Using current measurement to estimate palpation and grasping forces in robot-assisted minimally invasive surgery

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INTRODUCTION

Robot-assisted minimally invasive surgery (RAMIS) has gained popularity in recent decades through use of the da Vinci master-slave surgical system offering improved vision, precision and patient recovery time compared to traditional MIS [1]. However, certain shortcomings prevent RAMIS from fulfilling its maximum potential, including the lack of haptic feedback provided to the surgeon [2]. Attempts have been made to develop sensorised surgical instruments as a means to detect interaction forces during RAMIS and provide surgeons with haptic feedback. However, the size of force sensors and incision ports, the sterilisation of tools at high temperature as well as the disposable nature of surgical tools have so far prevented integration of end-effector/tissue force sensing in RAMIS [3, 4].

Force estimation algorithms that do not require sensing hardware at the operating site include visual estimation of the shaft deformation [5], modelling of surgical tool-tissue interaction [6] and the use of motor current, among others. Sang et al. modelled the dynamics of a da Vinci robot and, in conjunction with measured motor current, estimated the external force applied at the tip of the surgical tool [7], while Zhao and Nelson created a 3 degrees-of-freedom (DOF) surgical grasper prototype with joint dynamics modelled as individual linear 2nd order systems to estimate external forces [8]. These methods require some form of modelling and simplification (e.g. neglecting friction) which can affect the estimation accuracy. Further, the complexity of these algorithms may not allow for suitable update rates required for haptic feedback, thus affecting the system's overall stability and transparency.

In this work, we propose an alternative method to force estimation in a RAMIS context, using the real-time measurement of the instrument motor current. Off-the-shelf force sensors are characterised and then used to determine the correlation between the motor current and the applied force in palpation and grasping with DaVinci forceps.

MATERIALS AND METHODS

A load cell (CZL635, Phidgets, 49 N range) and a capacitive force sensor (SingleTact, 45 N range) were characterised through use of calibration masses. The load cell was orientated with its sensitivity axis in the direction of gravity and masses were hung from it. For the SingleTact sensor, a 3D printed (Nanocure, Envisiontec) hemispherical dome was attached to one side of the sensing element. Calibration masses were placed on top of a 1-DOF beam-pivot structure with their weight applied directly on the dome-sensor, placed underneath the beam and on high precision scales. In both cases, the associated voltage was recorded.

The sensors were then used to measure grasping and palpating forces exerted by the gripper of DaVinci forceps as shown in Fig. 1a-b. For grasping, two 3D printed (TangoPlus, Stratasys) hemispherical domes were attached to either side of the SingleTact sensor for even distribution of the applied load.

The instrument has 3 DOF, controlled by 4 motors: 2 for the pitch and roll and 2 for the yaw and grasping of the jaws. For the grasping and palpation experiments, the jaws of the forceps were actuated by 2 DC motors (Maxon, 3.89mNm, 62:1 reduction). The motors' shafts were connected to the gearbox of the instrument via the blue fixtures in the custom-made interface shown in Fig. 1c-d, while the pitch and roll were kept constant (red fixtures). During palpation, the two motors had equal current, while during grasping the motors had equal magnitude of current while turning in opposite directions.

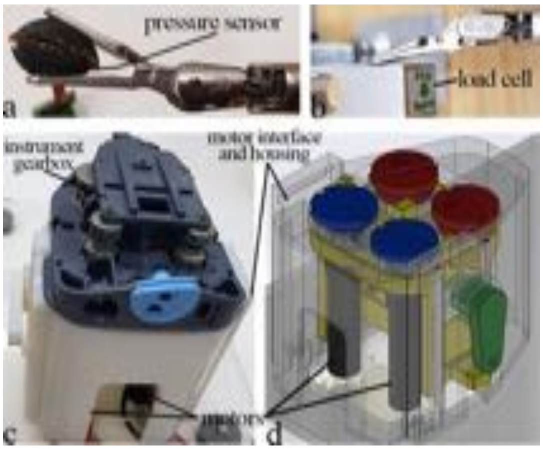

Figure. 1. Da Vinci forceps **a)** grasping the dome-sensor, **b)** applying vertical force to the load cell, **c)-d)** with a custom-made housing for the motors

