Engineering incipient slip into surgical graspers to enhance grasp performance

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***Abstract*—The surgical community has long reported the need for improved control of surgical graspers when handling delicate soft tissues, both to avoid the over application of force which leads to trauma, and to avoid tissue slip. The majority of research has sought to mitigate these issues through the integration of force feedback into the graspers. In this work we investigate an alternative strategy in which the grasper design is engineered to create preferential localised slip, also known as incipient slip, on the premise that this can be detected before the onset of macro slip, allowing graspers to use the minimum force required to maintain stable control.**

We demonstrate the ability to encourage incipient slip in a predictable and repeatable manner through the design of the grasper face profile and pattern. This provides an important foundation for development of sensing systems capable of detecting these slips during surgery to improve operative outcomes.

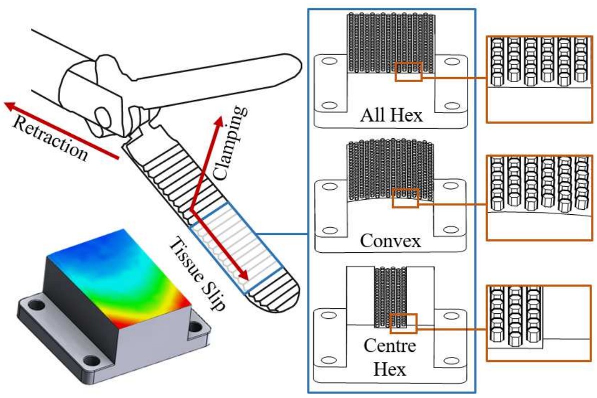


Fig. 1: Diagram of surgical grasper and the various grasper face designs investigated. Top: Control ("All Hex"). Middle: Convex. Bottom: Centre Hex. The colour map shows an example of the relative displacement of tissue across a convex grasper face due to incipient slip, prior to macro slip occuring.

I. Introduction

Robotic surgical devices provide significant improvements for procedures in Minimally Invasive Surgery (MIS), but the lack of haptic feedback is still considered a major issue by surgeons. Robotic surgical devices mechanically separate the surgeon and the patient, completely denuding the surgeon of their sense of touch. This leads to issues with the over application of force, limited grasp control and an inability to palpate tissue to identify abnormalities [1], [2].

Over application of force has been identified as a major issue within robotic and laparoscopic surgery causing up to 55% of consequential errors in surgical trainees [2]. The lack of haptic feedback means the surgeon is fully reliant on visual ques to estimate the magnitude of applied forces, which are insufficient for force regulation, resulting in increased tissue damage [3]. Equally, the use of too little force is also a common occurrence where as many as 17% of grasping actions fail as a result of tissue slip [4], which could lead to the occurrence of adverse events during surgery.

Efforts to improve grasping performance have predominantly sought to use haptic feedback strategies in which sensors provide force information to the surgeon. For example, *King et al.* [5] measured force at the grasper jaws with an array of capacitive sensors, which then relayed this information to the surgeon via small pneumatic balloons in contact with the surgeons fingers, this was found to reduce the mean force applied during grasping by 58%. However, such strategies increase cognitive loading on the surgeon, increasing the risk of fatigue and operative errors [6]. Automation can help to mitigate this effect, one approach to this is to automate grasp force using predetermined 'safe zones' [7]. Whilst this method has been successful it is constrained by the need to predetermine appropriate tissue-specific limits.

Less prescriptive approaches have been developed which look to detect tissue slip at the grasper interface. *Burkhard et al* [8] used thermal sensing to detect slip at the grasper face. In trials on porcine samples tissue slip could be detected after less than 2mm of displacement. Similarly, *Jiang et al.* [9] developed a slip sensor using hexagonal micro structures on the surface, coupled to a piezoelectric substrate, to detect vibrations arising due to surface movement. However, these approaches rely on 'macro slip' in which the whole surface is moving before mitigating action can be taken, which risks a loss of grip stability.

An alternative strategy is to sense the occurrence of *incipient* slip, the small localised slips which occur prior to the onset of macro slip. This phenomenon helps human fingers detect slip [10] and has been exploited by the wider robotics community to improve object manipulation [11], [12]. The majority of such systems use biomimicry of the human finger to encourage incipient slip, using curved finger-like surfaces to create a normal force distribution under contact [11], whilst others use pillars to produce stepped changes in the normal force [13]. However, the application of this phenomenon is limited in surgical manipulation, with the only example of its use looking to monitor change in stiffness as an indicator of incipient slip [14].

