Flexible surgical robotic device for spinal surgery

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***Abstract*— The present generation of surgical tools is reliant on drills and cutting tools that cannot navigate through small corners present in complex bones such as the spinal column. This paper summarizes the development of a flexible robotic surgical system to be used in minimally invasive spinal surgery (MISS), targeting the removal of cancerous tissue. The cutting system consists of a flexible drill and a water-jet cutter which may be used interchangeably; each capable of bending around the spinal column for tissue removal. A robot platform has been designed and fabricated that acts as a mount for the cutting system, and produces the desired range of movements. A graphical user interface (GUI) has been created to analyze the working envelope of the platform and provide an interface for control by a surgeon. Experimental testing shows that prototypes of both the drill and water jet cutter are able to go around angles up to 120° and remove soft tissues off the bone. The developed systems could be used to remove cancerous tumors surrounding the spinal column in MISS procedures.**

I. INTRODUCTION

The integration of robotic technologies in surgical instrumentation has contributed to the further development of Minimally Invasive Surgery (MIS), aimed at reducing patient trauma and hospitalization costs [2]. The main requirement for such procedures is the ability of surgical tools to reach the operative target through complex anatomical pathways. The present generation of surgical tools is reliant on drills and cutting tools which vary in their principles of operation. However, these tools cannot navigate around small corners present in complex bones such as the spinal column. The target application for the flexible surgical tool is the removal of cancerous tumors surrounding the spinal column (Fig. 1). This procedure targets the removal of cancerous tumors sitting on top of and around the lumber vertebrae. At present, the surgeon approaches the patient from the back of the body, and the tumor is removed only from the posterior side of the spinal column using the available rigid tools, which are typically hand-held. This approach, however, makes the removal of cancerous tissue on the anterior side of the spinal column extremely challenging. In extreme cases, the surgeon may attempt to remove additional tumor growth by entering through the mouth or front part of the neck; however this entails additional (typically unacceptable) risk for the patient and is extremely challenging for the surgeon.

Fig. 1. non-reachable cancerous tissue (red) on the anterior side of the spinal column (left) [1], and photographs of the actual surgery taken as a part of this study.

In this paper, a flexible surgical tool capable of going around the spinal column for removal of tissue on both the anterior and posterior sides of the spinal column is presented. The tool is designed such that it may integrate with a robot system and would allow the removal of tumor growth in front of the spinal column without the need for additional invasive entry; thus risk to the patient would be much-reduced.

Two alternative methods of cutting were applied: pressurized water-jet and mechanical drilling. Pressurized water-jet cutting was originally developed in the steel and glass-forming industries, where ultra-precise cutting was required [3]. This technique was adapted for medical applications [4] and was further developed and modified [5],[6]. It is used in many surgical applications including: Cutting Bone, Liver Surgery, Renal Surgery, Kidney Surgery, and Neurosurgery. Fig. 2 shows the typical constituents of a medical water jet cutting system [7]. The water reservoir normally contains sterile saline.

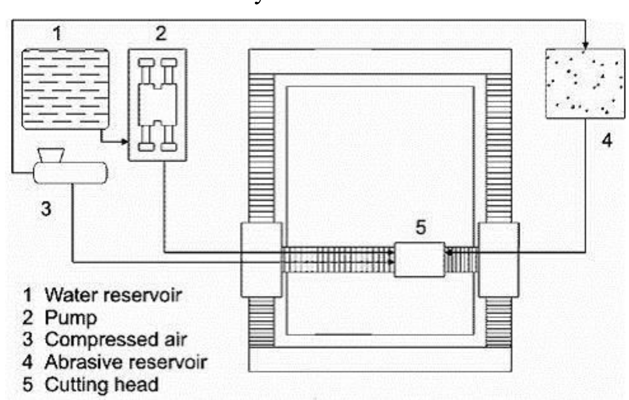

Fig. 2. Schematic of water jet device [7].

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Surgical drills are an essential tool in orthopedic surgery. They can be used for many purposes, such as for cutting holes in bone for the insertion of various implants. The modern drill bit is a complex engineering tool whose various design elements allow penetration of bone in an efficient manner, capable of consistently creating channels of uniform size [8].

