
   - **Literature Review:**
     **Depth Control for Blind Water Jet Drilling In Bone**
     The literature review completed in January of 2013 was preparatory to this thesis and investigated how depth control is achieved in both industrial and clinical WJs. Additionally, it reviewed the microfracture procedure and addressed the issues possibly regarding a future microfracture-WJ instrument.

3. Bachelor of (Applied) Science groups:
   - **Water Jet Cutting in Bone**
     This project, by T.R. Burki et al., produced several concepts for nozzle-integrated probe-based WJ shutoff systems. Their calculations in regards to nozzle pressurization and material thicknesses are referenced in Appendix C.
   - **Microfracture Tube**
     This project, E. van Dam et al., focused on the high-pressure water hose and concluded that it is both technically and surgically adequate. It was found that at 700 bar, the force on the cartilage inside the joint by the pressurized water hose is within safe limits.
Appendix B: Problem Analysis and Requirements

The main parameters involved with the drilling microfracture holes using an arthroscopic WJ are given in Figure 1 and 3, and tabulated below:

1. **Directly Controllable Parameter:**
   - Water pressure
   - Water flow
   - Orifice size
   - Standoff distance
   - Jet exit velocity
   - Irrigation pressure

2. **Indirectly controllable parameters:**
   - Hole depth
   - Hole width
   - Jet impingement velocity
   - Marrow bleeding
   - Bone debris
   - Marrow pressure
   - Backflow

3. **Uncontrollable parameters**
   - BV/TV

Two approaches to creating microfracture holes were identified, drilling to a target depth, and drilling until bone marrow bleeds through:

1. **Hole Depth:**
   - The hole is drilled until a predetermined depth is reached.

2. **Bone marrow bleed-through:**
   - The hole is drilled until the subchondral bed is penetrated and/or bone marrow bleeding is caused.

**B.1. Monitoring Approaches**

Any type of closed-loop control system will need to feature a type of sensor that monitors the process and provides feedback of the current state to the controller, which in turn adjusts the process accordingly. Ideally, a closed-loop control system will monitor the desired states directly; i.e., monitor the hole depth or marrow bleed-through. However, in cases where this is not feasible, monitoring a parameter which is strongly correlated to the desired parameter may suffice. The previously mentioned parameters, in regards to monitoring, are discussed below:

1. **Directly determine hole depth:**
   - **Measure hole depth:**
     - The depth of the hole is measured directly.
     - *Advantage:* Inaccuracies caused by indirectly determining the depth via a parameter that may not be perfectly correlated to it are avoided.
     - *Disadvantage:* Measuring the hole depth may prove difficult, especially in real-time and in holes with pores and irregular shapes.
Appendix B: Problem Analysis and Requirements

2. Indirectly determine hole depth:

- **Measure the hole width:**
  When drilled using a WJ, a hole’s width is in part correlated to its depth.
  - *Advantage:* The hole width lies on the subchondral surface and may therefore be easier to measure than the depth. The Healing Water paper "Water Jet Cutting in bone" entertains such a device.
  - *Disadvantage:* The relationship between width and depth relies on several other parameters and may prove impossible to accurately determine.

- **Measure the hole volume:**
  Similarly to the width, the volume of a hole is correlated to its.
  - *Advantage:* Could possibly be determined using novel methods not requiring physical contact, e.g. by pressurizing the hole, determining its acoustic reflection characteristics or measuring the removed material.
  - *Disadvantage:* Similarly to the width, a lack in perfect correlation to the depth may lead to inaccuracies. Additionally, because the holes are not ‘watertight’, determining the volume may prove difficult.

- **Measure the Acoustic Emissions:**
  The acoustic emissions produced by the interaction between the water jet and bone may be correlated to the drilling depth.
  - *Advantage:* Can be measured in real-time without interfering with the WJ process and may occur remotely.
  - *Disadvantage:* Considerable research is necessary to gauge the feasibility of this approach.

- **Determine the BV/TV:**
  The BV/TV is a strong determinant of the resulting hole depth.
  - *Advantage:* Will allow simple predictive control; if the BV/TV is known, the depth can be predicted using existing models.
  - *Disadvantage:* Because the BV/TV parameter is not a result of drilling, this method does not lend itself closed-loop control and may therefore prove inaccurate and not effective at dealing with perturbations. The BV/TV varies significantly across the subchondral bed, and with the depth beneath it. It may prove difficult to determine the BV/TV precisely for the jet impingement site.

Similarly to the depth, the marrow bleed-through criterion can be measured either directly or indirectly. When the assumption is made that subchondral bed penetration necessarily leads to bone marrow bleeding, additional monitoring approaches can be envisioned. When the WJ penetrates the subchondral bed, the characteristics of the backflow and the intraosseous pressure may be influenced. As such, these phenomena can be used as proxy indicators for marrow bleed-through.

1. Directly determine bone marrow bleed-through:

- **Detect bone marrow bleeding in the joint irrigation fluid:**
  Characterized by the fatty bone marrow flowing into the joint cavity.
Appendix B: Problem Analysis and Requirements

- **Advantage**: This criteria is the clinical goal of the procedure; it ensures bleed-though regardless of depth.
- **Disadvantage**: Only for the microfracture procedure. Relying only on bone-marrow bleed-though rather than also hole depth may not be safe.

3. Indirectly determine bone marrow bleed-through by assumption that it necessarily follows from WJ penetration of the subchondral bed:

   - **Measure the degree of backflow:**
     The mass flow or pressure of the backflow may change with the subchondral bed penetration.
     - **Advantage**: This criteria is closely related to the clinical goal of the procedure; it ensures that the subchondral bed is penetrated, and therefore, bone marrow bleed-through can be assumed.
     - **Disadvantage**: the degree of backflow may change considerably when holes are already present in the subchondral bed

   - **Measure intraosseous pressure:**
     When the water jet penetrates the subchondral bed, it may cause a detectable spike in the bone marrow pressure.
     - **Advantage**: This criteria is also closely related to the clinical goal of the procedure; it ensures that the subchondral bed is penetrated, and therefore, bone marrow bleed-through can be assumed. Additionally, the intraosseous pressure might be measurable away from jetting site, perhaps even externally.
     - **Disadvantage**: Perhaps invasive. If holes already exist, the degree of pressure spike may be reduced.

During a brainstorming phase, all the monitoring approaches described above developed into concepts and evaluated on feasibility.

B.2. Controlling the Depth

The basic process of predictive depth controlled blind drilling consists of predefining a jetting strategy based on information about the system and workpiece. Subsequently, the WJ is operated without any information regarding the real-time process state. The above-mentioned process is how most industrial WJ systems operate. They manage to accurately machine a workpiece by calculating the necessary WJ parameters using a model of the WJ-workpiece interaction. However, this is only possible if the workpiece properties can be accurately pre-determined, which is not easily the case for human bone. Therefore, an open-loop control system is inadequate at dealing with the perturbations and uncertainties present in the microfracture procedure and a closed-loop system is warranted.