RESULTS

For both sensors, the characterisation experiments were repeated 3 times and the resulting voltage averaged with a standard deviation of 0 (CZL635) and 0.0022 (SingleTact) (Fig. 2). The load cell has a linear relationship between force and voltage with an R^2 value of 1; while the SingleTact sensor has a cubic relationship between force and voltage with an adjusted R^2 of 0.9988. To map the measured force to the motors' current, the motors were driven using current control: sensor readings

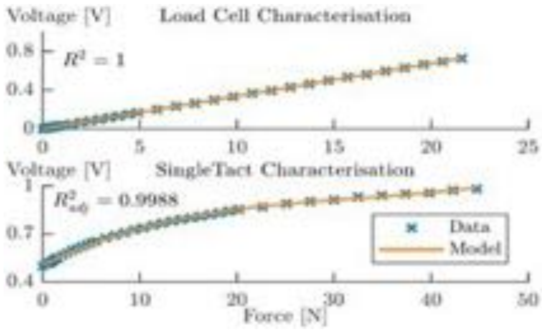

Figure. 2. Characterisation of the force sensors

were taken for every 0.1mA increase of the current between 10-309mA (maximum continuous current of the motors). The grasping and palpation experiments were each repeated ten times. The results were then filtered using smoothing splines (smoothing parameter in the range of [0.5, 0.53]) and averaged with standard deviation of 0.63 (grasping) and 0.12 (palpation). Fig. 3 shows that there is a linear relationship between current and force for the grasping, while the mapping during palpation can be modelled with a cubic polynomial.

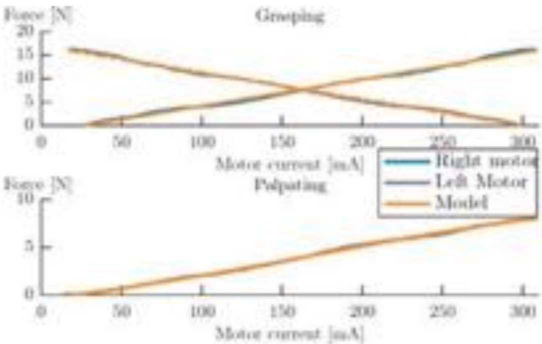

Figure. 3. Mapping of the motors' current to the grasping and palpating forces of the gripper for both motors controlling its right and left jaw

CONCLUSION AND DISCUSSION

The maximum (averaged) forces recorded were 17 N for grasping and 8 N for palpation, which were lower than expected. This was due to friction and the coupling of the instrument's cable-driven system [9] between the mechanisms responsible for the grasping/yaw and those for the roll and pitch. In this experiment, roll and pitch were kept constant (red fixtures in Fig. 1). Furthermore, the forceps used in these experiments was a retired Da Vinci instrument, with cables not operating in their nominal capacity.

Nevertheless, the results suggest that correlation between motor current and forces exerted by the end-effector can be found for both grasping and palpation. This is highly beneficial in surgical applications where due to miniaturisation and sterilisation of surgical instruments, attaching sensors directly to the end-effector has not yet offered an acceptable solution. Furthermore, the results show that palpation is possible by pushing with the grasper without having to grasp the tissue as previously done in [8], which can be more intuitive for the surgeon.

Our further work includes extending our testing to different surgical tasks where force and pressure estimation can improve surgical performance. This will mean combining all instrument DOF (including roll and pitch) as well as examining leverage effects caused by the point of grasping (distance from the tip of the instrument) and can be further applied to instruments with different articulation and actuation mechanisms such as finger-like tools [10].

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