We propose that if conditions can be created to promote incipient slips in a predictable and repeatable manner, these can be detected and mitigated prior to macro slip and a loss of grip occurring. Ultimately this offers the opportunity for closed-loop grip control independently of predetermined usage thresholds. In this paper we therefore investigate the efficacy of using incipient slip as the basis for monitoring and controlling surgical tissue manipulation. Informed by the basic mechanics of slip, we develop different grasper profiles designed to encourage preferential slip behaviour. These are evaluated experimentally using simulated soft tissues to determine the potential for using this technique in applied surgical contexts.

II. METHOD

A. Background

Our concept is based on a biomimetic strategy of preferentially promoting incipient slip at targeted regions of the contact surface [10], achieved through appropriate mechanical design of the grasper jaw. Slip mechanics is thus critical to inform the grasper design.

The development of a slipping contact has two key phases, incipient slip and macro slip [15]. Incipient slip occurs when local shear forces exceed the local friction forces, leading to localised relative displacements between two contacting points on the surface, while the body as a whole remains static. Then macro slip occurs when the total shear force begins to exceed the total friction force at the contact, and the two contacting bodies move relative to each other [15]. Thus to encourage incipient slip there must be a variation in the frictional force between adjacent points across the contacting surface.

B. Grasper Design

From Amontons' Laws of Friction two key methods of encouraging preferential incipient slip were identified; a) through variation of the normal force via changes to the grasper profile or b) through varying macro surface features to vary the Coefficient of Friction (CoF).

Informed by preliminary work which explored a wide array of potential jaw configurations, a set of jaw profiles were selected to correspond with each method, together with a representative control surface (Fig. 1). The control ("All Hex") uses an array of hexagonal pillars (0.75mm width and height) to create a 'patterned' high friction surface similar to a toothed grasper. To vary the distribution of normal force a shallow convex profile ("Convex") was used (radius 50.5mm) with the same hexagonal pattern across the face. To vary the CoF, a flat grasper face was used with a central 8mm strip of hexagonal patterning and smooth borders either side ("Centre Hex").

The three grasper designs were fabricated using a 3D printer (Form 2, Formlabs) from solid plastic resin (Rigid Resin 1L, Formlabs) at $\times 2$ scale to enable visualisation of slip, such that each contact face was 20mm$\times$30mm.

C. Experimental Setup

A test rig was developed to provide controlled simulation of tissue grasping and retraction, as shown in Figure 2. A linear load tester (Instron 5940, Instron) controlled retraction motion, whilst a pneumatic cylinder (MGPM20TF-75Z, SMC) was used to clamp a tissue simulant between the grasper face and an optically clear acrylic sheet at constant load. An electro-pneumatic regulator (ITV1030,SMC) was used to control clamping pressure, regulated with an embedded control system (MyRIO, National Instruments). The system was pre-calibrated against a load cell. To monitor the slip of the tissue simulant a video extensometer (AVE2, Instron) was positioned behind the acrylic plate, recording images at a rate of 50Hz, whilst the retraction force was measured using a 500N Load cell on the load tester.

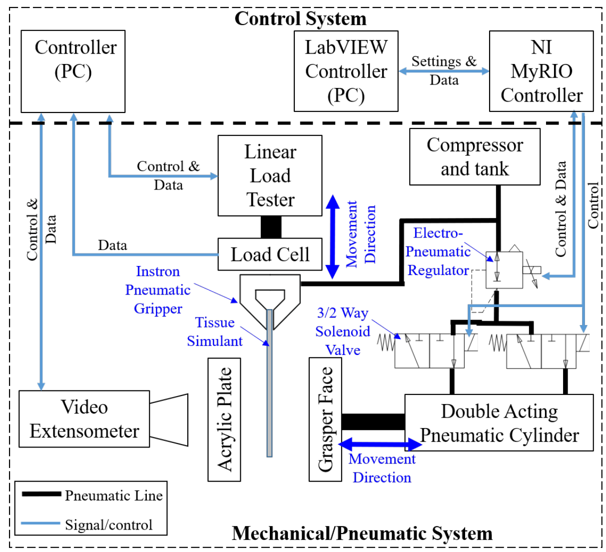


Fig. 2: Schematic of the control system used for the simulated grasping environment.

The tissue simulant was fabricated from three layers of silicone elastomer (Ecoflex 00-30, Smooth-on), each 1mm thick, with a reinforcement mesh embedded between each layer to represent the gross mechanical and strain-limiting characteristics of human tissue [16], this was done using the film application technique from [17]. Samples were laser cut (VLS 3.50, Universal Laser Systems) in 20mm$\times$100mm strips. A speckle pattern was then applied to the outer layer using black enamel spray paint for motion tracking. Surfactant lubricant was applied to the sample surface prior to each test to represent the serous fluid that coats most organs and provide representative surface adhesion characteristics [18].

