Hand-Finger Kinematics and sEMG-Based Muscular Effort for Ergonomic Analysis of Colonoscopy Insertion: A Preliminary Study

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INTRODUCTION

Endoscopic procedures involve repetitive movements of the fingers, wrists, and upper limbs, contributing to a rising prevalence of musculoskeletal pain and injuries (MSPI), affecting up to 89% of surveyed endoscopists [1]. Although recent advances in robotic endoscopy have helped reduce certain musculoskeletal demands [2], [3], these efforts mainly address arm and shoulder loads while overlooking the fine motor requirements of individual digits and overall muscular effort in the forearms. Once injuries are acquired, they can impact the operator's productivity and well-being, and potentially impact the patient. Consequently, investigating the effort required by endoscopists during colonoscopy is paramount to reduce MSPI. Surface electromyography (sEMG) has been widely used to assess muscle activity in minimally invasive surgeries [4], yet many studies do not capture digit-level joint motions or their correlation with respective muscle effort. To bridge this gap, we simultaneously recorded hand motion and muscular effort at different stages of colonoscope insertion. This paper contributes: a) A sensor-based ergonomic evaluation framework for digit-joint capture and sEMG recordings. b) Principal component analysis (PCA) to identify dominant digits and muscle activation, correlating their activity with colonoscope insertion stages.

MATERIALS AND METHODS

A. Experimental setup

Colonoscopy procedures were performed by an experienced endoscopist (36+ years in practice) using an Olympus endoscopy system and a Kyoto Kagaku M40 colon model. An overview of the data collection setup is shown in Figure 1.

Relevant hand motion data were collected using a pair of Manus Prime II gloves, while muscular effort was recorded by two sEMG Myo armbands. A Zed 2 camera was used to record the overall experiment in order to relate the hands motion and effort to the colonoscope insertion stages. The left hand of the endoscopist holds the colonoscope handle and turns the two dials that control the steering of the colonoscope's bending tip to negotiate tortuous colon anatomy. The right hand pushes, pulls, and twists the colonoscope shaft to overcome frequent looping of the colon and aids insertion. All data collection took place at Sheffield Children's Hospital under the clinician's routine conditions.

Fig. 1 Experimental setup involving a colon model with a clinician wearing data gloves and sEMG armbands.

B. Data processing and analysis

Both the gloves and armbands include embedded noise-reduction algorithms. Collected data were streamed into Robot Operating System (ROS) for synchronization at rates of 5 Hz for the gloves and 10 Hz for sEMG.

To analyze digit motion, PCA was applied to four joints of each digit, and the first two principal components (PCs) were selected to form a representative combination vector. Similarly, the first three PCs of the eight-channel sEMG data were selected for a combination vector. To quantify muscular effort in each hand, root-mean-square (RMS) envelope was then computed to smoothen each vector by applying a one-second moving window. Relative muscular effort was calculated in percentage by normalizing RMS values with respect to the clinician's maximum. To demonstrate probability distribution of muscular effort amplitude, static, median, and peak effort were extracted as the 10th, 50th, and 90th percentile of the RMS envelope. Exposure variation analysis was conducted for each effort amplitude range (e.g. 0-20%) and each time duration (e.g. 0-0.5s) [4].

RESULTS

Static, median and peak effort are respectively 13.6%, 36.9%, 64.5% for left forearm, and 20.3%, 38.3%, 68.4% for right. Right forearm's higher static and peak effort suggest sustained contractions in moderate-high range. Left forearm shows more variability with frequent short bursts (0-0.5s) and lower sustained effort. From Figure 2 and Table I, the right hand exerted more muscular effort than the left hand for 55.18% of total insertion process. Peaks in muscular effort were reached by both hands coordinately, and aligned more with dial tuning and colonoscope shaft twisting than with shaft insertion (push) and retraction (pull).

