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On the Feasibility of Continuum Dexterous Manipulators for Improving Minimally Invasive Spinal Fusion

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Abstract

Continuum dexterous manipulators (CDMs) have shown great potential when integrated with computer assisted orthopaedic surgery (CAOS) systems for minimally invasive surgery (MIS). We hypothesize that the enhanced dexterity of CDMs may allow for greater access to target tissue through a single port when compared to traditional, rigid MIS instruments. To assess such CDMs for intervertebral disc removal applications, a phantom study in the scope of MIS transforaminal lumbar interbody fusion (TLIF) was conducted to evaluate the achievable surgical workspace of the intervertebral disc (IVD) during disc space preparation. A CDM with 6 mm diameter and a conformable nitinol whisk tip was evaluated against three 135° lumbar curettes in a 2D L4-L5 IVD phantom by an experienced spine surgeon. Improvements of up to 41.7% in reachable IVD workspace are achieved with the CDM, demonstrating its viability in improving outcomes for MIS spinal fusion.

1 Introduction

TLIF is a common surgical procedure for patients with back pain and/or radiculopathy related to lumbar disc disease, spinal stenosis and instability [1]. Incomplete removal of disc materials and inadequate preparation of the endplate can result in implant subsidence and non-union [2]. Current literature indicates that a smaller area of endplate preparation decreases the success

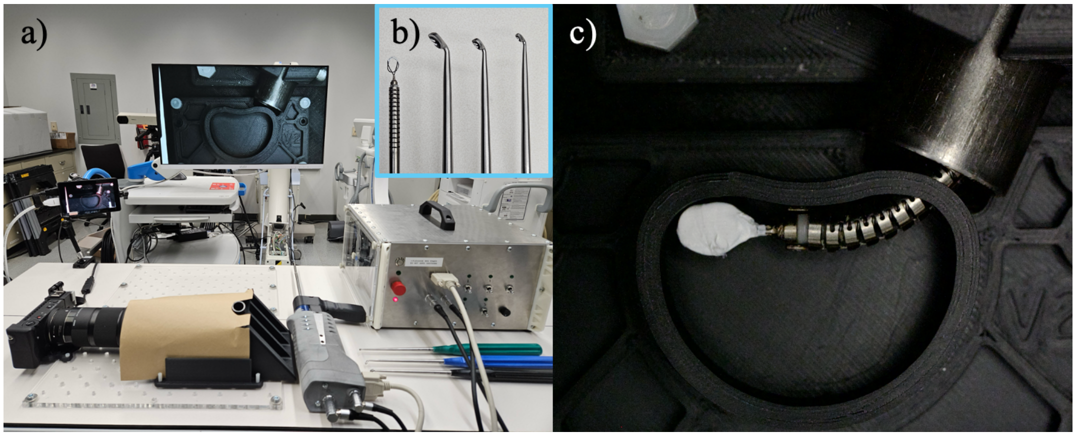

Figure 1: a) Experimental setup, b) instruments used in the experiments and c) the CDM inside of the L4-L5 disc phantom

rate of interbody fusion [3] and that traditional MIS methods result in limited disc space preparation [4].

Problems of workspace reachability have also been encountered in the treatment of osteolysis and osteonecrosis of the hip, where the inadequate removal of lesions or excessive removal of healthy bone may necessitate joint replacement or revision surgery [5],[6]. CDMs, capable of enhanced dexterity and reach compared to conventional instruments, have been proposed for use with an autonomous robot [7] or in a hand-held fashion [8] to address this, allowing for 94% of lesion removal in some cases [9]. The purpose of this study is to demonstrate that the CDMs' capabilities can also be leveraged in spinal fusion surgery to improve workspace reachability and ultimately enhance the success of the spinal fusion operation.

2 Materials and Methods

2.1 Instruments

The CDM system, shown in Fig. 1a, consists of a CDM, a robotic, hand-held actuation unit and a flexible instrument, similar to that previously developed by our group [8]. The CDM is a nitinol tube with a 35 mm long notched section capable of planar bending and an outer diameter of 6 mm, actuated by the cable-driven actuation unit. On the actuation unit is a pistol grip with a trigger for digital control the CDM's bending. On the end of the CDM is a conformable nitinol flat whisk designed for soft tissue debridement, with undeformed major and minor diameters of 10 mm and 7 mm respectively. Figure 1c shows the bent CDM with whisk. Three 135° angled lumbar curettes of head sizes 0, 2 and 4 and working length 144 mm (Tedan Surgical Innovations, Sugar Land, Texas), shown in Fig. 1b, are used for comparison.