II. SURGICAL CUTTING SYSTEMS

A. The Flexion system

The Flexion system (Fig. 3) is a surgical retraction instrument with an adjustable articulated tip (FE), and an overall length of approximately 250mm (NEWCO Surgical). It is primarily formed from a Ø5mm hollow round shaft (R) of 1.4301 surgical steel, which extends virtually the full length of the instrument. A handle (H) near the proximal end is formed from polyphenylsulfone (PPSU) plastic material. A revolving nut/tensioning screw (TC) is located beyond the handle at the proximal end.

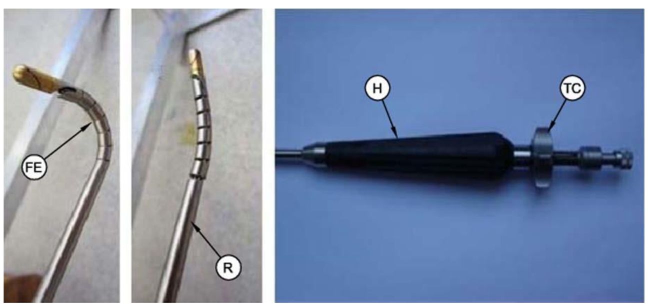

Fig. 3. The Flexion system.

An adjustable lower distal tip section (FE) is comprised of a series of links held together by one or more cables of 1.4305 steel, with the cables routed within the hollow round shaft (R). When the cables are tightened via a threaded mechanism connected to the nut/tensioning screw (TC), the tip bends to form an approximate arc or J-shape, with the radius of the arc diminishing as the tension increases. Conversely, as the cable tension decreases, the adjustable tip resumes its default near-linear form. Thus the tip can be made to bend in a controlled manner up to approximately 120° from the shaft axis.

B. Surgical water jet cutting prototype

The water-jet cutting system consists of a pressure washer (Nilfisk C110.4-5) with a pressure range of 75-100 bar. With reference to Fig. 4, the pressure washer, or source, is connected to a flow control valve, which controls the pressure and rate of flow. The flow control valve is then connected to a solenoid valve, which essentially acts as an on-off switch, allowing the flow of water to be controlled using a PS2 controller. Beyond this is a pressure gauge. The pressurized water is pushed through a Ø0.84mm high pressure solid stream nozzle via a high pressure reinforced tube with standard fittings. The water jet prototype (WJ) is then integrated with flexion system (FS) to complete the flexible surgical water jet prototype (Fig. 4).

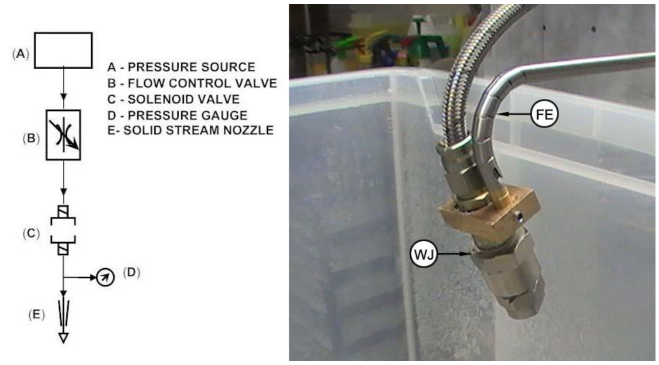

Fig. 4. Schematic of water jet system (left), and the integration of water jet and Flexion systems (right).

Generally, water-jet technology does not damage the surrounding tissues during the cutting process, partly as it only reaches a low temperature. It enables high-precision cutting, and leaves a clean cut as it instantly flushes out the debris, and decreases bleeding during surgery [7].

B. Surgical drill prototype

With reference to Fig 5, the drilling system consists of a flexible Ø3mm shaft (FS), made by twisting several layers of wire around a central core [9]. The flexible shaft is connected to an electrical drill (ED) via flexible coupling (FC). The drilling and Flexion (FE) systems were then integrated together along with the cutting burr using the housing (H), embedded with bearings and solid couplings.