A closed-loop depth controlled water jetting system uses feedback of the workpiece state to adapt the WJ strategy on order to achieve the desired depth. The feedback can happen either in real-time or offline. In the latter, an iterative closed-loop control system is employed; the workpiece state is measured while the jet is inactive and the subsequent jetting strategy is adjusted accordingly. This allows the desired depth to be approached stepwise without needing to overcome the challenge of measuring the depth in real-time.
Methods that do track the workpiece state in real-time can be subdivided into two categories; continuous and binary. The former continuously measures the state of the workpiece and feeds this information back to a controller which adjusts the jetting strategy accordingly. This allows for a high degree of controllability. Conversely, a binary system only tracks whether or not the workpiece state has surpassed a predetermined threshold. This allows the system to shut down when the desired state is reached, but not adjust its strategy in real time. The approaches to controlling a WJ are given in Figure 30.

For added safety, a combination of the abovementioned control methods is also possible. Note that a closed-loop control system-loop system was defined as a systems which feeds back a parameter related to the desired state of the system, either the depth or the mesenchymal bleed-through. However, systems which monitor the state of the WJ system itself or of a workpiece property also exist. In the case of a WJ microfracture instrument, a concept was entertained that measured the BV/TV immediately prior to jetting, by a nozzle integrated sensor. This parameter was then used to set the predictive control. Such concepts, however, were essentially open-loop and not deemed adequately enough to deal with perturbation. It was decided that all concepts would rely on open-loop style jetting-time limit to improve fail-mode safety; i.e., the jetting time, regardless of absence of a stop-condition, will be limited to a predetermined maximum. The closed-loops system, in turn, would improve the accuracy and robustness of the system.

![Figure 30: A schematic overview of an open-loop control blind drilling process](image_url)
Parameters which can be modulated to control the depth are:

1. **WJ Settings:**
   - **Jetting time:**
     Material is only eroded while exposed to a high pressure jet. Controlling the exposure time therefore controls the resulting depth.
     - *Advantage:* Can be triggered at the nozzle by a mechanical system, or remotely at the pump. Strongly influences resulting depth of cut.
     - *Disadvantage:* The drilling rate cannot be controlled by varying the jet time alone, unless it is pulsed. There is always a rise and fall time when—while the WJ is turned off—the system still drills.
   - **Water pressure:**
     An increase in water pressure leads to an increase in drilling rate.
     - *Advantage:* Can be controlled remotely or at the nozzle by a mechanical system. Strongly influences the depth of cut and can be modulated while jetting to control the drill rate.
     - *Disadvantage:* May create situation where the pressure is too low to cut.
   - **Orifice diameter:**
     An increase in orifice size, given the same pressure, will tend to increase the drilling rate and maximum hole depth.
     - *Advantage:* Can possibly be triggered at the nozzle by a mechanical system, can produce different sized holes (in terms of width)
     - *Disadvantage:* Must happen at the nozzle.

2. **Operation parameters:**
   - **Stand-off distance:**
     Larger stand-off distances reduces drilling rate and maximum hole depth.
     - *Advantage:* Can be triggered at the nozzle by a mechanical system
     - *Disadvantage:* Needs to happen at the nozzle, limited space inside the joint cavity
   - **Jet angle:**
     Oblique impingement angles reduces drilling rate and maximum hole depth
     - *Advantage:* -
     - *Disadvantage:* Needs to happen at the nozzle, limited space, holes need to be perpendicular to surface.
   - **Backflow:**
     Restricted backflow reduces the drilling rate
     - *Advantage:* can be triggered at the nozzle by a mechanical system
     - *Disadvantage:* controlling the backflow may not ensure control over the resulting depth under all circumstances.
     Due to the limited separation of the joint surfaces, a maximum height of 5 mm is required.
Appendix C: Concepts

A brainstorming session was carried out to produce concepts for a depth control system. The session took into account the parameters, approaches and requirements identified in the problem analysis. Additionally, several concepts which were presented by earlier Healing Water project are presented and discussed.

The most straightforward way of determining the hole depth proved to be though probing; several concepts were devised using this approach. Additionally, concepts featuring lasers and novel methods of detecting marrow bleed-through and subchondral bed penetration are entertained.

C.1. Analysis of Probing

Probing relies pushing a probe down a hole until it is impeded, the depth can then be determined from the displacement. The probe can be either a solid pin or hollow containing the WJ orifice, i.e. the nozzle probe. The concept relies on the assumption that the probe can be lowered into the hole and is impeded when it reaches the bottom. The depth of the hole can then be calculated based on the displacement of the probe.

When integrating a probe into the nozzle, placement of the probe in regards to the water jet needs to be taken into account. In order for the probe to most effectively travel down the hole made by the water jet, it needs to be as concentric to it as possible. For perfect concentricity, the probe would need to extend out of the jet orifice. Alternatively, the orifice can be located on the probe so that the probe itself forms the nozzle. Methods for placing the probe, as a pin or containing a nozzle, are presented in Figure 31.

![Figure 31: Water jet and probe placement. The water jet is depicted as the blue stroke and the probe as the green pin](image)

The advantage of probing is that it directly and mechanically measures the depth; it is mechanically simple and doesn't rely on a correlated parameter to estimate it. Unlike concepts involving lasers or sensors, it doesn't require optical or electrical connection between the nozzle and the controller. Additionally, it is applicable in any WJ applications where depth controlled blind holes of limited depth are desired.

The efficacy of probing relies heavily on the shape of the hole; therefore, proper design of the probe in terms of placement, shape, rigidity and thickness is very important. The probing can happen either in real-time or iteratively; the advantage of measuring while not jet-
ting is that there is no jet or backflow to interfere with the probe, and no probe to interfere with the jetting.

C.2. Rigid Probe Concepts

When a probe is applied to a WJ nozzle, the displacement of the probe can be used to measure the depth or to directly control the WJ at the nozzle itself. Several novel concepts were created, exploring all combinations of monitoring approaches, control approaches, probe placement, probe flexibility, etc. The most noteworthy concepts are briefly mentioned in this section.

Binary Flow/Pressure Pin Concept

This novel concept uses a mechanical iterative closed-loop control approach to drill holes up to a certain depth. The sprung probe can be extended and the depth gauged by modulating the water pressure. The pin is used to probe the depth before drilling; if the depth is shallower than what is maximally allowable, a short drilling session is automatically performed. The system features a pump programmed to oscillate the water pressure between two pressures, this toggles between the probing mode and jetting mode. The system features a valve which directs the water to either the probe, or the WJ orifice, depending on the pressure. The operation is as follows:

1. **The Pump:**
   The pump is programmed to oscillate the pressure about a "WJ-Activation" pressure, with a predetermined amplitude.

2. **Probing mode:**
   The water pressure is below the WJ-activation pressure; water can flow to the probe but not to the WJ-orifice. The water pressure pushes the probe down the hole, if the hole is shallower that allowable depth, no bypass is activated and the pump increases the water pressure.