D. Experimental Parameters

A set of test conditions were defined to emulate surgical practice; a 20N compression force was applied to simulate the pressure range used during surgical grasping [19] combined with a retraction speed of 5 mm/s [20]. In each test, the clamping force was slowly applied to the tissue before retracting the tissue by 30 mm using the load tester. 5 repeats were carried out for each test condition investigated.

E. Analysis Method

Digital Image Correlation (DIC) was used to track the displacement, and thus slip, of the tissue simulant. Data from the video extensometer was processed using DIC software (GoM Correlate, GoM), enabling the displacements in x and y of a grid of 35 points to be extracted for each video frame. Results were analysed up to the onset of macro slip (defined as when all points had moved >0.05mm).

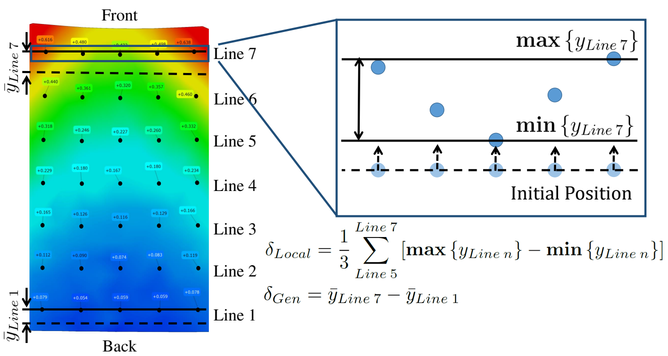


Fig. 3: Image displaying the grid of 35 dots used for tracking the displacement, with the major metrics used for the calculation of local and general distortion marked on, as well as the relevant equations.

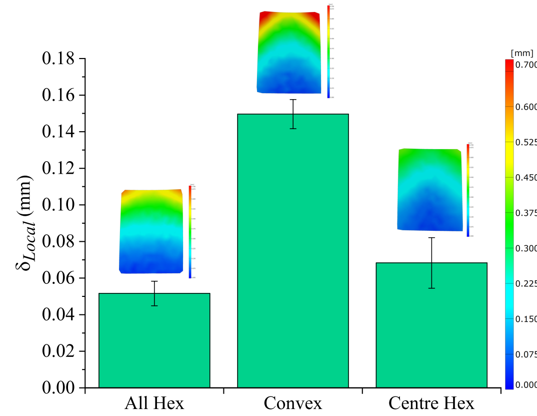
To characterise the incipient slip we determined the distortion of the tissue as the relative displacement between points. Both local distortion (δ_{Local}) and general distortion (δ_{Gen}) were calculated to monitor relative slip across the width of the grasper, and between the front and back edges respectively. Local distortion was based on the difference between the maximum and minimum displacement of points along each of the front three lines, general distortion was calculated from the average displacement of the lines ($\bar{y}_{Line\ n}$) at the front and back edge of the sample (Fig. 3).

III. Results

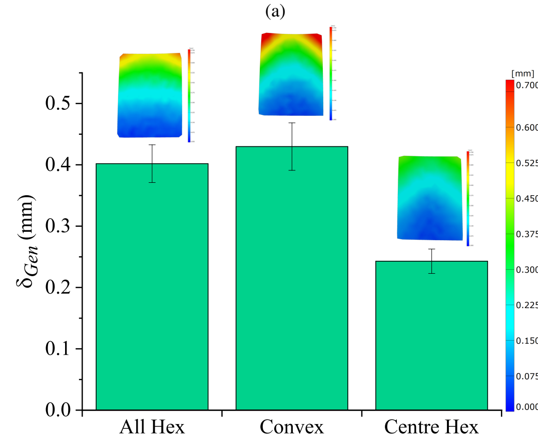
Results from the study are presented in Figure 4 which shows the average local and general distortions for the three grasper faces under nominal conditions after 5 repeats. It is evident that both methods of promoting incipient slip are effective with respect to the control surface when looking at local distortion. However, the Convex profile yields significantly more local distortion, and thus incipient slip across the width of the grasper. The magnitude of the general distortions just prior to macro slip is significantly higher than that observed for local distortion, particularly for the All Hex and Convex graspers, indicating that greater relative slip occurs between the front and back edge than across the width.