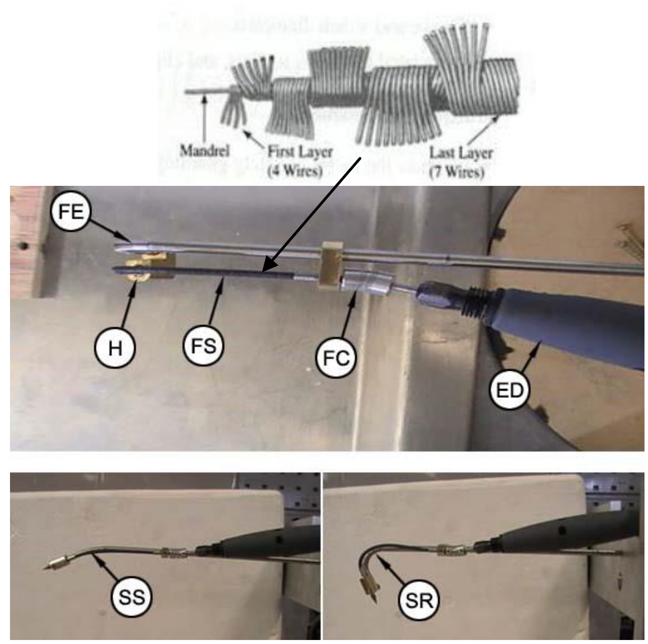

Fig. 5. The flexible drilling system, showing non-tensioned distal tip (SS), and predetermined 'J'-shape of tightened distal tip (SR).

III. SURGICAL ROBOT SYSTEM

With reference to Fig. 6, both of the surgical cutting tools (T) need to be positioned and moved around the dorsal parts (e.g. the vertebral cavity VC) of patient (P), who would be laying face-down during the surgical procedure. The tools could be hand-held and manipulated by a surgeon, but there is an intrinsic problem with fatigue in the human hand during longer length procedures [10]. To overcome this, a parallel manipulator robotic platform, which is also called the octahedral platform [11] (OP), has been designed that acts as a mount for the tools (T), and produces the desired range of movements. The octahedral platform is a six degrees of freedom (6DOF) parallel manipulator, which is comprised of a fixed top (FT), and a mobile base (MB), connected by six individually-powered extensible linear actuators (LA) or 'legs'. The linear actuators are configured in an octahedral arrangement, commonly known as a Stewart Platform. This configuration was chosen over a serial manipulator due to it producing an inherently more stable end effector position. The octahedral platform is intended to be suspended from a rigid structure (RS) located above the prone patient (P).

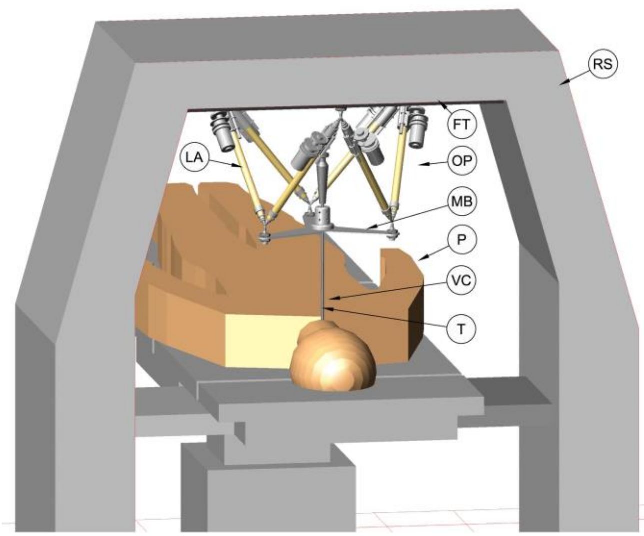

Fig. 6. An illustration of the assembled surgical robot device installed in an operating theatre environment.

A. The Design of the Mechanical System

With reference to Fig. 7, the vertebral cavity (VC) containing the spinal column of a typical prone adult patient (P) has a cross-sectional area of very approximately 60mm width and 80mm height, and an average length of approximately 700mm.

However, with reference to Fig. 1 it will be seen that the tumors that are the device's target are typically less than approximately 100mm in length along the axis of the spinal column. Therefore it was decided that the surgical cutting tool (T) need access a section of the vertebral cavity only approximately 120mm in length, rather than the full 700mm or so. This helped to simplify the mechanism, and prioritized end effector accuracy within a smaller working envelope.

