Rate Dependency during Needle Insertions with a Biologically Inspired Steering System: an Experimental Study

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***Abstract*— Percutaneous intervention is a common Minimally Invasive (MI) surgical procedure for the treatment of various disorders. It generally involves the insertion of slender needles deep within tissue, as lesions can be several centimetres below skin level. Consequently, deviations might occur which need to be accounted for and corrected by steering the needle tip during the insertion process. Needle steering systems, however, are necessarily disruptive to the substrate, with the potential to cause larger migrations of deep-seated targets, as well as potentially increasing the extent of tissue trauma at the needle interface, when compared to straight needles.**

This study aims to investigate different insertion modalities for a biologically inspired multi-segment needle, which is able to steer along three-dimensional trajectories by exploiting a quasi-linear relationship between the relative displacement of the needle segments and the curvature magnitude and direction plane at the tip. We demonstrate that different segment insertion speeds do not affect this relationship during experiments in gelatine, and thus a new steering approach is proposed to steer the needle into the substrate which substantially improves upon the manoeuvrability (i.e. the rate of change of steering angle) of the needle.

I. INTRODUCTION

In modern surgical practice, Minimally Invasive (MI) instruments have become the preferred choice due to the reduction in intra- and post-operative risks when compared to open surgical access [1]. MI procedures generally involve the insertion of rigid tools either through small ports in the skin (e.g laparoscopy) or a keyhole aperture in the skull (e.g. keyhole neurosurgery). A wide range of technologies have been developed to assist the surgeon during these procedures: from visual feedback systems, such as interventional Magnetic Resonance Imaging (MRI) and Computer Tomography (CT), to assistive systems, such as robots and mechanical fixtures (e.g. the stereotactic frame). With straight MI instruments, the surgeon must evaluate if a target is reachable through a straight line path. If this is not the case, for example due to 'no go' areas between an entry point and the target, the procedure must generally be carried out with an open surgical approach.

In the last decade, several solutions have been proposed to address this issue by means of steerable needle systems which are able to travel along curvilinear trajectories within a substrate. These solutions can be classified into four main categories: needle steering methods based on the lateral motion of an external base and deformation of the soft tissue [2], [3]; steering control of flexible needles with a fixed-shape bevel tip [4], [5], [6], [7]; steering control using concentric tubes [8], [9]; and steering using a bio-inspired multi-segment flexible needle [10], [11], [12], [13], [14].

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This paper is part of the body of work on STING, a biologically inspired multi-segment needle system, which was recently shown to be able to steer in full three dimensional (3D) space by controlling the relative offset between the segments [15]. In [15], the importance of the insertion cruise speed was demonstrated, while a simplified 3D kinematic model of the needle was published in [16], which describes key simplifications and assumption made to establish a relationship between the steering angle of the needle and the offset between the segments. Among these assumptions, a quasi-linear relationship between the relative offset between segments and the steering angle of the needle tip is established for a fixed cruise speed of $1 mm/sec$ when the needle is inserted with a series of fixed offsets within a sample of 6% by mass of gelatine within a temperature controlled room.

This paper aims to investigate whether the linear coefficients found under these experimental conditions are rate dependant: in fact, the major factors which contributed to the bending of the needle are the cutting force and the friction force which are dependent on the insertion speed [17]. Furthermore, we aim to compare different steering (i.e. offset generating) mechanisms with a view to optimise both the insertion speed (Heverly et.al [18] demonstrated that, in certain needle-based applications, minimizing the displacement and deformation of the tissue can be achieved by maximizing the needle speed) and manoeuvrability of the needle.

Section II summarises the main aspects of the kinematic model developed for a 3D steering STING. Section III and Section IV describe the experimental set-up and results obtained for a set of needle insertions with different cruise speeds and curvature setting methods, performed in gelatine samples of the same consistency as in previous work. Section V provides a discussion of the results, while conclusions and future work are included in Section VI.

II. KINEMATIC MODEL

This section briefly outlines the model presented in [16], which forms the basis for this work.