The mean CoF (at the onset of slip) was calculated for each grasper profile to assess their overall grip stability with respect to the high friction control. This gave CoFs of $\mu_{All\_Hex} = 0.33$, $\mu_{Convex} = 0.31$ and, $\mu_{Centre\_Hex} = 0.14$, indicating that changing profile from flat to convex had little effect but the addition of low friction sections impaired grip stability.

Figure 5 shows a typical temporal slip response for the Convex grasper face. The plot shows six lines representing the displacement of the left, right and central points at the front and back edge of the grasper face. These show an increasing displacement between the front and back edge of the profile, reaching ca. 0.5mm prior to macro slip. Similarly, the relative displacement across the width increases, showing a difference between central and outer sides reaching ca. 0.15mm when macro slip starts after 1 second. The All Hex grasper has a similar response but for the Centre Hex pattern macro slip occurs far earlier, after only 0.2 seconds, indicating lower grip stability.



(a)



(b)

Fig. 4: Affect of grasper design on the level of incipient slip, indicated by the magnitude of tissue distortion. The colour maps show typical y displacements for each grasper face. (a) Local Distortion. (b) General Distortion.

IV. Discussion

The results of this study demonstrate that incipient slip can be promoted in contact conditions representing a grasper contacting soft tissue. It is interesting to note that the incipient slip manifests both between the front and back edges, and across the width, with respect to the direction of pull (see Fig. 1). Prior to macro slip, both grasper profiles exhibited significantly higher general distortion, indicating greater incipient slip between then front and back edges due to the natural slip progression of the elastomer (Fig. 4). This indicates that sensing slip differentials between the front and back edges of a grasper face may be preferable to maximise the time required to effect mitigating action. For this configuration, the Convex

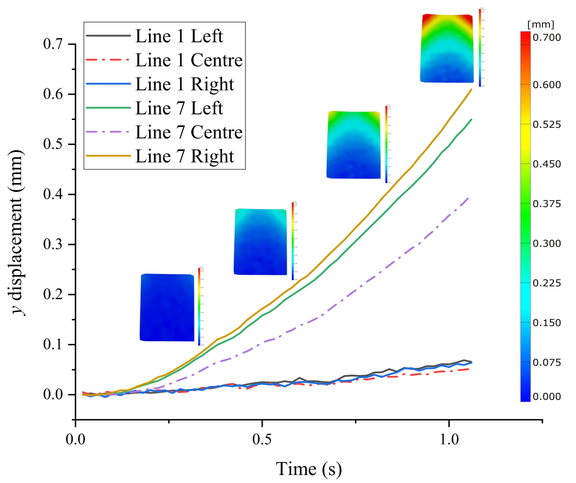


Fig. 5: Typical response for displacement over time of the central and outer points for Lines 1 and 7 of the Convex grasper face. Colour maps show how the y displacement of the whole face changes over time.

and All Hex profiles provide the greatest slip differential, likely due to their high CoF slowing the propagation of the slip front along the grasper.

Both spatial and temporal characteristics of the incipient slip are important when considering how they could be exploited in a potential sensing system for tissue manipulation. A sensing configuration would be required with sufficient spatial sensitivity to detect the displacement differential which indicates incipient slip. This initial study indicates that sub millimetre sensitivity would be necessary. Similarly, based on the temporal development of slip (Fig. 5) and DIC framerate, a sensing frequency of 60+ Hz would be required, although it is noted that this will also be a function of retraction speed.

The work presented here is intended to show proof of principle, demonstrating the potential for using incipient slip as a mechanism to sense, and thus avoid, macro slip during grasping. Accordingly, this work focuses on a narrow set of experimental conditions based on preliminary testing. Our ongoing research aims to investigate and characterise the effect of a wider range of factors, including aspects of natural tissue variability, grasper profile and surface design and the operating conditions (e.g. lubricants). These findings will be used to inform the design of a macro slip sensing system which utilises incipient slip and is optimised toward soft tissue interaction.

V. Conclusions and Further Work

This pilot work shows that it is possible to induce incipient slip in a predictable manner using variation of both surface profile and surface features. Of these methods, surface profile variation was found to be more effective. Incipient slip was observed across the width, and between the front and back edges, but the greater general distortion observed suggests that sensing incipient slip between the front and back edges of the grasper has the most virtue. Importantly, this can be achieved without compromising the overall grip stability of the grasper.

The next stage of research is to exploit this fundamental mechanism of preferential incipient slip within a sensing system that monitors local shear forces. This will inform the selection and development of transducer technology capable of detecting incipient slip with a sufficient resolution and speed that mitigating action can be taken before gross tissue slip.

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