Towards Robot Guided Waterjet Surgery

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Abstract:

Papachristou and Bartes [1] first used a waterjet in the medical context. By using a waterjet in ablative liver surgery intrahepatic parenchyma could be washed away whereas vessels and ducts stay undamaged and intact which leads to less interoperative loss of blood. The aspect of tissue selectivity is one of the major advantages of using a waterjet to prepare soft tissue. This work first explains the physical basics of this method and differs between relevant properties which are responsible for the cutting effect. From that, the method of handling a waterjet applicator is derived. Furthermore, the restrictions of handling a waterjet applicator in laparoscopic surgery are shown and a robotic supported solution for this problem is announced. Finally, first experiments of the robotic solution using gelatin samples are presented and discussed.

Keywords: Waterjet Surgery, Medical Robotics, Minimally Invasive Robotic Surgery

1 Problem statement

Waterjet surgery uses a thin and high pressure jet to prepare soft tissue. The cutting effect depends mainly on the velocity of the jet which is proportional to the pressure and the characteristics of the soft tissue to be prepared [2, 3]. The soft tissue characteristics are patient specific. Therefore, the cutting effect is adjustable by varying the pressure of the jet. If the jet hits the tissue cutting is a result of either the impact pressure or the stagnation pressure [2]. The impact pressure is more effective but has to be maintained by the common oscillating movement of the waterjet applicator. In laparoscopic surgery this method is limited due to kinematic constraints. By the use of robotics these restrictions can be overcome and the full functionality of the waterjet applicator can be restored.

2 Materials and Methods

Using a waterjet to prepare soft tissue was first announced by Papachristou and Bartes in 1982 [1]. A conventional agricultural sprayer in combination with saline, a special nozzle and a pressure regulator were used to perform an intrahepatic dissection in ablative liver surgery. 45 lobectomies on dogs and 4 liver resections on humans show the selectiveness of this preparation method. Parenchyma can be washed away whereas vessels stay intact. This effect depends on the mechanical characteristics of the material. Each tissue has a specific mechanical resistance against the effect of the jet which corresponds to a specific pressure. As long as there is a clear difference in the resistance of two materials the pressure of the jet can be adjusted to wash away one material whereas the other one stays intact. These effects are also verified by different other works e.g. [4, 5]. The waterjet technique is also used in other surgical fields e.g. neurosurgery, orthopedics and otolaryngology [6, 7, 8, 9, 10].
The physical basics of the waterjet technique are understood in mechanical engineering, where it is used for material processing. According to [2] with the assumption of an adequate plunger pump the nozzle diameter does not affect the velocity of the jet. Due to this, the velocity of the jet depends only on the system pressure. In a first approximation Bernoulli's equation for incompressible fluids is applicable [2]:

$$v = \sqrt{2\frac{P}{d}}$$

$$v = velocity$$
$$P = pressure$$
$$d = fluid\ density$$

Hence, the cutting effect can be adjusted by varying the pressure. The geometry of the jet changes with increasing distance to the nozzle [3]. Directly at the nozzle the jet consist of a single liquid volume. With increasing distance the

compact jet decreases whereas the share of drops is increasing. Therefore, the best cutting effect can be achieved in the distance of a few centimeters to the nozzle [2].
Two different effects are responsible for the cutting [3]: the impact pressure and the stagnation pressure. The impact pressure (see left side of Fig. 1) is effective when the jet first hits the material. It only lasts for a view microseconds but has a very high impact during this phase. Afterwards, radial flow is formed around the target of the jet. This phase is called the stagnation pressure (see left side of Fig. 1) and the impact decreases significantly.

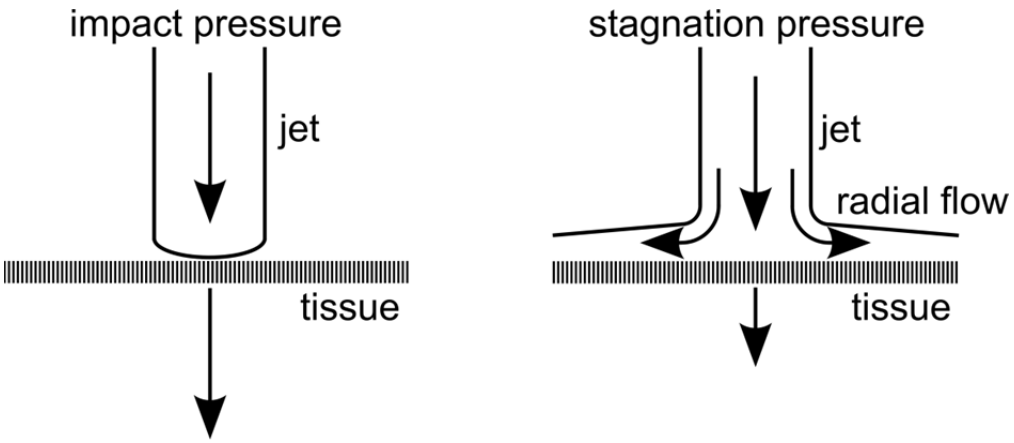

Fig. 1: Cutting effects, impact pressure (left side) and stagnation pressure (right side)

Assuming the depicted physical behavior of the jet can be transferred to soft tissue the common method of handling a waterjet applicator in surgery (Fig. 2) is comprehensible. By performing an oscillating movement tangential to the dissection trajectory the impact pressure can be maintained. This method can easily be performed in open surgery. However, in laparoscopic surgery the use of this method is limited. In laparoscopic surgery two degrees of freedom (DOF) are blocked at the fulcrum. With an applicator without additional DOF every location at the tissue can only be reached in one orientation (see left side of Fig. 3). By the use of robotics additional DOF can be integrated and every location is reachable in different orientations (see right side of Fig. 3) within the valid workspace of the robotic system. The actuation of the applicator inside the body overcomes the kinematic restrictions of laparoscopic surgery. Additionally, the tangential oscillation can be implemented as a semi-autonomous functionality supporting the surgeon. This approach enables the use of the waterjet technique in other interventions which are not using this technique so far.