Time (s)	Left hand movement	Right hand movement
14 & 31	Thumb, Outer dial, ACW	Insert + Twist CW
47 & 49	Middle, Outer dial, CW	Retract + Twist CW
61	Thumb, Inner dial, ACW	Retract + Twist CW
84	Thumb, Inner dial, ACW	Twist CW
105	Holding handle	Retract
119	Middle, Inner dial, CW	Retract + Twist CW
141	Thumb, Inner dial, ACW	Insert
145	Middle, Inner dial, CW	Insert

TABLE I Annotations of key hand poses (CW: Clockwise, ACW: Anti-clockwise)

Stage-by-stage observations revealed that the right hand dominated effort when entering the rectum, which primarily involved shaft insertion without dial tuning, and throughout the challenging sigmoid colon segment, which accounted for over 71% of insertion time and required frequent shaft twisting. This was especially evident during 'hook'—a de-looping technique where the bending tip engaged the sigmoid's first u-turn and straightened it by pulling. Here, continuous clockwise shaft twisting was necessary to navigate and prepare for entering the second u-turn. Once in the descending colon, the left hand's dial tuning became more critical, while the right hand kept pushing forward. Approaching the ascending colon (with over 90 cm of shaft inserted), increased friction again demanded greater insertion force and twisting torque from the right hand.

Correlation between digit motion and muscular effort was explored by overlaying the combined vector of each dominant digit with the corresponding sEMG RMS envelope (see Figure 3). We identified four dominant digits (left thumb, left middle finger, right thumb, and right pinky finger) based on their larger motion ranges and higher variance. On the left hand, the thumb and middle finger were essential for tuning the two colonoscope dials that control the colonoscope tip steering, with the thumb used primarily for anti-clockwise and the middle finger for clockwise motions. On the right hand, the thumb and pinky finger exhibited the largest range of movement—especially the pinky, which flexed substantially during twisting to maintain the grip.

DISCUSSION

This study clarifies the relationship between finger movements and muscle activation, providing preliminary evidence for precise strain quantification. However, several limitations exist. First, during the first half of sigmoid colon, the researcher manually straightened the colon model segment due to suboptimal inflation, reducing muscular effort of both hands. Additionally, even though the colon model requires thorough lubrication to minimize friction, the force felt by endoscopists is generally higher than that during colonoscopies with patients. Further, this study is based on a single trial, while a comparative analysis between experienced and novice endoscopists will be presented in future work. We will also compare muscular effort with similar clinical procedures that involve prolonged instrument manipulation (e.g. manual and robotic laparoscopy). Lastly, fixed armband size and electrode placement may incur noise due to variability of clinicians' forearms and armband fitting, underscoring the need for signal calibration.

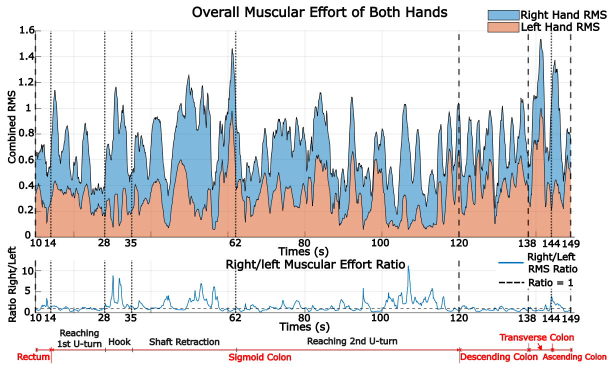

Fig. 2 Above: Overall muscular effort of both left hand (orange) and right hand (blue); Below: Ratio of right to left hand muscular effort.

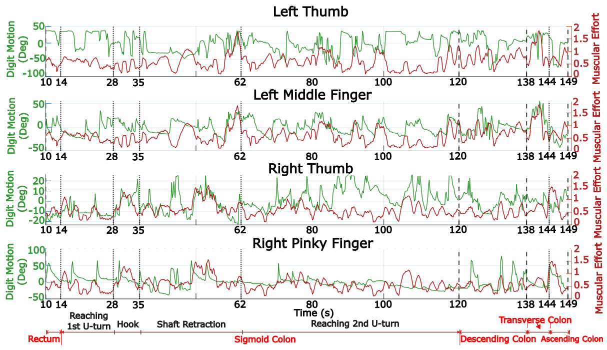

Fig. 3 Motion of four dominant digits (green) vs. hand muscular effort (red).

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