Our first attempt at establishing a 3D kinematic model of

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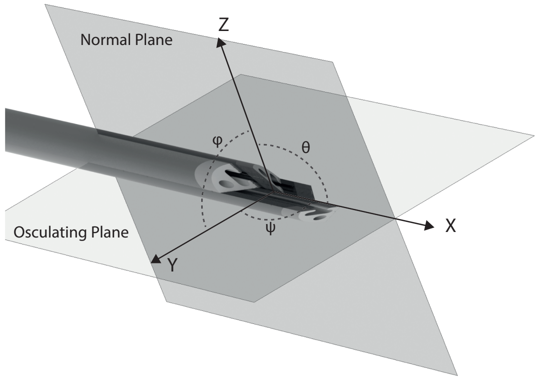

Fig. 1. Kinematic view of a four-part needle. The insertion is performed along the X direction. [16]

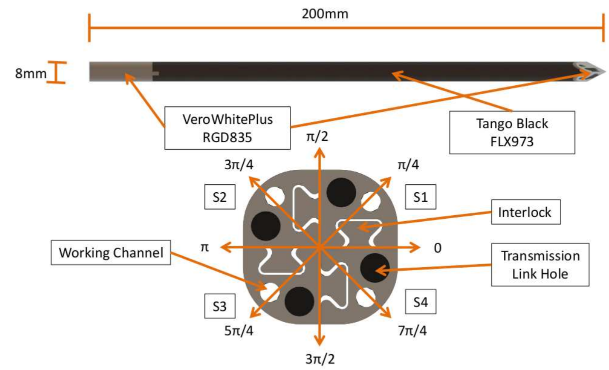

Fig. 2. A 4 part needle cross-section which segments are labelled S_i $i = 1,2,3,4$. Details of the needle geometry are reported in [15].

the needle [16] is summarised by the following equations:

$$\begin{aligned}
\dot{x}(t) &= \cos(\theta)\cos(\psi)v_1 \\
\dot{y}(t) &= \cos(\theta)\sin(\psi)v_1 \\
\dot{z}(t) &= -\sin(\theta)v_1 \\
\dot{\theta}(t) &= k_1\delta_{prZ}v_1 \\
\dot{\psi}(t) &= k_2\delta_{prY}v_1 \\
\dot{\delta}_{prZ} &= v_2 \\
\dot{\delta}_{prY} &= v_3
\end{aligned} \tag{1}$$

The system defined in SO(3), has 3 inputs: the insertion cruise speed v_1 and the change of projected steering offsets ($\delta_{prY,Z}$) along the normal and osculating planes, represented by v_2 and v_3 respectively, which cause the needle to steer along a predetermined direction by a prescribed amount. The functions $k_{1,2}$ are experimentally derived and, in a first approximation, considered to be constant. Angles θ and ϕ are defined in Fig.1. A high level controller, which linearises the kinematic system by means of chained-form transformation, generates the references v_i for a low level controller. This latter performs the actuation of the 4 segments, which work together to produce a specific tip orientation and prescribed steering offset. In [15], we demonstrated how the probe can naturally steer along 8 principal directions, as shown in Fig. 2, by having either one or two leading segments with a fixed and equal offset to the remaining segments, and how the quasi-linear relationship between relative offsets and curvature holds for different planes.

In this work we investigate how the cruise speed and different offset modalities can affect this relationship. In particular, two modalities for achieving any prescribed offset between segments are investigated:

- **(a) Leading Forward**: This method has been employed in all previous work, where the predefined relative offset between segments is achieved by moving one or two leading segments forward of the others. In these experiments, the chosen maximum speed for leading segments was set to $v_{cruise} + 3mm/s$;
- **(b) Leading Forward - Body Backwards**: Here, the leading segment/s is/are pushed forward while the other segments are pulled backwards. In this case, the chosen maximum speed for all segments was set to $v_{cruise} \pm 1.5mm/s$ to maintain an equal duration for the generation of equivalent offsets between the two modalities.