Taking the spinal column as being very approximately cylindrical in form, and based on the dimensions as above, the end-effector working envelope was established as an approximate sphere (S) of Ø120mm. Based on the ability of

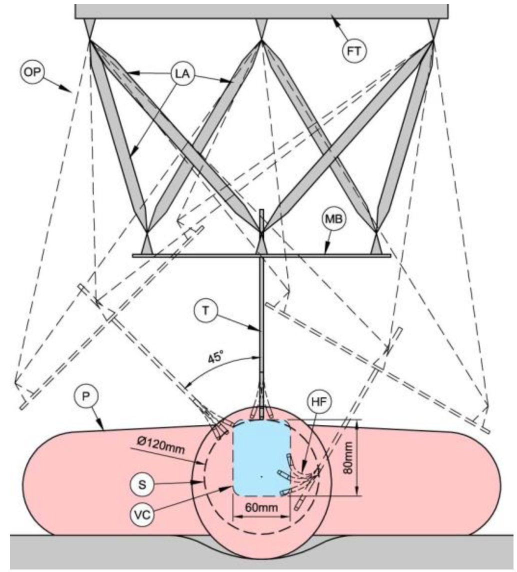

Fig. 7. Surgical tool (T) working envelope relative to vertebral cavity (VC).

the Flexion system to assume a hook-like form (HF) around the spinal column, the platform was configured to give an angular displacement of ±45° from the z-axis, thus giving the surgical tool complete access to all sides of the spinal column.

For the variable-length linear actuators, or legs, a relatively simple single-portion extension configuration was used; with reference to Fig. 8, this comprises only two main groups of components: an outer, cylindrical 'barrel' (B) and a corresponding inner 'piston' (P). The lengths when fully retracted/ fully-extended are approximately 270mm and 450mm respectively, i.e. a ratio of approximately 1:1.7. A single lead screw mechanism, powered by a DC motor (M) via a gear assembly (G), produces the linear movement.

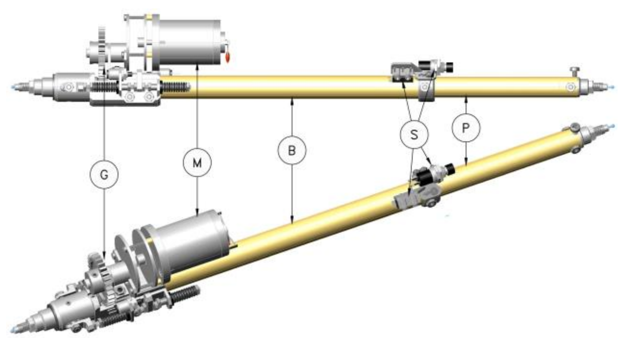

Fig. 8. Variable length linear actuator.

To connect the linear actuators/legs to the stationary/fixed top and lower mobile base, existing octahedral robotic surgery platforms typically utilize two degree-of-freedom pivot joints. These are robust, but not concentric at the end vertices of the adjacent legs. Primarily to simplify the kinematics, near-concentric (within 1-2mm), passive, free-rotation, multi-leg joints [12] are used. These were originally developed for use in variable-geometry space frames. The joints (Fig.9) consist of a number of sub-assemblies (SA), which each connect to the ends of the linear actuators (LA), or legs, and the mobile base (MB). A flexible, slightly elastic cord (C) passes through each subassembly. The cord is precisely adjusted via a threaded mechanism (TM) to pre-tension it. The tips of the sub-assemblies are hollow barrel forms (HB), through which the cord passes, and the ends of the cords are tightly intertwined with each other. The pre-tensioning of the cord pulls the ends of the nylon barrels together, thus allowing free rotational movement, but resisting the primarily tensile and compressive forces imposed by the legs.

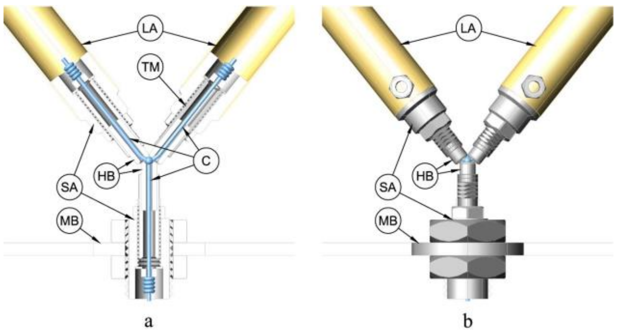

Fig. 9. Connector joint assemblies, shown in (a) section and (b) side view.

B. The design of the control system

The control system comprises two main elements: the electronic hardware, and its programming language.