3. **Jetting mode:**
   The water pressure is above the WJ-activation pressure; water can now flow to the WJ-orifice but not the probe. As a result, a powerful WJ exits the orifice while the probe loses water pressure and is retraced by a spring. This allows for water jetting without inference from the probe. After a short jetting session, the hole is again probed for depth. When the desired depth is reached, the probe extends all the way out and opens a bypass. The pump then detects that the mass flow needed to increase the pressure is above a preset threshold, realizes that the depth has been reached, and shuts down.

*Advantage:* Probing while not jetting does not cause interference and may therefore allow for thicker probes. This novel concept uses the relationship between pressure and waterflow to determine the depth, in a binary manner. This method uses the water hose itself to transmit the depth data and, therefore, does not require any auxiliary connections.

*Disadvantage:* The concept features moving parts inside the nozzle. These may be prone to breakdown or leakage issues. The system will only work for a specific preset depth. Due the arthroscopic limitation, this depth may be very limited.
Appendix C: Concepts

The concept is visually represented in Figure 32 via a schematic, note that it was never developed beyond a rough concept.

Iterative Jetting and Probing:

Pressure Profile: e.g.: depth reached at 3rd peak

Pressure < P1: Probe is pushed down
Pressure > P1: Jetting activated
Depth reached

System cannot be pressurized

**Figure 32: Visualization of the binary-iterative nozzle-integrated CL-control pin concept**

Continuous Flow/Pressure Pin Concept

As hinted at in the previous concept, the relationship between pressure, discharge orifice size and mass flow can be used to determine the depth. This is done by having the probe extension determine the discharge orifice size and subsequently measuring the other two parameters. This concept exploits this phenomenon in a continuous manner; i.e., the value of the depth is measured rather than the binary state of whether or not it surpassed a preset threshold. As with the previous concept, the jetting or probing modes can be toggled by setting the water pressure.

*Advantage:* No interference between probe and WJ. No auxiliary connections necessary. The depth of any sized hole can be measured, up the length of the probe. Probing occurs iteratively and does not interfere with the WJ.

*Disadvantage:* Moving parts inside the nozzle. These may be prone to breakdown or leakage issues. Due the arthroscopic limitation, this depth may be very limited. Accuracy of the depth measurement may prove inaccurate due to the high sensitivity to friction of the pin, pressure inside the joint cavity, fidelity of the pressure an flow meters, etc.

**Continuous-Iterative Jetting and Probing:**

<table>
<thead>
<tr>
<th>Pressure &lt; P1: Measure Mode</th>
<th>Pressure &lt; P1: Measure Mode</th>
<th>Pressure &lt; P1: Measure Mode</th>
<th>Pressure &gt; P1: Drill Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>No outlet/hole</td>
<td>Small outlet/hole</td>
<td>Large outlet/hole</td>
<td>No outlet</td>
</tr>
</tbody>
</table>

**Figure 33: Visualization of the continuous-iterative pin concept**

This concept is further developed in Appendix D.3: Flow/Pressure Pin.
C.3. Flexible Probe Based Concepts
As summarized in the scientific paper, the flexible probe concepts addressed the dimensional limitations of the rigid pin concepts. In addition, the flexibility of the probe allows it to transmit its own displacement to the ex-vivo depth calculating mechatronic ancillaries. This negates the necessity for sensor miniaturization.

Flexible Probe Concept
The concept features a tunnel located adjacent to the WJ orifice. This tunnel guides the flexible probe from its sleeve down towards the hole. The proposal is to have it operate in an iterative manner; i.e., quickly alternate between probing and drilling until the desired depth is reached. This concept is

*Advantage:* Mechanically simple and only one moving part inside the joint cavity (the probe). Probing while not jetting allows for thicker probes, preventing backflow and jet interruption issues. Allows for deep probing, probe extension can be measured ex-vivo. The probe does not operate inside the high pressure section of the water jet nozzle. Therefore, it does not introduce any leakage issues.

*Disadvantage:* Probe needs to traverse a sharp bending angle. This might cause friction and probe deformation. If the probe is not rigid enough it may buckle when extended. This prevents the system from correctly determining when the probe reached the bottom.

![Iterative Jetting and Probing](image)

Figure 34: Flexible probe concept

C.4. Bleeding-based Concepts
When design a system specifically for the microfracture procedure, having bone marrow bleed-through as the desired criteria becomes possible. The advantage is that methods utilizing this approach produce what is clinically desired; namely, mesenchymal bleed-through.

Backflow Marrow Detector
This concept features a system which “catches” the backflow and routes it through a sensor. When bone marrow is detected in the backflow, the system knows that the subchondral bed has been penetrated. The sensor was envisioned as being either optical or electrical. In the former, an ex-vivo optical sensor connected to the nozzle via an optical fiber would detect a change in the back-flow's reflectivity and/or transmittance due to the presence of fatty bone marrow. Alternatively, an electronic sensor was envisioned as possibly detecting a change in back-flow conductivity.
Appendix C: Concepts

Advantage: Subchondral penetration and mesenchymal bleed-through are highly likely, regardless of depth.

Disadvantage: Detecting bone marrow in the back-flow as envisioned may prove infeasible. Additionally, the system is not technically depth controlled. Therefore, an additional mechanism is necessary to prevent over erosion in cases where bone marrow bleed-through does not occur or is not detected.

![Backflow Marrow Detection](image)

**Figure 35: Backflow marrow detection concept**

C.5. Subchondral Penetration Based Concepts

These concepts rely on the assumption that when the WJ penetrates the subchondral bed into the porous underlying trabecular structure, it affects the pressure of the backflow and the intra-osseous pressure.

Remote Trabecular Pressure Detector

The intraosseous pressure—i.e. the pressure inside the trabecular structure—may feature a sudden pressure spike and/or distinguishable characteristic when the WJ pierces into it. When these phenomena are detected, the WJ is shut off. This method proposes a detector which is located away from the jetting site.

Advantage: Detection the intraosseous pressure may occur remotely, perhaps even non-invasively.

Disadvantage: Drilling next to existing holes may considerably reduce or change the detectable pressure characteristic. Getting intraosseous pressure may prove difficult. Technically not a depth control methods; additional steps to ensure safety are required.
C.6. Optical Concepts

Because of the limited timescale of the project and its mechanical nature, advance optical systems such as low coherence interferometry were deemed outside of the scope of this thesis. Nevertheless, several novel optical concepts were devices. Most noteworthy was Triangulation concept. It consisted of a laser and detector system, which, through triangulation, could determine whether or not the target depth has been reached. The detector would use the orifice as a collimator and only detect light reflected off of the bottom of the hole. The left image in Figure 33 shows how the light source directs a laser into the hole. The laser is aimed at a depth where the bottom is desired (see the diagonal dotted line in Figure 33). The orifice, nozzle and detector aperture act together as a collimator; i.e., only the light travelling along the axis of the jet is allowed to enter the detector (see vertical dotted line in Figure 33). This means that the detector observes a peak in refracted light when the desired depth is reached.

