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Comfort and Learnability Assessment of a New Soft Robotic Manipulator for Minimally Invasive Surgery*

A. Shafti, F. Andorno, N. Marchese, S. Arolfo, A. Aydin, O. Elhage, Y. Noh, H. A. Wurdemann, A. Arezzo, P. Dasgupta and K. Althoefer, *Member, IEEE*

***Abstract*— Laparoscopic surgeons perform precise and time consuming procedures while holding awkward poses in their upper body and arms. There is an ongoing effort to produce robotic tools for laparoscopic surgery that will simplify these tasks and reduce risk of errors to help both the surgeon and the patient. STIFF-FLOP is an ongoing EU FP7 project focusing on this by creating a stiffness controllable soft robotic manipulator. This paper reports on a study to test the soft manipulator's learnability and the effort associated with its use. The tests involved a limited prototype of the manipulator with a custom built test rig and EMG acquisition system. Task times and video recordings along with EMG waveforms from the forearm muscles of participants (n=25) were measured for objective assessment. A questionnaire was also provided to the participants for subjective assessment. The data shows that in average EMG levels were 25.9% less in RMS when using the STIFF-FLOP arm than when conventional laparoscopic tools were used. In terms of learnability, from the first to the second attempt on the STIFF-FLOP manipulator, elapsed time was reduced by an average of 32.1%. Further details and analysis of the EMG signals as well as time and questionnaire results is presented in the paper.**

I. Introduction

Advances in medicine have led to minimally invasive surgery (MIS) which allows procedures in the abdominal area to be performed through a small 5-15mm incision using especially designed tools. This reduces risks to the patient as it limits exposure of the internal organs as well as general damages and decreases recovery time and scars [1]. However MIS is a very difficult procedure with surgeons training for years to get used to its tools and the limited environment they enforce.

Roboticists have been working on improving methods for surgery and in particular MIS for more than two decades [2]. The main challenge can be formulated as follows: augment laparoscopic surgery using robotics so it becomes as simple and easy to conduct as open surgery. Robotic surgery tools have the potential to even go beyond open surgery by aiding the surgeon during surgery, increasing precision and reducing errors. This means that such a tool would improve conditions for both the surgeons and the patients. There have been many efforts in this field, from robots that handle the camera for surgeons removing the need for assistants [3] to complete surgical systems such as the commercially available Da Vinci Surgical System which provides a master-slave setup to the surgeon to perform the surgery remotely, with benefits concerning ergonomics as well as movement scaling and precision.

However, while robotics is assumed to be helpful to our lifestyles and working conditions there are few studies that scientifically and objectively assess the extent of these improvements or lack thereof. The Centre for Robotics Research at King's College London (King's CoRe) has been central in the creation of a new soft robotic manipulator to be used in laparoscopic surgery applications, specifically in the framework of EU project STIFF-FLOP (STIFFness controllable Flexible and Learn-able manipulator for surgical OPerations). The aim of the project is to create a soft manipulator that can squeeze through a trocar port, form complex shapes as required to reach relevant organs, increase its stiffness when required to keep a specific pose and perform the necessary task, whilst ensuring overall safety.

Each STIFF-FLOP module is made of soft silicone material in a cylindrical shape with 3 chambers equally spaced in radial positions which are used to actuate the manipulator pneumatically [4]. For the control and learning aspects of the manipulator, several sensors have been created and implemented. Tactile force sensors were created using fiber optics and vision sensors [5] which later evolved into body contact sensors [6]. Continuum body force sensors were made using photo sensitive diodes and transistors [7]. This later evolved into a 3-axis body force sensor [8]. A bio-inspired tactile sensor sleeve was also made based on cucumber tendrils and using optical fibres [9]. Surface characterisation and stiffness sensing were also looked into to be implemented into the manipulator. Sensors were designed using novel methods to detect force and stiffness based on visual information [10,11]. Other actuation methods similar to the octupus' antagonistic muscle system have also been explored in parallel, this method uses pneumatic pressure and tendons antagonistically to create a shrinkable and stiffness-controllable soft manipulator [12].

The above has provided us with different means to achieve the goals of the STIFF-FLOP project. Assessment of comfort and effort levels are required to benchmark different approaches during project development and settle on what is best for achieving a required task while at the same time conserving the ergonomics and intuitiveness of the system.

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A. Shafti, Y. Noh, H.A. Wurdemann, K. Althoefer are with the Centre for Robotics Research at King's College London, WC2R 2LS, London UK – ali.shafti, yohan.noh, helge.wurdemann, k.althoefer@kcl.ac.uk.

A. Aydin, O. Elhage and P. Dasgupta are with the Department of Urology, Guy's and St Thomas' Hospitals, NHS Foundation Trust, Guys Hospital, King's College London, UK – abdullatif.aydin, oussama.elhage@kcl.ac.uk, prokarurol@gmail.com.