The user input device selected was the NOVINT Falcon. This controller allowed a translational input of x, y and z coordinates (3DOF's). However, a graphical user interface (GUI) was generated using MATLAB to control the three rotational input values (θ, φ, Ψ). The structure of the code used to process the user input into meaningful motion of the platform is shown in Fig. 10 and was written in MATLAB.

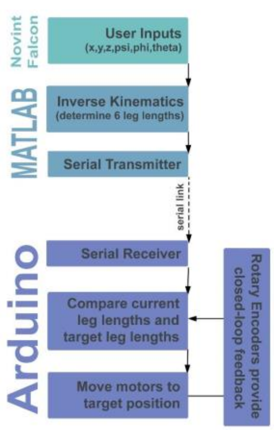

Fig. 10. Code structure.

The position of the end-effector is specified by the input controller. In this case, the orientation and position of the flexible probe in 6DOF is specified by the user. It is then necessary to calculate the required leg lengths of each of the six platform legs in order for the robot platform to impose the desired orientation of its end-effector.

This backwards calculation is known as inverse kinematics. Based on [13], the inverse kinematic was formulated for the 3-3 parallel octahedral platform.

The layout of the electronics used, along with the associated program code that implements full positional control of the platform, can be seen in Fig. 11. The figure clearly illustrates how each electronic component is connected, powered electrically and controlled electronically from the input side through to the output side.

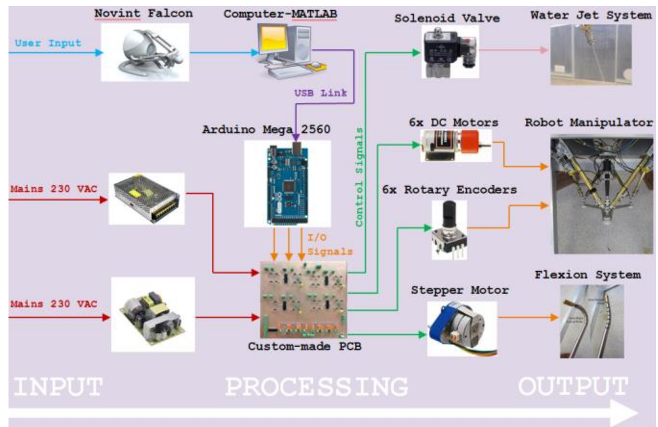

Fig. 11. Component layout of the system.

IV. MODELLING AND SIMULATION

A. Modelling

The robot was modelled as six leg subsystems attached to the top and base plates to form the plant block of the model. Fig. 12 shows the full block diagram of the platform.

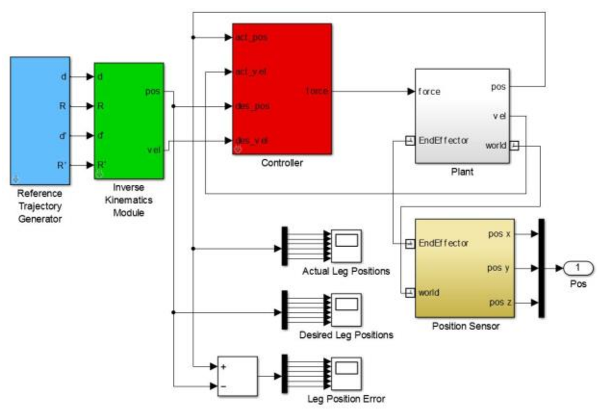

Fig. 12. The complete platform model.

The reference trajectory is specified in six degree pose space, and an inverse kinematics module converts it into one through six degree leg position space. A generic Proportional-Integrator-Derivative (PID) controller attempts to drive the manipulator along the desired trajectory.

The output data of the behavior of the surgical platform system is obtained via a position sensor block. Fig. 13c shows the x, y, and z values of the position of the body block, representing the end effector moving over time as the model simulates. Fig. 13a represents the 2D form and Fig. 13b the 3D working envelope of the end effector.

