Hand exoskeleton for remote control of minimally invasive surgical anthropomorphic instrumentation

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INTRODUCTION

Minimally invasive surgery (MIS) has evolved from traditional laparoscopy, which involves the surgeon using hand held tools through small incisions on the patient's body, to robotically assisted (R-A) surgery, during which the surgeon remotely operates articulated instruments attached to the end of robotic arms. Advances in the design, articulation and flexibility of the instruments have added to the popularity of R-A MIS [1]. Nevertheless, the way that the instruments are controlled affects not only their efficacy, but also the ergonomics and the learning process for the surgeon.

In [2], we have presented a concept for hand-like instruments, each carrying an articulated 3-finger system which imitates the surgeon's fingers' exact movements. The anthropomorphic system design aims to reduce the 'cognitive gap' between the way that instruments are manipulated and the surgeon's natural hand movements. The master controls of the Da Vinci Surgical System [3] manipulate a simplified gripper attached to a 3-DOF wrist. In a very similar way, the Phantom Omni haptic device is used to control surgical instruments in various other designs of MIS instruments [4]. If the instruments to be controlled are more complex, more complex master devices are required.

Systems for motion capturing of hands span from on-the-hand hardware with finger position capturing, such as data gloves and exoskeletons, to external imaging systems based on intensive image processing and often covering a limited field of view. Data gloves, used for similar tasks, are expensive and generally lack durability [5]. Besides being non-adjustable and requiring calibration for each user, data gloves do not offer detailed joint tracking. In [6], a wrist-worn real time hand tracker is proposed, which avoids burdening of the hand with extra load. Limitations include occlusions resulting from overlapping fingers. Besides finger tracking, wrist rotation and bend tracking is very important especially during surgical tasks. However, these cannot be modelled using a wrist-worn tracker or a data glove.

Consequently, we report here on the development of a lightweight and adjustable hand exoskeleton that can sense movements of the surgeon's finger's joints and translate it to movements in the joints of the instrument, such as the one we presented in [2]. Most exoskeletons in the literature are aimed at actuation of hands or arms [7], often ending up being bulky and heavy. By removing all the motors and encoders, the design can be simplified. The following sections present the design of an initial prototype of a hand exoskeleton for control of the MIS instrumentation in the MIS concept described in [2].

MATERIALS AND METHODS

The proximal interphalangeal (PIP) and distal interphalangeal (DIP) joints of the fingers are hinge joints capable of only flexion and extension (1 DOF each). The metacarpophalangeal (MCP) joints at the base of the index and middle finger, however, are saddle joints, and hence capable of abduction and adduction (2 DOF). The thumb can also be modelled by having two 1-DOF (interphalangeal-IP and metacarpo-phalangeal-MP) and one 2-DOF (Carpometacarpal-CMC) joints. The exoskeleton was designed according to this layout, so that it can follow the fingers' natural motion.

The angle of each joint is measured using two types of hall-effect sensors (MLX90316 and MLX90333, Melexis, Belgium) measuring 1 DOF and 3 DOF. The 1-DOF sensor can give absolute angular position of a small magnet located parallel to the sensor in a rotary type joint. The 3-DOF sensor senses the magnet position anywhere in its surroundings, being suitable for a ball type joint. In order to simplify the exoskeleton design, the PIP and DIP of the index and middle fingers were considered coupled (as they are in the human hand). Therefore, instead of having different sensors for each joint, the exoskeleton carries only one sensor for the PIP joint, while the position of the DIP is calculated by the relationship between the PIP and the DIP given in [8]. The whole structure comprises seven sensors in total: three 2-DOF (MCPs and CPC) and four 1-DOF (PIPs, IP and MP).

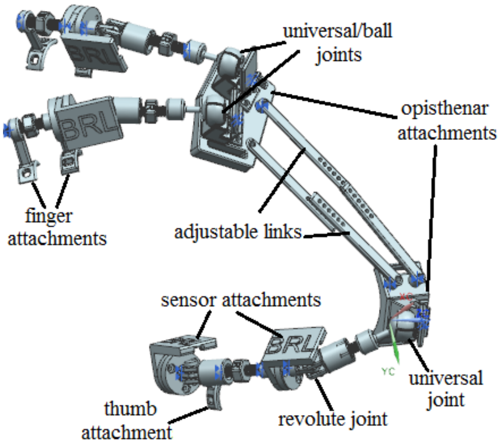

Fig. 1 CAD drawing of the exoskeleton assembly

RESULTS

The computer-aided drawing with the main exoskeleton components is shown in Figure 1. Each exoskeleton joint is fastened to the hand with a flexible attachment. The joints are connected to each other via adjustable links. The MCP and CPC joints were designed as ball joints in order to reduce the bulkiness and the complexity of the component. The sensors are attached at the side of each joint on the non-contacting parts, as shown in Figures 2 and 3.