F. Andorno, N. Marchese, S. Arolfo, A. Arezzo are with the Department of Surgical Sciences, University of Turin, Turin, Italy - federica.andorno@gmail.com, nicola.marchese@hotmail.com, simone.arolfo@tiscali.it, alberto.arezzo@mac.com

At this point in the research, spatial motion and targeted movements were tested for learnability, comfort and effort involved.

Usual studies into comfort and ergonomics in medical activities are based on video monitoring and questionnaires. Borg scales are in particular a focal point for this type of studies. This is a self-evaluation method providing a scale of numbers relevant to the level of perceived exertion. Examples of this type of studies are readily found in medical publications [13-16]. While these methods when used with a statistically sound number of participants can provide an estimate of comfort and ergonomics, they are still subjective. Comfort and efforts involved in a task need to be assessed objectively as well to provide referable and trusted results. That is why in our study, aside from timing, video monitoring and questionnaires, we relied mainly on our purpose-built electromyography (EMG) acquisition system to record muscle activity from participants (n=25). This provides us with an objective and comparable parameter directly relevant to the surgeon's effort involved with the test tasks.

The paper is organised as follows: Part II describes the test protocol, test rig and tools used within the experiment. Part III describes the custom built EMG acquisition system as well as the methods used for data processing and analysis. Part IV presents the results of the experiments and statistical analysis. Finally, part VI concludes the papers and provides a discussion on results.

II. Experiment Setup and Protocol

The aim of the tests was to assess the current prototype for learnability and satisfaction, i.e. how easy it is for participants to use STIFF-FLOP the first time they encounter it and how comfortable do they find its use. A spatial motion test consisting of movements between predefined target points was designed. In order to better simulate real-life surgery environments a 3D phantom of the pelvis and inferior abdominal cavity was specifically designed and created for the test by Fundacja Rozwoju Kardiochirurgii (FRK), one of the STIFF-FLOP partners. The phantom is scaled 2:1 as the current STIFF-FLOP prototype is larger than the final laparoscopic size. Figure 1 shows the test set up.

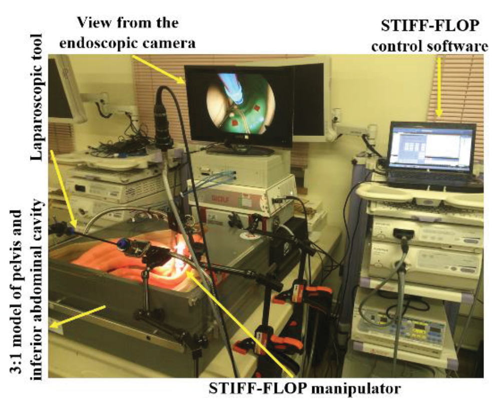

Fig. 1 Test set-up

Initially the participants (n=25) were asked to start with the STIFF-FLOP prototype. The prototype is controlled with an XBOX controller. Three areas were clearly marked inside the phantom. The participants were told to start on the marked area to their right (point A) and move on to the next points in a clockwise direction (points B and C consecutively). At each point, the participants had to press a button on the controller 2 times. They were then asked to repeat the task in a counter clockwise direction (A to C to B). Points A, B and C are located in a circular (diameter≈20cm) pattern, at 120 degree intervals.

The same task is then repeated using a conventional laparoscopic tool. The participants would move the tool to the same marked areas and in the same directions as before. At each marked area they now had to open and close the laparoscopic grasper tool 2 times, to mimic the button-press action on the XBOX controller. Once the laparoscopic task was finished the participants were asked to perform the STIFF-FLOP task once more. Number of trials per participants is limited to this as the study involves learnability and how fast the user can adapt to the new tool during the first encounter. Time spent on each task was recorded. For all the above tasks, direct internal view of the phantom was obstructed to simulate an actual laparoscopic procedure. A zero degree endoscopic camera from WOLF is used to provide indirect view on a monitor as can be seen in figure 1. The camera view for each participant is recorded for the duration of all tasks.

Surface EMG signals from the flexor and extensor muscle groups in the forearm were recorded during the test. At the start of the study, participants were asked to perform 3 sets of maximum contractions on these muscles in a static position. This provides us with a measure of their maximum voluntary contraction (MVC) which can be used for normalisation during signal processing. Normalisation of the EMG signal to each participant's MVC will allow a fair comparison between different participants of different ages, muscle sizes and skin types. EMG signals and elapsed time were recorded concurrently when the participants performed the tasks: MVC, 1st STIFF-FLOP trial (SF1), Laparoscopic trial (LAP) and the 2nd STIFF-FLOP trial (SF2). Figure 2 shows the custom built surface EMG acquisition system being used during the laparoscopic tasks.