*Figure 36: Remote trabecular pressure detector*

*Figure 37: Laser triangulation concept*

**Advantage:** No moving parts.

**Disadvantage:** Can only measure around a certain depth. Sensitive to debris obscuring the light.
Appendix D: Concept Refinement and Selection

The brainstorming session produced three concepts which were deemed as warranting further attention. A probing concept using a flexible probe, a probing concept using a rigid probe, and a concept using optics:

1. **D.1: Optical Triangulation**

5. **D.2: Flexible probe**

6. **D.3: Flow/Pressure Pin**

This part of the report discusses the development of these three concepts into more concrete design proposals. The advantages, disadvantages and possible pitfalls of each proposal are discussed and a choice is made on how to carry the project on. All concepts will be developed to meet the requirements discussed in Appendix B: Problem Analysis and Requirements. Additionally, concepts should be able to handle WJ orifices between 0.3 and 0.4 mm.

Next to the dimensional requirements, the project also faces practical and clinical considerations. The chosen concept will need to be dimensioned, fabricated and tested within a limited time frame; the development of the design proposals and ultimate selection will take these issues into account.

**D.1. Optical Triangulation**

The original Laser Triangulation concept is pictured in Figure 33. For the initial dimensioning of this concept, the desired hole is assumed to feature a top diameter of 1 mm and a target depth of 4 mm. The orifice diameter is set to 0.3 mm at a 1.5 mm standoff distance. As such, aiming the laser down the hole towards the target depth from the same standoff distance requires an angle of 7.13 degrees. Note that the nozzle walls of the required 0.6mm thickness are also visualized. This indicates that the laser cannot be placed immediately adjacent to the orifice when both are at a standoff distance of 1.5mm.

![Image of Optical Triangulation concept]

Figure 38: Dimensioning of the concept featuring a 0.3 mm WJ orifice at a standoff distance of 1.5 mm and a desired hole depth of 4 mm. The nozzle walls are 0.6 mm thick as required by the high pressure of the WJ.
Figure 39: Visualization explaining collimator resolution. Ideally, only light parallel to the collimator would pass through, but because the tunnel is of finite width and length, light at small angles can also make it through. The rightmost image shows the “cone” of light which can traverse the collimator uninterrupted.

The collimator efficiency is determined by its “narrowness”; if we assume that all light which traverses the collimator in an uninterrupted manner reaches the detector, we see that for a collimator of finite width and length, light rays at small angles to the collimator also make it through, reducing the accuracy of the collimator.

Another way to increase the resolution of the system is to increase the angle between the collimator and the laser and decrease its standoff distance. When the angle is small, inaccuracies in the resolution of the collimator translate to greater errors in depth, as opposed to larger angles. This phenomenon is visualized in Figure 40, which is drawn to scale. A laser tilted at 7.13 degrees is aimed at the desired bottom of the hole. The figure features two collimators; one located vertically above the center of the hole, and one positioned off-center but aimed at the desired bottom at an angle of 7.13 degrees. The angle between the vertical collimator and the laser is half of that between the tilted collimator and the laser. Ideally, only light reflected from the desired depth (4 mm) enters the detector through either collimator (the green lines in Figure 40). In reality however, this is not the case; because of finite resolution, a “cone” shaped space of reflected light is allowed into the detector causing erroneous triangulation (red lines in Figure 40).

From Figure 40 it is clear that a 0.3 x3 mm collimator is not accurate enough. The original idea of using the orifice itself as part of the collimator will be replaced by a new concept featuring a dedicated collimator.
Figure 40: Visualization of collimator accuracy. A laser light source is shown along with two collimators for comparison. The green lines indicate the ideal path of the light. However, light not parallel to the collimators also manage to traverse it (red lines). The result is that light entering the detector may trigger a depth detection prematurely. This is visualized with the two horizontal red lines.

The new proposal for nozzle head design is as follows: a central 0.3 mm nozzle, flanked on both sides by the laser and detector tubes. The detector tube, which acts as a collimator, should be 0.2 mm wide, approx 3 mm long with an standoff distance of 0.2mm, giving an accuracy of approximately 0.7 mm; i.e., at approx. 3.3 mm reflected light starts passing through the collimator. Furthermore, to increase accuracy, the detector tube should be placed as close to the hole surface as possible, the jet orifice, however, needs a larger standoff distance to allow water to escape. This is solved by extending the detector and laser tubes downwards, while maintaining backflow escape routes.

Figure 41: The triangulation concept
The concept can be further improved by making it continuous rather than binary; i.e., measure the depth across a wider spectrum rather than only near the target depth.

This can be done by using multiple lasers aimed at various angles with identifiable characteristics like different colors or time-based encoding. Additionally, a dispersion prism can be used which splits light into a rainbow of its color spectrum. The detector can continuously triangulate the depth based on the received light wavelength. This can be done either using a dispersion prism or a special optical grating. A visualization of this concept is presented below:

![Figure 42: Spectrum based depth triangulation concept](image)

The final concept consisted of a nozzle head as visualized in the rightmost image in Figure 42. A central WJ orifice flanked by a collimator and detector on one side, and a dispersed light source on the other. White light is reflected at various discrete angles and with varying characteristics into the hole. This is done using a special type of grating. From the detected light characteristic, the depth can then be determined in a pseudo-continuous manner.

**D.2. Flexible probe**

This concept involves pushing a flexible probe down to hole to gauge its depth. The system features a nozzle head with integrated probe tunnel and a servo to move the probe. The servo features a load and displacement sensor to detect bottom contact and measure the displacement. The feasibility of this concept relies on the flexible probe's ability to transmit compressive force back to a sensor while bent at about 90 degrees with a radius of approximately 2–3 mm. The main obstacles are therefore friction in the bent and buckling in the hole. If we assume a 1 mm standoff distance and a hole depth of 4 mm, the buckling length becomes 5 mm.
The NiTi probe was modeled as having a 0.3 mm diameter, a Young's modulus of $E = 80$ GPa, a fixed end at the nozzle, and a pinned end at the hole bottom. The maximum compressive force that the probe can transmit while spanning 5 mm was calculated at 25.6 N:

$$F_{\text{Buckling}} = \frac{\pi^2 \cdot E \cdot I}{(0.7L)^2}, \quad I = \frac{1}{4} \pi r^4$$

$$F_{\text{Buckling}} = \frac{\pi^3 \cdot E \cdot r^4}{4 \cdot 0.49 \cdot L^2} = \frac{\pi^3 \cdot 80 \cdot 10^9 \cdot 0.000154}{4 \cdot 0.49 \cdot 0.005^2} = 25.6 N$$

The elastic probe also needs to be bent approximately 90 degrees; using the formula for distributed loading, the necessary load was calculated at 13.5 N:

$$\phi = \frac{w \cdot L^3}{6 \cdot E I} = 90 \text{ degrees}$$

$$w = \frac{\phi \cdot 6 \cdot E I}{L^3} = \frac{0.5\pi \cdot 6 \cdot 80 \cdot 10^9 \cdot \pi \cdot 0.000154}{4 \cdot (0.25 \cdot 2 \cdot \pi \cdot 0.003)^3} = 2865 \text{ N/m}$$

$$F_{\text{Bend}} = 2865 \cdot 0.25 \cdot 2 \cdot \pi \cdot 0.003 = 13.5 N$$

The coefficient of friction was assumed to be $u = 0.3$, which is a conservative estimate. The total friction as a result of the force needed to bend the elastic probe was calculated at 4.1 N:

$$F_{\text{Friction}} = 0.3 \cdot 13.5 = 4.1 N$$

Additional friction in the tunnel is introduced when the probe is exposed to opposing non-collinear forces. This was modeled using the capstan equation for an angle $\alpha = 0.5\pi$ and friction $u = 0.3$, the capstan equation used was:

$$F_{\text{out}} = F_{\text{in}} \cdot e^{-u \cdot \alpha} = F_{\text{in}} \cdot 0.62$$