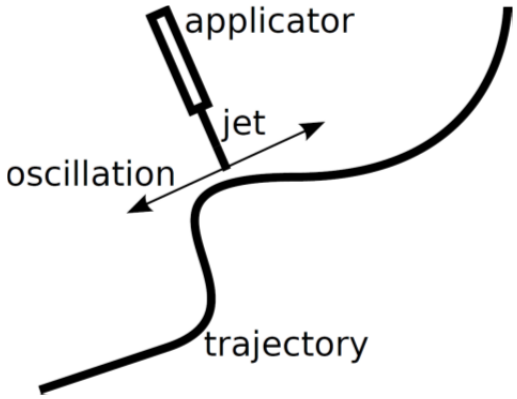

Fig. 2: Oscillation along trajectory

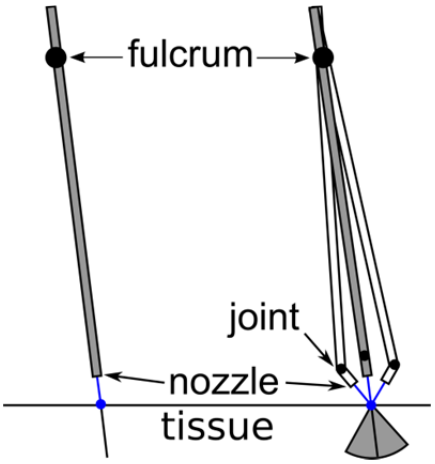

Fig. 3: Reachable applicator orientation

The common oscillation method of handling a water jet applicator was ported to a robotic system comprising the DLR MIRO robot [11, 12] and the DLR MICA instrument [13]. In the experiments the ERBEJET® 2 and its associated flexible probe is used. By coupling the nozzle of the flexible probe to the end effector of the DLR MICA the full manipulability can be restored. The waterjet can be handled in the manner known from open surgery. Furthermore the exhausting

task of generating an oscillation is carried over to the robotic system. The surgeon only commands the desired dissection trajectory and oscillation amplitude. The tangential orientation is derived from the desired trajectory and the oscillation is performed by the robotic system. As the desired frequency of the oscillating movement is in the range of 3-6Hz (derived from manual oscillation) the entire robot would move at this frequency outside of the patient. This is avoided by adapting the oscillation to some kinematic constraints of the robotic system. The oscillation is only applied to the universal joint of the DLR MICA. Hence, only the low mass of the end effector plus nozzle has to be accelerated to perform the oscillating movement. So, the DLR MIRO robot only follows the movement related to the commanded trajectory.
To model soft tissue ballistic gelatin (GELITA® GELATIN Type Ballistic 3) is used. Ballistic gelatin is characterized by its good comparability to human tissue. Its mechanical characteristics are adjustable by the mixing ratio. Furthermore, the good transmission factor is suitable for visualization of the preformed trajectories.

3 Results

As experimental trajectories a square and a circle are used. The square is suitable to show the behavior of the implemented method in case of an abrupt change in the direction of the trajectory. The circle shows the tangential approximation of the trajectory quite well. Both are simulated user trajectories generated by a trajectory generator.
The water pressure is adapted to the number of repetitions of the trajectory, the velocity along the trajectory and the mixing ratio of the gelatin samples. Every trajectory is repeated five times at a velocity of 0.015m/s. By using a mixing ratio of 93:7 (water : gelatin) and a jet pressure of 55-60bar a good cutting effect can be achieved without full penetration of the gelatin samples. In the experimental setup the trocar position is 120mm away from the end effector at the shaft of the instrument and the distance between the waterjet nozzle and the gelatin sample is 10mm.

Fig. 4: Circle trajectory


Fig. 5: Square trajectory

The resulting ablation of the test trajectories is shown in Fig. 4 and Fig. 5. For both the commanded amplitude of the oscillation is 3mm at a frequency of 4Hz. The radius of the circle trajectory is 9.5mm. The length of a square side is 20mm.

4 Discussion

The experiments show that the implemented method is able to follow an arbitrary trajectory. The course of both trajectories after five repetitions is thin and exact which shows the good repeatability of the trajectories. The tangential approximation to the commanded trajectory can be investigated by the circle trajectory (Fig. 4). The commanded circle is clearly approximated by a polygon. The frayed shape is a result of the amplitude of the oscillation. It is willfully chosen bigger to visualize the tangential approximation. In case of a human commanded trajectory the amplitude of the oscillation is adjusted by the user to achieve the desired ablation rate and accuracy. The square trajectory (Fig. 5) shows that the implemented method is also able to react to abrupt changes in the direction which can be recognized at the accurate corners. The slight overshoot in the forward direction is a result of the synthetic trajectory as the amplitude of the oscillation is constant along the commanded trajectory. This behavior is not relevant in case of a human commanded trajectory. Due to the fact that the user has knowledge about the course of the trajectory the amplitude of the oscillation can be adjusted accordingly.

5 Conclusions

The common method in handling a waterjet can be adapted to laparoscopic constraints. In spite of the promising results of the first experiments further tests are necessary especially with a human in the loop. The usability has to be checked concerning the control of the oscillation as well as the handling of an oscillating end effector. The oscillation poses an additional challenge to the surgeon because a virtual point in the middle of the oscillation has to be commanded. Besides this, additional surgical applications to liver tissue resection have to be identified which can profit of this improvement in handling a waterjet applicator in minimally invasive interventions.

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