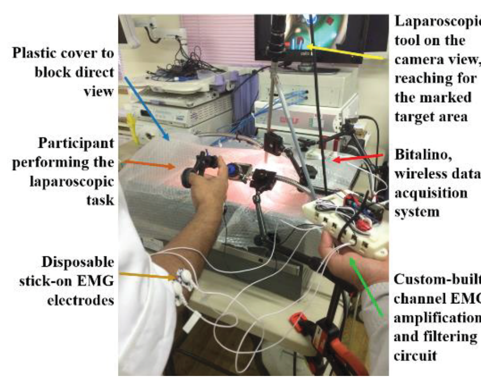

Fig. 2 EMG acquisition during the laparoscopic test

The participants were finally handed a questionnaire about their experience. This involved statements regarding ease of use, exhaustion during use and ergonomity to be rated from 1 to 5, with 1 meaning "strongly disagree" to 5 meaning "strongly agree". These are to provide a subjective assessment of the system to use alongside the objective results from the EMG measurements. The tests were performed at the Sherman Education Centre, Guy's Hospital, London. A total of 25 participants were tested consisting of 8 experts and 17 novices. Experts were defined as those with combined number of laparoscopic and endoscopic procedures of at least 500. The rest of participants were categorised as novices. Ethical approval was previously obtained for these tests (reference number BDM/13/14-123).

III. EMG Acquisition and Analysis

A low-cost 6 channel surface EMG acquisition circuit was specifically designed and built for this study. The circuit's first stage is an instrumentation amplifier selected for its input buffers and high input impedance, suitable for interfacing with the skin plus its high common-mode rejection ratio for noise removal. The output of the instrumentation amplifier is connected to a 4^{th} order Butterworth high pass filter followed by a 4^{th} order Butterworth low pass filter. These provide band pass filtering in the range of 20Hz to 450Hz. Butterworth filters were selected for their maximally flat response so as to not affect the signal's amplitude linearity in the passband. The circuit provides an overall gain of 10^3 V/V. The output of the filters is passed on to the analogue input ports of the Bitalino microcontroller system, which samples the signal at 1 kHz and transmits it wirelessly using Bluetooth to a nearby computer. The computer is then able to display the signal and record it in real-time. Recommendations from SENIAM (Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles – SENIAM.org) were used during system design and use.

The signal recorded on the computer is raw EMG signal. Initially the signal's dc level is removed. During the MVC task, the maximum absolute value of the raw EMG signal is identified and used to normalise the signal. The signal is then high-pass filtered using a 4^{th} order Butterworth filter with a cut-off frequency of 20Hz to remove any remaining effect of the participant's arm movement and other artefacts. In order to acquire a linear signal envelope, the sliding root mean square method was used. Root mean square (rms) is defined as the square root of the mean of the squares of a sampled signal and is a measure of the signal's power. The sliding rms is done by selecting a small window of the signal and calculating the rms value for it. The window is then advanced slightly forward and the rms is calculated again. Employing an appropriate window length will result in a time varying rms for the signal, which can be used as a linear envelope. A 200msec window was used for this procedure.

Apart from the amplitude analysis, a frequency domain analysis was also performed on the signals. The median frequency (MF) of the signal spectrum is defined as the point in the frequency spectrum that divides it into two parts of equal power. If the MF is obtained as a function of time it will effectively describe the shift in EMG frequency throughout a certain task. A time varying MF can be obtained by calculating the MF for smaller sliding windows of the signal. To compare different participants we looked at the variation of their muscles' MF while they were performing the prescribed tasks. During an isometric contraction, a decrease in the median frequency would represent fatigue. For our experiments, we were particularly interested to extract the firing rate from the recorded signals. When comparing two participants, the one with less variation in their firing rate, is assumed to move the tool in a more steady and more controlled manner. The coefficient of variation (CV) was used to assess this. The CV is defined as the ratio of the standard deviation to the average of the data and it is used as a measure of dispersion.

A MATLAB routine was created including all above functions and processes to perform the complete signal processing automatically for all participants.

IV. Experiment Results and Analysis

Figure 3(a) shows average time results for different tasks and different types of participants. SF1 takes in average a longer time than the other tasks, i.e. 36.4% more than LAP ($p=0.0071$). However, from SF1 to SF2 there is in average a 32.1% reduction of time spent by participants ($p=0.0232$). Results follow the same pattern when looked at for novices and experts specifically, but times are generally longer for experts.