III. EXPERIMENTS

A. Materials

A 4-part needle with an outer diameter of $8mm$ and a bevel angle tip for each segment of 20 degree was designed and manufactured. Fig. 2 shows a cross section of this design, which is symmetrical about the four main projection planes. The needle is $200mm$ long, and each segment possesses two lumens: one has and OD of 1mm, which runs the entire length of the needle and is used as the working channel; a second, $1.5mm$ OD hole is only $15mm$ deep and is employed to anchor a transmission link to the back of each segment. All segments were manufactured using the same combination of a flexible material and a relatively rigid material, TangoBlack FLX973 (Shore Hardness 75-85 Scale A) and VeroWhitePlus RGD835 (Shore Hardness 76.1-81.7 Scale D) respectively, as shown in Fig. 2. VeroWhitePlus is used at the base of the needle to support and attach the transmission links and it is also used on the tip of the needle as a stiffer bevel has been shown to improve the needle's steering capabilities. Differently to previous work, Tango Black has been used for the body of the needle instead of DM9860 (Shore Hardness 57-63 Scale A) in order to reduce the friction between the segments and thus provide smooth movement in sliding. The 3D position of the needle was recorded at 30 Hz using an electromagnetic sensor (Mod. Aurora, Northern Digital Inc. - 5 degree of freedom, root mean square error - 0.9mm, confidence interval - 95% within 1.8mm) embedded within the tip of each segment. The experimental setup is the same as in [15], where linear actuators are used to push the needle into the gelatine.

B. Experimental Procedure

The experimental trials were randomized and divided into two main groups: the group with $1mm/s$ cruise speed (**A**) and the group with $4mm/s$ cruise speed (**B**). In addition, each group was divided in two subgroups, depending on the methodology used to perform the offset: a subgroup employed the *Leading Forward (a)* method and a subgroup the *Leading Forward - Body Backward (b)* method. Also, two separate offsets were tested for each subgroup : 20mm (**1**) and $40mm$ offset (**2**). A total of 8 randomized trials for each configuration was tested, coded as follows: e.g. **Aa1**: group **A** with $1mm/s$ insertion speed **a**, using *Leading Forward* method and using $20mm$ offset.

All trials were performed in a 6% by weight (elasticity between $1.9-2KPa$) gelatine phantom, as done previously [13], at a controlled room temperature between $19°C$-$20°C$. Differently from previous work [15], the offsets were performed during the insertion of the needle (i.e. without stopping the motion) and after an initial straight insertion of 10mm into the gelatin phantom. The overall insertion length was $120mm$.

C. Curvature Calculation

As in [15], the overall curvature of the needle was calculated using the geometric centre of the bevel tip, coupled with the following assumptions:

- The needle moves along a plane for the whole insertion sequence, as the steering plane.
- Once the offset is set, it is kept constant for the whole insertion (i.e. with no mechanical slack between segments) and the curvature is constant along the trajectory.

The curvature ρ is calculated using the projected points of the leading segment trajectory (without considering the initial insertion of 10mm) on the best fitting plane (defined using the Principal Components Analysis algorithm in Matlab, Mathworks inc.). The circle is estimated using the hyper circle fitting algorithm, as reported in [19], then:

$$\rho = \frac{1}{R} \tag{2}$$

with R being the radius of the fitted circle.

IV. RESULTS

The mean curvature values for each subgroup are reported in the Table I.

TABLE I
MEAN CURVATURE VALUES FOR EACH SUBGROUP

Subgroup	Mean Curvature $[mm^{-1}]$	STD
Aa1	0.0022	0.0008
Ab1	0.0022	0.0011
Aa2	0.0039	0.0013
Ab2	0.0046	0.0013
Ba1	0.0029	0.0005
Bb1	0.0024	0.0009
Ba2	0.0046	0.0014
Bb2	0.0049	0.0012

In order to compare different subgroups, a two-tail unpaired parametric *t-test* with Welch's correction (standard reference p value of 0.05) was performed after a Shapiro-Wilk Normality test.

The comparison between subgroups with common cruise speed and offset but with different offset-modalities shows no significant differences in the curvature values, as shown in Fig.3 and in Fig. 4. Furthermore, no statistical differences were found when comparing subgroups with different cruise speeds, but with similar offsets and offset-modalities. Finally, the two offsets used in the experiments produce statistically different curvatures (group A: $p = 0.0152$, group B: $p = 0.0071$), as shown in Fig. 3 and Fig. 4, which is in line [15], where the relationship between offset and curvature was found to be approximately linear.