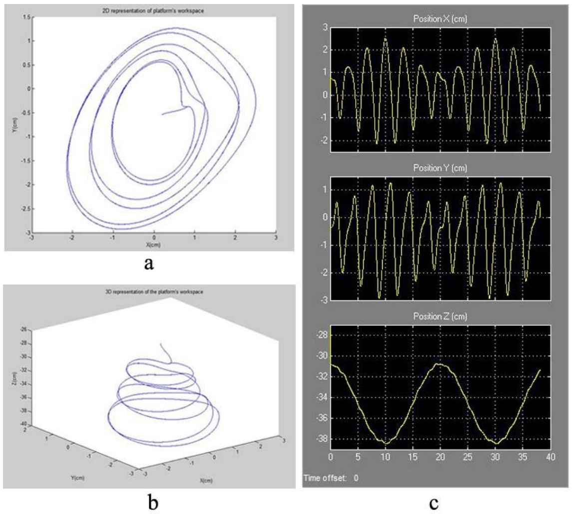

Fig. 13. Output data representation, working envelope in (a) two and (b) three dimensions; (c) x y and z position of the end effector.

B. Simulation Using Graphical User Interface (GUI)

In order to validate the inverse kinematics formulated in section III-B, a simulation of the HexaSlide Manipulator type designed by Merlet and Gosselin [14] was created in MATLAB that simulated the movement of a 6DoF model receiving inputs from the Novint Falcon. The desired position (x, y and z) and orientation (φ, θ and Ψ) of the end-effector was specified and inverse kinematic equations were used to calculate the nominal leg lengths of each of the six platform legs. The leg lengths were plotted real-time on a 3D model figure as can be seen in Fig 14.

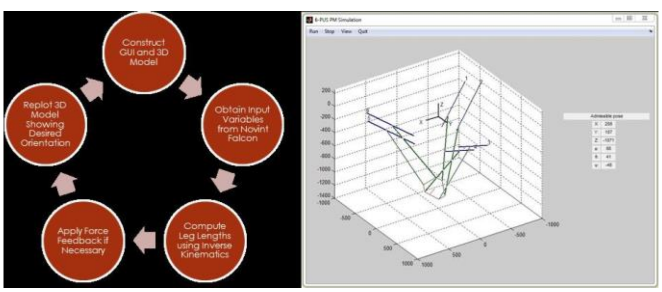

Fig. 14. Logic flow chart of the simulation (left) and the resultant simulation of the platform (right).

The simulation structure consists of three main subsections: the model construct, the graphical user interface (GUI) initialization, and the draw function. The draw function runs in an infinite loop so as to continuously update the figure of the platform in real time until the simulation is closed. The end product is a simulation of the parallel platform in 6DOF controlled by user input from the Novint Falcon.

V. Experimental Testing and Results

A model of a human lumbar spine was used to test the position and the degree of angulation of the flexible system. The flexible drill/water jet was inserted between L2 and L3 of the lumber spine model. The test showed that the flexible drill/water jet was able to move between the transverse processes of the lumber vertebrate freely and bend to reach the lower mid-line of the vertebrate body (Fig. 15). This suggests that the size and the full curve of the 'J'-shape of the device is very suitable for such surgeries.

A human femur model was used to test the ability of the flexible surgical drill system. The speed range of the drill used in this test was 25,000 - 30,000 rpm. The experimental result showed that the prototype was able to drill a hole of Ø3mm and 10mm depth rapidly and smoothly, whilst the Flexion system forms a 'J'-shape. However, as the bend angle of the flexible tip became more pronounced, a slight increase in the temperature of the flexible shaft was noticed, which could affect its mechanical properties over time.

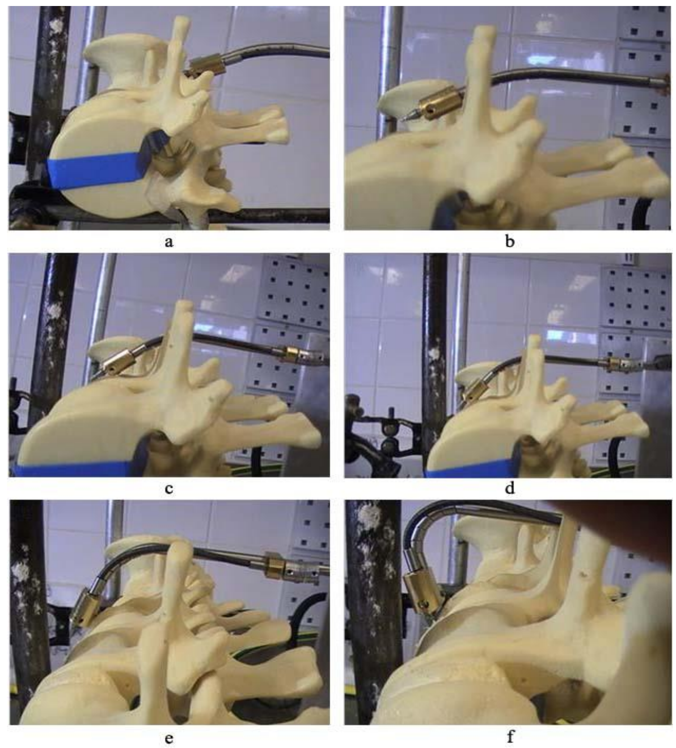

Fig.15. Side view of the flexible drill from insertion (a) to full bending (f).