The trigger value was set at 5 N and, assuming that the friction associated with the tunnel bending the rigid probe is subtracted from the pushing force, the force exerted on the workpiece was calculated at 0.56 N:

$$F_{\text{out}} = (5 - 4.1) \cdot 0.62 = 0.56 N$$

For a probe diameter of 0.3 mm, this means a contact pressure of 7.9 MPa:

$$P = \frac{F}{A} = \frac{0.56}{\pi \cdot 0.00015^2} = 7.9 \text{ MPa}$$

The probe can exit the nozzle body either true the WJ orifice, or through a dedicated port. The advantage to having the probe exit through the WJ orifice is that it is concentric to the hole. The disadvantage, however, is that the probing section is then connected to the high pressure section of the nozzle body. This introduces new leakage and sealing issues.

The final concept uses a dedicated opening adjacent to a slightly tilted jet orifice. To assist fabrication, the design proposal is to build the nozzle head out of two sections. One section
Appendix D: Concept Refinement and Selection

will feature the water inlet, and both sections will have half the jet orifice and a milled-out groove for the probe. The two sections will be screwed together with two small screws. A gasket in between the two sections should protect against leakage. A preliminary design concept is given in Figure 43. In the figure, the 4mm deep back part is shown. On top of it (the side facing towards viewer), a 1mm plate is screwed, with milled in it: half of the probe groove (0.5*0.4=0.2 mm deep) and half the jet orifice (0.5*0.3=0.15 mm deep). The complete nozzle head is 5mm high and wide.

Figure 43: The first draft of the flexible probe concept

**D.3. Flow/Pressure Pin**

In a steady state system, the water flow can be considered a function of the orifice and pressure. With this in mind, the Flow-Pressure concept was devised. By using a flow meter and pressure meter, the orifice size can be determined. If the orifice size is proportional to the depth, the depth can in turn also be determined:

**Continuous-Iterative Jetting and Probing:**

<table>
<thead>
<tr>
<th>Pressure &lt; P1: Measure Mode</th>
<th>Pressure &lt; P1: Measure Mode</th>
<th>Pressure &lt; P1: Measure Mode</th>
<th>Pressure &gt; P1: Drill Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>No outlet/hole</td>
<td>Small outlet/hole</td>
<td>Large outlet/hole</td>
<td>No outlet</td>
</tr>
</tbody>
</table>

Figure 44: Original Flow-Pressure Pin Concept

To measure and jet iteratively, without interference, a pressure or flow valve is imagined which at lower pressures activates only the probe, and at higher pressures only the jet. The probe is sprung to keep it inside the nozzle head when not in use.
Figure 6 shows a preliminary dimensioning of the concept. The proposal features a sprung cylindrical valve which, depending on its position, either directs water towards the probe, or towards the jet orifice. To achieve maximum sensitivity, no "chokes" should be present between the water inlet and the measurement outlet; i.e., the water flowing to measurement outlet should not have to pass through openings smaller than the measurement outlet (when fully opened). If the flow needs to traverse such a choke, it will be restricted and the effect of the measurement outlet on the flow will be minimal. The original design featured a probe which restricted the flow through the measurement outlet with the surface on its top end. A revised proposal features a probe which restricts the flow along its side, allowing for an "un-choked" flow. This is visualized in Figure 45.

At this stage of the design it was already apparent that, given the dimensional constraints, the probe can have a maximum length of approximately 4mm. This was a major disadvantage of this concept over the flexible probe concept.

D.4. Concept Selection
The three concepts in consideration for further development and research are:

1. **D.1: Optical Triangulation**
2. **D.2: Flexible probe**
3. **D.3: Flow/Pressure Pin**

These were judged based on the criteria listed below. Each concept was given a score of between 1-3 for each criteria. After summation, the best concept is chosen.

1. **Functionality:**
   The ability to achieve the main goal, depth controlled 4mm deep holes, is a must. Additionally, the features—and lack thereof—for each concept is discussed.

2. "**General applicability**":
   The ability to be used for WJ applications other than the microfracture procedure.
3. **Limitations:**
The possible limitations and pitfalls which have been identified. These issues may prevent the concept from functioning as desired.

4. **Safety:**
Concepts which feature less failure modes and/or less damage in case of failure will be preferred.

5. **Pragmatism:**
The degree of remaining uncertainties, in regards to whether or not the concept can or will work, and the required additional research to prove/disprove the concept will be considered.

**Functionality**
In terms of functionality, the triangulation concept ideally manages to gauge the depth of the hole when the WJ is turned off. The range in which depth can be measured depends on how the grating or prism is implemented. Because covering the whole depth range of the hole may prove difficult, and if done in a discrete manner, may come at the cost of continuous depth measurement, this concept scores a 2 in the functionality category.

The flexible pin concept manages to probe the depth in a continues manner over a wide range of depth, namely as long as the probe can traverse down the hole and does not buckle. Additionally, the probe may possibly be used when the WJ is turned on, albeit at the cost of interfering with the WJ. This concept scores a 3 for this category.

The Flow/Pressure pin concept is able to continuously measure the depth, albeit over a severely limited range; the advantage and novelty of not needing an auxiliary connection is overshadowed by the fact that using a rigid probe limits the depth to maximum height of the working environment. For having a range of no more than 4mm, this concepts scores a 1 in this criteria.

**General applicability**
In terms of general applicability, the Triangulation concept can easily be used for other WJ procedures. A change in the angle and positioning of the collimators can vary the working range as needed. It scores a 3 in this category.

Similarly, the flexible pin concept does not rely on parameters unique to the microfracture surgery and is therefore applicable in other procedures. The depth range is mainly limited by the buckling of the probe. This concept scores a 2 in this category.

For this category, the Flow/Pressure pin concept suffers from the same limitation as in the functionality category; the limited reach reduces its applicability for other procedures. It scores a 1.

**Limitations**
The scores for the limitations criteria are negative and are subtracted from the final tally.

Limitations of the Triangulation concept and possible pitfalls includes the possibility that bone marrow droplets, bone material or other debris may occult the laser or detector. Additionally, fat droplets may alter the behavior in which light is transmitted through the water in
such a manner that it introduces errors into the measurement. Additionally, the bottom of the hole cannot be detected if it is not in the direct line of sight of the light beam and detector. Solving this by placing the light beam and detector close to each other, however, severely reduces the accuracy of triangulation. The concept scores a -3 in this category.