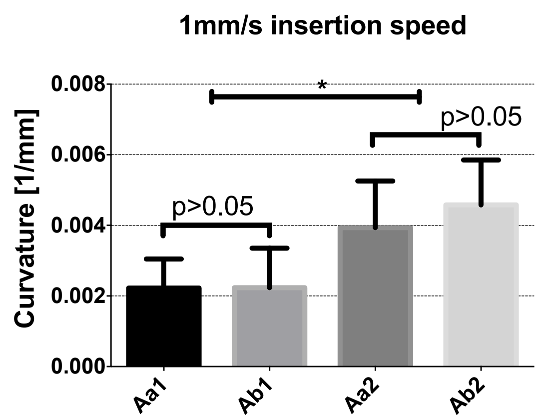

Fig. 3. Subgroups with an insertion speed of $1mm/s$. "*" highlights a significant statistical difference between subgroups with different offsets. **a1**) *Leading Forward* - 20mm offset, **b1**) *Leading Forward - Body Backward* - 20mm offset, **a2**) *Leading Forward* - 40mm offset, **b2**) *Leading Forward - Body Backward* - 40mm offset

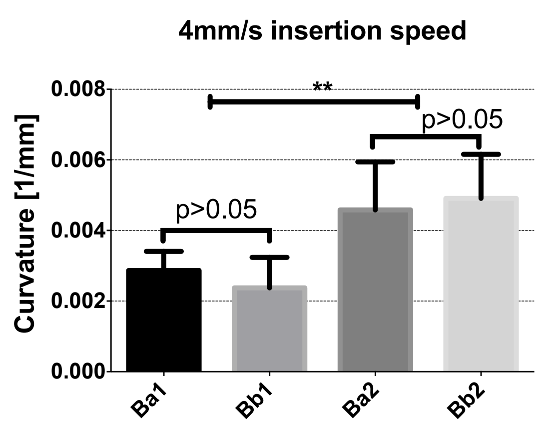

Fig. 4. Subgroups with an insertion speed of $4mm/s$. "*" highlights a significant statistical difference between subgroups with different offsets. **a1**) *Leading Forward* - 20mm offset, **b1**) *Leading Forward - Body Backward* - 20mm offset, **a2**) *Leading Forward* - 40mm offset, **b2**) *Leading Forward - Body Backward* - 40mm offset

V. DISCUSSION

This study employed a number of experiments to evaluate the effect of changing cruise speed on needle performance, as well as measuring the effect of two different offset generation methods on the ability of the needle to steer along a single circular path. The lack of any statistical difference between experiments carried out with the two modalities (Leading Forward vs. Leading Forward - Body Backwards) confirms the hypothesis that the relative motion between needle segments can be altered to fine tune needle performance without affecting the well established linear behaviour between offset and curvature found in previous work. Similarly, the lack of any statistical difference between experiments run at $1mm/sec$ (Fig. 3) and $4mm/sec$ (Fig. 4) suggests that cruise speed, which is an input parameter to the low level needle controller, does not need to be fixed, but can rather be modulated to optimise needle behaviour without the risk of adverse effects. Indeed, given that the two modalities produce similar curvatures, the ability to alter the offset between segments "on the spot" has the potential to enable tighter bends to be achieved within a given insertion length, which has significant future potential.

VI. CONCLUSION AND FUTURE WORK

Recent work has demonstrated how a needle made up of four interlocked segments can be controlled along curvilinear trajectories within a soft medium thanks to an approximately linear relationship between the relative offset imparted to each segment and the magnitude and direction of the steering angle of the tip. In this study we explored how changes in the overall cruise insertion speed affect this relationship and demonstrated that, within gelatine, there is no appreciable change in performance as the speed of insertion is increased or decreased. Given this apparent lack of significant rate dependency, two different steering methods were then compared and contrasted with a view to improve upon the manoeuvrability of the needle. It was shown that, by generating an offset between segments by simultaneously pushing and pulling on leading and lagging segment/s respectively (i.e. akin to "turning on the spot"), the needle could be made to change direction over a shorter distance. This result has important implications with regards to how the needle can be made to respond more quickly to changes in trajectory and future work will thus centre on how to exploit these findings within the context of needle steering within a dynamic environment. Additionally, only a few experiments were carried out on selected configurations and a single gelatine composition, thus future research will expand upon this work to investigate the impact of other steering parameters on performance, as well as estimating rate dependant behaviour within other substrates.

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