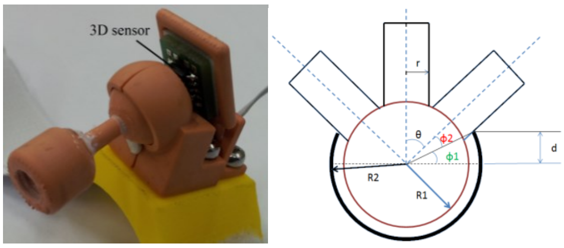

Fig. 2 Ball joint prototype and range of motion calculation

The typical ranges of motion of each joint in degrees are: 0-90º for the MCP, 0-110º for the PIP and 0-70º for the DIP. To ensure unrestricted motion, the range of the ball joint was set to be at least 90º. From the parameters in Figure 2, the range of the ball joint can be calculated as:

$$2\theta = 2\left(90 - \phi_1 - \phi_2\right) = 2\left(90 - sin^{-1}\frac{d}{R_2} - sin^{-1}\frac{r}{R_2}\right)$$

where $R_2 = 6\,mm$, $d = 3\,mm$ and $r = 1.5\,mm$.

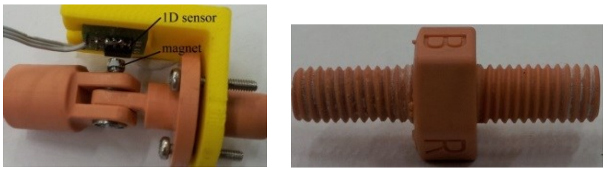

Fig. 3 Revolute joint and double threaded adjustable link

The joints are connected to each other via double threaded links (Figure 3). One side has a left-hand thread, while the other has a right-hand thread so that, by turning the link, it can be extended (clockwise) or shortened (anti-clockwise).

DISCUSSION

The design for a sensory hand exoskeleton presented in the previous section meets the design requirements. The double thread links not only make the mechanism adjustable to a variety of hand sizes, but also allow the exoskeleton to be lightweight (approx. 130 gr), without added material for modifications as in [7]. Furthermore, each of its joints covers a range of motion similar to, or greater than, that of a human hand, which ensures natural unrestricted hand motion and comfort. The whole structure is as compact as possible and it has twelve DOF, ten of which are actively sensed while the other two can be calculated from the neighbouring joints. The next version of the exoskeleton will include sensors for wrist motion tracking, in contrast to the methods used in [5-6], where this would not be possible.

The exoskeleton was fabricated using 3D printing (NanoCure, Envisiontec, Germany). Figure 4 shows part of the exoskeleton fitted on the side of the index finger and the electronics attached to the wrist. Sensor processing electronics will be placed in a compact box, the size of a hand watch.

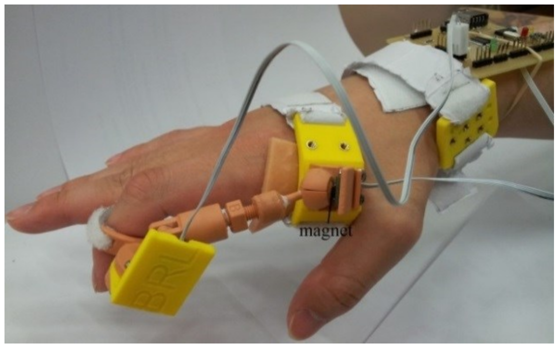

Fig. 4 Testing the exoskeleton on one finger

In the first phase of our investigation, the surgeon will explore use of the exoskeleton to manipulate virtual objects. The sensory electronics will be connected to a PC via USB and the output of the sensors fed into a 12-DOF hand kinematic model. The user will wear the exoskeleton and the movements of his/her fingers will be simulated in real-time. This will form the basis of a surgical simulation environment, where the surgeon will be able to test the concept of controlling hand-like instruments as described in [2]. The accuracy of the structure needs to be tested and the teleoperation suitability will be evaluated in our future work. At that stage, the exoskeleton will be connected directly to two corresponding surgical hands.

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