The Flexible Pin concept has limitations regarding the dimensioning of the probe and hole. Firstly, the probe, which cannot be concentric to the hole, still needs to be able to navigate it without getting stuck. This might prove difficult for irregular holes and holes with porous features. Additionally, possible deformation of the probe due to repeated bending needs to be taking into account. The score for this criteria is a -2.

The main limitation to the ideal functioning of the Flow/Pressure concept is leakage. Sealing miniature moving parts from 700 bar pressure is extremely difficult. Additionally, it is difficult to gauge how accurate such a novel approach to depth measurement is; the fidelity of the system is likely very sensitive to leakages and expansion/contraction of the water hose. The score in this category is -2.

Safety
The Triangulation concept features no moving parts; mechanical breakdown and/or break-off is therefore judged as being less likely than with the other concepts. This concept score a 3 in this category.

The flexible pin concept does feature a single moving part; break-off and/or breakdown is therefore judged as being more likely than the laser concept. Additionally, breakage of the probe can introduce foreign debris into the patient cavity. It scores a 2.

The Flow/Pressure pin concepts features several moving parts and springs. Additionally, thes moving parts are exposed to very high pressures. The likelihood of a breakdown is therefore higher than with the other concepts. Additionally, the damage to the patient due to breakage is more severe. This concepts scores a 1 in this category.

Pragmatism
To design a prototype of the Triangulation concept, considerable research into optics in necessary. A dedicated research and testing session is probably necessary to determine the best prism or grating necessary for the prototype. If laser cut sapphire is require, additional manufacturing hurdles need to be overcome. This is possible, however, the preference of this project leis is a mechanical solution and the recourses and available rime are limited. This concept scores a 1 in this category.

The flexible pin concept is fully mechatronical and can be manufactured into a prototype in-house. It scores a 3 in this category.

The Flow/Pressure concept is also fully mechatronical and a prototype can probably be manufactured in house. Tweaking the dimensions, sensors and algorithms for proper depth measurement may require considerable extra research. This concept scores a 2 in this category.
### Table 5: Concept rating and selection

<table>
<thead>
<tr>
<th>Concept: ➔ Criteria: ↓</th>
<th>Triangulation:</th>
<th>Flexible Probe:</th>
<th>Flow/Pressure Probe:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Functionality:</td>
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<td>3</td>
<td>1</td>
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<td>Applications:</td>
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<td>-2</td>
<td>-2</td>
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<td>Safety:</td>
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<td>2</td>
<td>1</td>
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<td>Pragmatism:</td>
<td>1</td>
<td>3</td>
<td>2</td>
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<tr>
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<td>8</td>
<td>3</td>
</tr>
</tbody>
</table>

The Flexible pin concept proved to be the best and was further developed into a prototype and tested.
Appendix E: Prototype Development

Following is a log detailing the two design iterations, and the concerning reasoning, that led to the final prototype design.

E.1. Total System Overview and Design Steps

The total depth control system consist of four sections:

1. The **nozzle head**

2. The **piping:**
   - The high pressure hose.
   - The probe sleeve.

3. The **mechatronics:**
   - The probe actuator.
   - The position sensor.
   - The probe force sensor.

4. The **controller and pump:**
   - A controller (a laptop running LabView).
   - A pump (a UTM in the case of this project).
   - A valve between the UTM and nozzle, for easier integration with the controller and more efficient control of the water jet.

![Figure 46: Total system overview](image)

E.2. Mark I Prototype Design

A first proposal for a prototype was created, aka "Mark I". This section describes the decisions made in that design process.

**Integrated vs. non-integrated nozzle head**

Due to the high pressures involved, the high pressure section, i.e., the water jet cavity and orifice, will need to be manufactured out of a strong material. For the prototype, the choice was made in consultation with the engineers and fabricators associated with the project to use surgical stainless steel. The probing section, however, does not necessarily need to be under high pressure, leading to two possibilities for nozzle head design:
Appendix E: Prototype Development

1. Integrated nozzle-head
   - In this design both the high pressure and probe sections are made out of stainless steel, allowing for both sections to be machined into the same stainless steel piece. The curved nature of the probe groove however, means that it cannot be machined monolithically, meaning the nozzle head would need at least two separate parts.

2. Non-integrated nozzle head
   - In this design, only the high pressure section is manufactured out of stainless steel, and then inserted into the probing section, which can be made out of a different material. This freedom in material selection means that the probing section can be e.g. 3d printed, allowing for the probe section to be a single piece featuring intricate details and hollows cavities.

The decision was made to design Mark I with an integrated probe and WJ and a workpiece which is producible in-house. As proposed in the concept phase, the 0.3mm orifice and ~2mm water inlet are drilled into the nozzle-head workpiece, and the probe groove is milled on the surface. A cover plate is then used to seal the piece.

Tilted jet vs. tilted probe.
Because of limited space, either the water jet or the probe may be tilted to allow for non-concentric placement, while still maintaining a mutual focus point (at the target depth of 4 mm). Five approaches to placing the jet and probe are illustrated below:
1. Perpendicular WJ with tilted probe
   The advantage of having a perpendicular water jet is that it creates perpendicular holes, which according to existing literature on the microfracture procedure, is the preferred type of hole. The disadvantage of having a tilted probe, however, is that the probing is not done along the axis of the hole, and may therefore not reach the bottom. Furthermore, when probing sideways, the reaction forces on the probe may push the nozzle head sideways, rather than purely upwards as with a vertical probe, this may cause the nozzle head to move.

2. Perpendicular probe with tilted WJ
   The disadvantage of this approach is that a tilted jet creates a sideways trust force and asymmetric holes; this behavior will still need to be investigated empirically.

3. Tilted probe and WJ
   This approach features the disadvantages to tilting mentioned above. Additionally, because the WJ and probe are tilted oppositely, it is only near the targeted depth that they closely converge. The advantage to this system is that it allows for maximum spacing between the probe and WJ.

4. Adjacent perpendicular probe and WJ
   This approach does not feature the disadvantages of tilting, however, since the probe and jet are placed adjacently, they do not converge at a single point, making aiming both down the hole difficult.

5. Concentric and perpendicular probe and WJ
   This approach is conceptually ideal; it produces perpendicular holes and probes it concentrically. The disadvantages are that the probe needs to be thinner than the jet orifice, the probe cavity needs to be sealed off while jetting to prevent (high pressure) water from entering the probe sleeve, and probing can only occur while not jetting.

Preliminary tests with Nickel Titanium probes showed that when repeatedly pushed through a sharp bend, it will progressively acquire a curvature. This might be mitigated by turning the probe around its own axis while pushing it through the bend, not allowing it to curve into a single direction. Alternatively, the degree of curvature may be incorporated into the design, as shown below. This might allow the probe to be placed further from the jet and/or at a sharper angle. The disadvantage to having a curved probe is that it is severely weaker in terms on buckling load (compared to a straight probe).
Figure 49: Tilted curved probe. The initial angle is 7.14 degrees and the curvature is purely for visualization.

Because the literature explicitly states that the holes should be perpendicular to the subchondral plate—albeit without strong evidence—the final prototype will feature a perpendicular WJ. Furthermore, the behavior of bone when exposed to a tilted submerged WJ has not yet been investigated adequately to determine the resulting hole shape.