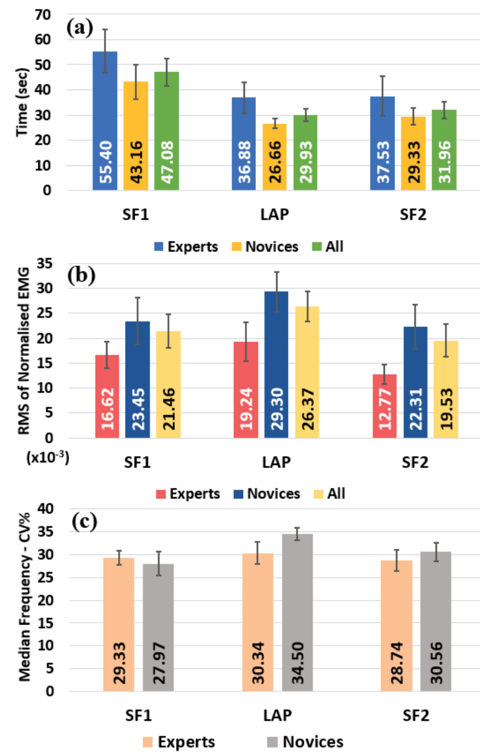

Fig. 3 Experiment results for all, expert and novice participants – (a) Comparison of average time spent on different tasks with standard error marked (b) Comparison of average rms EMG levels for the flexor muscle group during different tasks with standard error marked (c) Comparison of flexor muscle group EMG median frequency CV for different tasks with standard error marked.

EMG amplitude analysis shows a higher overall average muscle activity during LAP. Moving from LAP to SF2 there is a 25.9% reduction in average muscle activity ($p=0.0128$). Results follow a similar trend in experts and novices, e.g. LAP to SF2 shows a 33.6% average reduction in novice participants' EMG levels ($p=0.0193$). Figure 3(b) shows these results for comparison. The EMG recording for one expert participant was corrupted and therefore removed from the analysis (i.e. $n=24$ for EMG results). P-values were obtained through t-tests. The XBOX interface was familiar for younger participants who were mainly in the novice group, while it was not so easy to use for older participants, mainly in the expert group. Also, experts tend to perform directed procedures at lower paces to retain precision. This can explain differences in timing and muscle activity of the two groups. In case of frequency analysis for EMG, changes in median frequency were considered. CV was calculated for all participants and tasks as described in III.

Figure 3(c) shows the comparison for an average CV in median frequency for the flexor muscle. Results show small differences in average CV percentage, with it being slightly higher for all types of participants when working with the laparoscopic device. However the differences are about 5% in the case of novices and about 2% for experts. This makes the result less significant and is possibly more of a representation of the expert participants' skills in keeping steady force levels rather than a result of the device used.

The answers to the questionnaires, in particular questions most concerned with comfort and ergonomics are shown in figure 4. Answers show that subjectively, most participants found no mental or physical exhaustion in using the new STIFF-FLOP manipulator. However, as figure 4(a) and 4(d) suggest, a majority found it not so easy to use and not ergonomical in its current state.

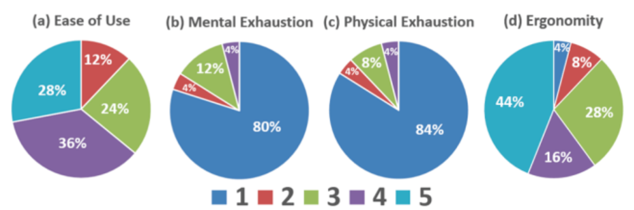

Fig. 4 Questionnaire results – (a) How easy is it to use the manipulator (b) Did you feel mentally exhausted when using the manipulator (c) Did you feel physically exhausted when using the manipulator (d) How ergonomical was the system.

V. Conclusion and Discussion

This paper described a set of experiments designed to test a new soft robotic manipulator's learnability and comfort in a clinical scenario. Participants were all of clinical background. Targeted movement tasks were performed with the new manipulator for 2 trials and with a conventional laparoscopic tool for 1 trial by all 25 participants. Time, muscle activity and video were recorded. Participants also answered a series of questions about the experiment conducted. Results showed that in average the new manipulator requires less effort to be operated when compared with a laparoscopic tool. Also, the new manipulator took 32.1% less time to operate during the second attempt, showing the device's learnability. However as results when comparing the two types of devices are close, there is room for further improvement of the STIFF-FLOP prototype in terms of ease of use, ergonomics and learnability. Also the questionnaire suggested that the majority of participants had issues with ease of use and ergonomics of the new manipulator. The data from these tests needs further analysis. In particular, looking at the video recordings closely for errors and mistakes. Correlation of these recorded movements and questionnaire responses with the relevant sections of the EMG signal will also be of interest.

It must be noted however that this test involved a limited prototype of STIFF-FLOP only capable of general spatial motion – a very easy task to be performed with a laparoscopic tool. Furthermore the 2:1 scaling of the phantom organ benefited the laparoscopic tool. Newer STIFF-FLOP prototypes are able to perform complex tasks involving bending around organs and reaching different areas with control which would be far more difficult to do with a conventional laparoscopic tool. Future tests will focus on such prototypes which should provide a far higher margin of improvement in experience with the STIFF-FLOP arm.

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