2.2 Experimental Setup

Figure 1a shows the experimental setup. The 2D disc phantom, shown in Fig 1c, is modeled from the cross-section of a CT reconstruction of a male spine and is 3D printed with black, carbon fiber acrylonitrile–styrene–acrylate thermoplastic. The annulus fibrosis (AF) has a thickness of

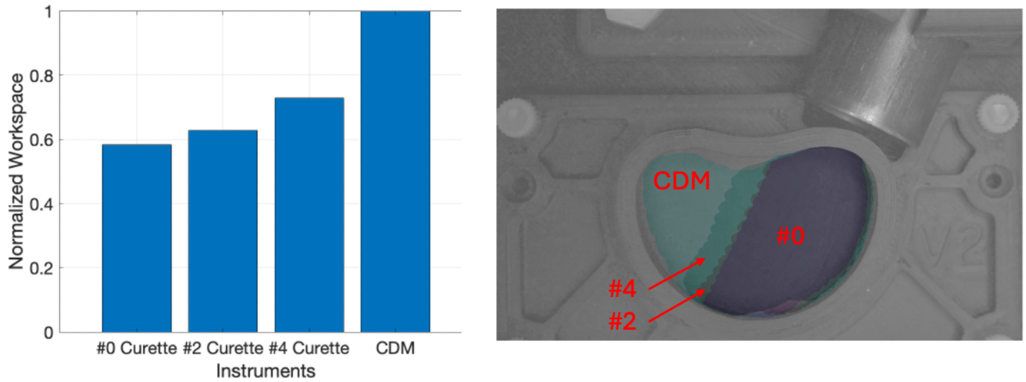

Figure 2: Bar plot of achieved workspaces normalized to the CDM and its visualization.

3 mm and height of 10.9 mm and the nucleus pulposus (NP) and endplate are represented by the resultant cavity with area of 892.1 mm^2. On the right anterior surface of the phantom is a slot cutout with 10 mm length and 8.5 mm width, angled 25° medially and aligned with the phantoms's centroid.

The phantom is fixtured on an acrylic baseplate in the manner of patient prone positioning during TLIF surgery. Aligned with the slot is a 70 mm long tubular retractor with inner diameter of 16 mm. A video camera (Sigma Corporation, Kawasaki, Kanagawa, Japan) with a 70 mm focal length macro lens is positioned facing the phantom and shrouded to minimize reflections. Camera output is fed to two monitors for focusing the camera and for providing visual feedback of the instrument position to the surgeon, simulating state-of-the-art navigation platforms [10], [11].

2.3 Methods

For each instrument, the surgeon was tasked with performing disc space preparation on the phantom with the goal of maximizing the workspace reached, with no time limit enforced. Each instrument tip was wrapped with 89 micron thick, white thread-seal tape to aid in image segmentation. Motions for each instrument were recorded with the camera for workspace measurement.

A thresholding-based image segmentation pipeline was used to determine the workspace achieved by each instrument. Each recording was converted into a sequence of gray-scale images, then a gray-level threshold was iteratively chosen until the instruments were fully segmented from the phantom without noise artifacts. Each image consecutively undergoes logical disjunction, median, and fill operations to create a pixel-level mask of the achieved workspace. The total number of segmented pixels in each mask is used to quantify each workspace.

3 Results and Discussion

Figure 2 shows the relative workspace of each instrument, normalized to the CDM, and their overlays against the phantom. At best, the CDM shows a 41.7% improvement over the #0 curette and at worst, a 27.2% improvement over the #4 curette, demonstrating superior reachability. On average, the CDM is able to access almost all of the disc space unlike the curettes, which cannot access the contralateral posterior quadrant. A positive correlation between instrument size and achievable workspace can be observed, showing the marginal improvement between successive curette sizes, contrasting that between the #4 curette and the CDM.

These results exhibit the CDM's potential in spinal fusion surgery. The importance of disc preparation area has long been established [12], where fusion on the endplate periphery is preferred, for which the CDM is able to access in all four quadrants. This factor has led to approaches like extreme lateral interbody fusion (XLIF), whose larger implant covers more surface area than TLIF [3] and is analogous to the CDM's workspace improvement. The CDM's reachability promotes more thorough disc space preparation and enables larger fusion area despite smaller incisions.

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