The prototype will feature a probe which is tilted and placed adjacent to the WJ. As opposed to the concentric option, which I think also merits attention, this approach allows for investigation into the feasibility of probing while jetting; if the same orifice is used to jet and probe, only one can be performed at a time (properly). Furthermore, keeping the WJ and probe separate negates the need for a valve system to keep the high pressure water out of the probe piping (or using high pressure resistant piping for the probe).

Placing the Tilted Probe
A pilot experiment showed that pushing the NiTi probe repeatedly through a bend will cause it to curve. An subsequent experiment was carried out to quantitatively determine the curvature. A 0.4mm super-elastic Nickel Titanium probe was repeatedly pushed through a bend of 0.3mm until the acquired curvature no longer changed. The following observations were made:

- As expected, the curving occurs in the same plane as the bending
- Repeated pushing of the probe through a 0.3mm bend quickly causes it to curve at the section which traversed the bend.
- The acquired curve has a radius of approximately 15mm, at the sharpest section
- Once curved, it is very difficult to uncurve the probe. The probe was turned 180 degrees so that the curve was opposite to the bend and repeatedly slid through it. This however, did not manage to undo the curve. It proved extremely difficult to hold the probe curve at 180 opposite to the bend: i.e., the curved section of the probe simply rotated and "snapped" into the bend.
- The curve was approximately the same for when the test was repeated for the 0.2 and 0.3mm diameter probes
- Note, tests were done manually, a motor might be able to uncurve/prevent curving much more effectively
The decision was made to take the curvature into account when dimensioning the nozzle head, and not rely on in-axis turning to keep the probe straight.

**High Pressure Hose**

The design for the high pressure piping, including the nozzle-pipe connection, will build on previous projects. A high pressure water hose and connection has been chosen and tested, and will be used into this design. Note, the connection is the interface between the water hose and the nozzle body. The existing concept relies on a press fit coupling, this is described later in this section.

**Probe conduit**

The flexible probe will be guided from the in-vivo nozzle body towards the ex-vivo mechatronics via a sleeve which runs alongside the water hose. The sleeve will prevent the probe from buckling when transmitting compressive force, and, along with the water hose, provide tensile reaction force to the nozzle body; i.e., hold it so that it doesn’t get pushed away when the probe is pushed through the bend. The hollow plastic sleeve chosen for the prototype was taken from a catheter instrument and has an outer diameter of 1mm and an inner diameter of 0.5mm.

The prototype will assume the following data as design parameters:

- Target hole: 4 mm deep with a 1 mm top diameter
- Orifice: 0.3 mm diameter
- NiTi probe: 0.4 mm diameter
- The probe tunnel will be 0.5 mm in width and height.
- Minimum wall thickness for high pressure cavity in stainless steel is 0.6 mm
- High pressure hose connection will follow Steven den Dunnen's design and be attached to the nozzle head via a screw connection (at the "Tabbed Water inlet" in Figure 50)

**Mark I Prototype Proposal:**

Like the original concept, the prototype will be build in two halves. The probe groove will be milled, and the waterways will be drilled. The two halves are join together using M1.2 fasteners. A thin gasket between the two halves will work to prevent leakage. The walls of the probe tunnel is formed by the milled out contours of two halves.

---

![Diagram of prototype components: Fasteners, Tabbed Water inlet, Orifice-Inlet connector, Fastener, Top halve of probe groove, Catheter tube connection.]
Because the orifice and the probe tunnel are in the same plane, it is difficult to connect the orifice and the water inlet. To address this, the probe groove can be tilted out of plane, but this has its dimensioning and manufacturing disadvantages. Instead a orifice-inlet connector hole is suggested which connects the water inlet and the orifice, and is sealed off at the top to prevent leakage. Below is a cutout through the orifice, showing the orifice-inlet connector hole.

The design for the Mark I prototype was finished and brought before a technical committee. Some points regarding this first design iteration are:

The probe groove radii are preliminary and a result of some design assumptions, namely the preference to make the bends as wide as possible, whilst still fitting in the 5 mm height. This has led to a rather long nozzle, namely 17.4 mm long. This can be addressed by reducing the probe bending radii to the original design of around 4 mm.
Appendix E: Prototype Development

In this version, the probe is in the central plane, and exits the nozzle head in the middle of the cross section. The high pressure hose enters the nozzle head adjacent to it, off center. A redesign step will attempt to create some symmetry by placing both the probe and the hose slightly off center. This however, will mean that the probe is no longer in a single plane and therefore complicates the manufacturing process.

E.3. Mark II Prototype Design
After the first attempt of designing a prototype, a new design iteration is performed using lessons learned from Mark I.

Lessons from Mark I
The first iteration of the prototype (Mark I) revealed points listed below:

- It is difficult to connect the water inlet with the jet orifice if the probe is in the central vertical plane, to address this, a third borehole was proposed, see Figure 52. However, sealing this third borehole may prove problematic so it will be avoided in the next design.
- The original design aimed at using a 0.3 mm nozzle. However, upon consultation with Steven den Dunnen, this was increased to 0.4 mm, which is able to drill deeper holes in harder bone.
- Placing the probe outlet next to the orifice, so that both aim towards the hole, is problematic. This will be addressed by increasing the standoff distances; i.e., the probe and WJ will emerge from the nozzle head further upwards from the bone surface.
- The coupling between the nozzle and water hose, as designed by Steven den Dunnen, features a rigid “plug” which is inserted into the hose and clamped in. This means that if this insert sticks out of the nozzle head, the hose will have an approx. 8mm long section which is rigid and cannot flex. This will be avoided in the next design by incorporating it into the nozzle head. Additionally, the standoff distance will be incorporated into the design dimensions; i.e., the nozzle head will occupy the whole gap between the joint surfaces, which may have a maximum separation of 5 mm.
- The hose connector has a maximum diameter of 4.3 mm, the diameter of the catheter sleeve is 1 mm. If these are placed directly adjacent to one another, this is 5.3 mm; the design goal of a nozzle head no wider than 5 mm will therefore not be met. Instead, outer cross-sectional dimensions of 5x6 mm will be aimed for. Note that the probe should be placed on the neutral axis to avoid stretch/compression when the hose is bent.
- The points mentioned above suggest that the high pressure section (orifice/connector/hose) be integrated as a whole into a separate nozzle head piece which features the depth control mechanism. 3d printing the nozzle head will be considered.
**Figure 53:** The old vs. the new design. In the new design, the nozzle connector is incorporated into the nozzle body and the standoff distance is included into the height of the nozzle. This reduces the length of the non-rigid section of the instrument, increasing mobility inside the joint cavity.

**Figure 54:** Visualization for the new dimension of the prototype. Its shows the 5x6mm cross-sectional area of the nozzle head, the 1mm diameter probe sleeve and the 4.3 mm diameter water hose.
Modifying the Hose Connector

The original dimensions of the existing water hose connector, as tested for up to 150N, are illustrated in Figure 55, shown with a nozzle length of 3mm.