A surgical environment was replicated, representing a typical surgical procedure on the lower lumbar section of the body (Fig. 16), with the aim of removing tissue in a controlled manner from a lamb femur.

The water jet system was connected to the functional head. The aim of the test was to assess the effectiveness and performance of the robot in controlling the movement of the surgical tool. It did this by entering the body, navigating the probe tip to the target surgical site, conducting a dissection of tissue, controlling the orientation and curvature of the probe tip, and exiting the body cavity, whilst always avoiding contact with any internal organs. Overall, the tissue was successfully dissected and the robot functioned well in carrying out the procedure in 5 minutes and 20 seconds; this time is likely to improve with practice and following improvements to the platform hardware.

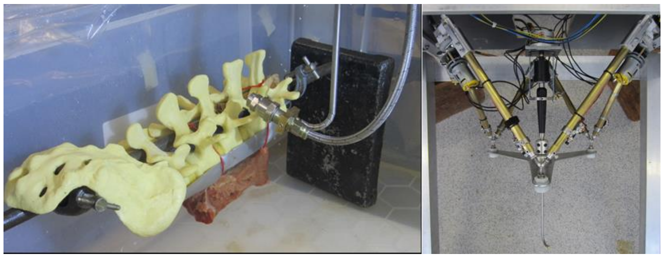

Fig. 16. Mock surgical setup – flexible tip/probe equipped with water jet tool.

VI. DISCUSSION

Despite the advantages of implementing a water jet system to cut tissues in a surgical environment, there is a risk of the jet cutting through the target tissue, and then going on to hit the underlying tissues and damaging them. By varying the jet pressure, a degree of control can be given over its effective cutting depth. This could be calibrated by measuring the cutting depth at various pressures via experiment. The distance moved by the nozzle could be measured by fixing a distance measuring sensor on the nozzle and another on the incision access. The overall depth of cut would then be the distance moved by the moving nozzle added to the effective cutting depth of the jet at the pressure as set.

Testing of the water-jet shape showed that the spray pattern of the output jet affected its cutting ability. It was thought that a turbulent flow was generating at the entrance of the nozzle, caused by the high pressure flow. To overcome this defect, the fluid mechanics theory of 'T' junction [15] flow was applied by using a second flow-controlling valve. This formed a 90° 'T' branch arm, and the pressure at the nozzle was reduced by discharging a set amount of water from the second valve, leading to a solid stream output jet.

Implementing the 'T' junction modified the pattern of the outlet jet and greatly improved its effectiveness; at 25 bar it could remove 15mm depth of meat off the bone of a lamb femur (Fig.17).

a b

Fig. 17. Experimental water jet cutting, tissue removal from lamb femur (a), meat separated off the bone (b).

The robot platform built used high-speed geared DC motors, coupled to leadscrew mechanisms, to extend and retract the platform's legs. Whilst cost effective, the DC motors were inadequate in actuating the lengths of the legs in a timely manner. The trajectory control is obtained by limiting the input velocity within a certain threshold, in order to allow sufficient time for the system to catch up with the input signals. The slow leg extensions made the threshold value very small, which meant that the velocity of the input signals was limited to a very low value as well. Instead of low-cost DC motors, pneumatic actuators or higher-torque/higher-geared servo motors could be used. These alternatives would almost certainly give improved response times, whilst still delivering sufficient accuracy and rigidity for the intended surgical application.

VII. CONCLUSION

We have developed a surgical robotic system that could be used in spinal surgery procedures, with promising early results. Successful feasibility tests, modelling, and simulations were all undertaken. The next steps in the development of the system will be implementing the proposed method of controlling the depth of water jet cut, exploring different means of powering the platform legs, and further testing and modelling.

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