![Figure 55: original hose connector dimensions (all measurements are in mm)](image)

This design will be incorporated into the prototype, with two modifications. Firstly, to achieve maximum clearance between the nozzle and the probe, the orifice is positioned as off-center as possible; i.e., in tangent to the inner diameter. To maintain a symmetric exit orifice, the bottom of the nozzle cylinder is flattened out. To maintain a minimum cylindrical wall thickness of 0.5 mm, the outer diameter is increased to 2.4 mm (up from 2.1 mm). Note that the fillet is also reduced. The modified design is illustrated below.

![Figure 56: new hose connector design (mm)](image)

The hose/orifice assembly, as shown above, and the probe sleeve will be placed adjacently in the nozzle head, preliminary dimensioning of the situation is given below:
The probe needs to make a non-planer 3d curve in order to traverse from the catheter to the outlet, which is aimed down the hole. This bend is created by approximately projecting two \( r = 3 \) mm curves onto each other, as illustrated below. Note that in the final design, the actual 3d curve is somewhat more complicated. Note the \( r = 15 \) mm acquired curvature (this is the curvature the probe assumes after repeated passing through the \( r = 3 \) mm bend). The nozzle head casing is built around the probe and the nozzle, with the previously discussed dimensions: The outlet-nozzle (the part below the orifice) is modeled as two mirrored \( r=1 \) mm quarter circles, with an open front, a flat back plate, and a clearance of 0.6mm. This can be optimized to enhance the WJ cutting performance (especially the outlet nozzle shape). The curve dimensions are illustrated by means of project radii in Figure 58 and an overview of the dimensions of the final design is given in Figure 59.

Figure 57: Dimensioning of the Mark II prototype

Figure 58: Visualization showing the 3D curvature
Appendix E: Prototype Development

Figure 59: Dimensioning for the final design of the Flexible Pin prototype

Figure 60: Rendering of the final Flexible in prototype design
Appendix F: Proof of Concept

F.1. Testing Set Up

To expedite the testing of the system, the decision was made to use an existing desktop testing machine as the for the mechatronics section; it features all necessary sensor but lacks a servo. Therefore, the probe will be extended manually.

The design and fabrication of the test setup and its backend have been completed; it features a fake nozzle with integrated probe and a flexible sleeve of approximately 15 cm (through which the probe runs). The probe is connected to a load cell and is advanced manually. The extension is measured using a displacement meter, which, together with the load cell, is read out via a DAQ box by a LabView program.

![System Overview](image)

**Figure 61: System Overview**

![Probe and workpiece](image)

**Figure 62: Probe and workpiece (workpiece load cell used to measure force applied to the workpiece by the probe). Nozzle body mock up not shown, only the probe tunnel. The nozzle body was made from modeling clay and encapsulated the probe tunnel. Additionally, it featured a retractable pin where the water jet would be, for alignment.**
F.2. PMMA Workpieces

The holes were manually drilled to the reference depths and the actual resulting true depths were measured using a depth caliper with a 1 mm probe. A column drilling machine was used and great care was put into accurately replicating the depths. Nevertheless, the true depths varied from the reference depths.

In the fake trabecular bone, the measured true depth varied considerably from the reference depth due to drilling inaccuracies and the porous nature of the material. The effects of the pores, which were up to approximately 0.6 mm wide, on the measurement of the true depth were minimized by using a 1 mm probe. It was noted that the 0.4 mm probe used in the nozzle can penetrate through the pores, making accurate and repeatable measurements difficult.

Table 6: The actual depths of the holes used in the pilot experiment, as well as experiments 1 & 2.

<table>
<thead>
<tr>
<th>Diameter (mm)</th>
<th>Reference Depth (mm)</th>
<th>True Depth PMMA (mm)</th>
<th>True Depth Fake Bone (mm)</th>
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</table>
F.3. Pilot Experiment results
In the pilot experiment, 80 measurements were performed on the holes given in Table 6, as well as on undrilled surfaces. All measurements are given below.

![Figure 63: Results from the pilot experiment, showing the measured depths (red crosses) and the true depths (blue lines), plotted for against the hole depths.](image-url)
F.4. Experiment 1 Results

Experiment 1 consisted of 3 sets, in each set the holes were probed 5 times. The workpiece featured 15 holes with depths of 1, 2, 3, 4 and 5 mm, and widths of with 1, 1.5 and 2 mm. The surface measurements (depth = 0 mm are given in set 1).

![Figure 64: Results from experiment 1, showing the measured depths (red crosses) and the true depths (blue lines), plotted for against the hole depths](image)

![Figure 65: Errors from experiment 1 plotted against the (reference) depths.](image)
F.5. **Experiment 2 Results**

![Figure 66: Results from Experiment 2, showing the measured depths (red crosses) and the true depths (blue lines), plotted for against the hole depths.](image1)

![Figure 67: Errors from experiment 2, plotted against the (reference) depths.](image2)

Experiment 2 shows that the presence of the trabecular structure has a considerable impact on the accuracy of the device. This is especially true when probing a 1mm wide hole.

The positive errors indicate that the 0.4 mm probe extended beyond the bottom of the hole; i.e., the experimental depth was more than the true depth as measured using a 1mm probe.
Negative errors indicate that the probe produced a bottom detection event before it reached the true bottom depth, likely indicating that it became stuck. Across all holes, the measurements had a mean error of 0.26mm with a SD of 1.31mm.

Interestingly, it appears that almost all measurements performed on 1 mm wide holes in trabecular holes have considerable errors; both positive and negative.

![Figure 68: A comparison of Experiment 2 Errors, w/o compensation, with compensation and with compensation without results from the 1 mm wide hole](image)

If we ignore the 1mm results, the accuracy of the system improves considerably. Using the compensation function improves it even further. For the 1.5 and 2 mm wide holes and using the compensation function, an error mean of 0.29mm with a standard SD of 0.61mm was realized.

To test how the pores of the fake trabecular bone influences the measurement when using a 0.4mm probe, 5 sets of 5 measurements were performed on the surface of the workpiece (i.e., depth = 0 mm). The results are given in Figure 69. It is noteworthy that set 1 of the surface measurements produced results which had errors of approximately 3 mm; i.e., the device measured 3 mm deep holes when probing on the surface (where no holes had been drilled). Indeed, as discovered before, the 0.4mm probe can penetrate through the trabecular pores. The negative errors produced by sets 3 and 4 are likely the result of the calibration process. When calibrating, the "zero position" is determined by probing on a undrilled surface; if the probe penetrates the surface (e.g. by probing in a pore or crater) during calibration, it produces a negative bias.

![Figure 69: Surface measurements on trabecular foam](image)
Appendix G: Simulation Experiment Results

Table 7: Hole properties, including hole code, for reference.

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<tr>
<th>Hole ID</th>
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<th>BV/TV:</th>
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The results from the simulation experiment are given in the following tables.

Table 8: Simulation results for the 0.4mm probe.

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### Simulation Experiment Results

#### Table 9: Simulation results for the 0.3mm probe.

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#### Table 10: Simulation results for the 0.2mm probe.
## Appendix G: Simulation Experiment Results

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Appendix H: References


