Characterization of right wrist posture during simulated colonoscopy: an application of kinematic analysis to the study of endoscopic maneuvers

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Background: Endoscopic maneuvers are associated with a high incidence of musculoskeletal injuries.

Objective: To quantify wrist motion patterns during simulated endoscopic procedures to identify potential causes of endoscopy-related overuse injury.

Design: Twelve endoscopists with different levels of experience were tested on 2 simulated endoscopic procedures that differed in their level of difficulty.

Setting: Right wrist movement patterns were recorded during simulated colonoscopies by using a magnetic motion-tracking device. Analysis focused on 3 wrist degrees of freedom: abduction/adduction, flexion/extension, and pronation/supination.

Interventions: Subjects were tested on 2 GI lower endoscopies (colonoscopies) on a simulator.

Main Outcome Measurements: Time spent within ranges of the entire wrist range of motion for 3 wrist degrees of freedom.

Results: Endoscopists spent up to 30% of the duration of the procedures at the extremes of the wrist joint range of motion. Endoscopic experience did not affect the time spent at the extremes of the wrist joint of motion. The time spent within each range of motion differed depending on the wrist degrees of freedom and difficulty of procedure.

Limitations: This study examined only 1 upper limb joint in a limited number of subjects and did not measure interaction forces with endoscopic tools.

Conclusions: We identified wrist movement patterns that can potentially contribute to the occurrence of musculoskeletal injury in endoscopists. This study lays the foundation for future work on establishing links between upper limb movement patterns and the occurrence of overuse injury caused by repetitive performance of endoscopic procedures. (Gastrointest Endosc 2014;79:480-9.)

Repetitive strain injury (RSI), also referred to as overuse syndrome, is associated with repetitive physical activities in the workplace, monotonous work, and psychological distress. With regard to repetitive physical activities, when muscles are contracted at static joint positions for extended periods of time, they are not able to relax rhythmically. This results in less oxygenated blood flow to the tissues. In the upper limb, wrist flexion, extension,
abduction, and adduction movements have been linked to RSI. Specifically, when the wrist is moved from its neutral position, the effort required to complete a task increases while muscle strength decreases. Once these muscles become fatigued, other muscles that are not designed to do a particular task take over. This, in turn, results in undesired loading of the wrong muscles.2 Although it has not been established that movements of the upper limb during GI endoscopy are associated with RSI, it would seem possible that this is the case because endoscopic maneuvers share features associated with other types of repetitive movements that have been associated with RSI.1 This work focuses on the problem of RSI associated with endoscopic maneuvers by examining upper limb kinematics during simulated endoscopic procedures.

Another goal of this project was to introduce GI endoscopists to kinematic analysis of endoscopic maneuvers. Kinematic analysis is commonly used in the field of ergonomics, and this paper explores whether this approach has the potential to provide insight into the factors underlying musculoskeletal injuries in endoscopists.

BACKGROUND

The musculoskeletal maneuvers that are required for endoscopy put GI endoscopists at risk of RSI. The prevalence of musculoskeletal injuries among endoscopists is estimated to be between 37% and 89%.3-7 The most common sites are the thumb (19%), low back (19%), hand (17%), and neck (10%). Endoscopic maneuvers require repeated pinching or gripping of the endoscope; uncomfortable hand, wrist, elbow, shoulder, and neck postures; and awkward movement of the upper extremities and can induce high muscular loading.9 In an effort to gain insight into the link between endoscopic maneuvers and RSI, several studies have used self-administered questionnaires and structured surveys.4-8 Although there are several surveys enumerating the prevalence of the problems, there are few publications that study the etiology of the problem. One study evaluated pinch-force in the right thumb during 9 routine colonoscopies10 and found that thumb forces were above injury threshold. A second study did combine force measurements with the assessment of positional data in a limited endoscopic maneuver.11 Even though these surveys have provided important information about the incidence and type of overuse syndromes associated with endoscopic maneuvers, the extent to which they can be used to identify the etiology of the problems is limited. Moreover, despite the fact that many injuries involve the arm, hand, wrist, and thumb, studies of upper limb kinematics during endoscopic maneuvers are limited. We proposed that an examination of upper limb movement patterns might provide insight into important movement features and potential links with RSI, such as how long certain upper limb movement patterns occur during endoscopy and the frequency at which endoscopists strain their joint at extremes of the joint range of motion. Additional questions include the extent to which these movement patterns change as a function of experience with endoscopic maneuvers and their difficulty. Several recent studies showed the validity of using simulation to reproduce endoscopic procedures.11,12 Similar techniques of ergonomic assessment have also been used during endoscopy simulation.13 This study was designed to quantify the duration of wrist movement patterns during simulated endoscopic procedures. Specifically, we sought to determine the range of wrist motion patterns during the performance of endoscopic procedures to improve our understanding of potential links between wrist movement patterns and the risk of musculoskeletal injuries.

METHODS

Participants

Wrist motion data were collected from 12 right-handed endoscopists (8 men, 4 women) at the Mayo Clinic in Arizona. Endoscopists were arbitrarily categorized as either being less or more experienced based on the number of years of endoscopic experience. All participants were blinded to the purpose of the study and gave their written informed consent according to the Declaration of Helsinki. The protocols were approved by the Office of Research Integrity and Assurance at Mayo Clinic and Arizona State University.

Measurements

We used a position/orientation magnetic tracker (0.075-mm resolution; Polhemus Fastrack, Colchester, Vermont) to record 3 degrees of freedom (DoFs) of the right wrist movement during endoscopic maneuvers on a simulator (Fig. 1A). Endoscopists wore a right arm sleeve and glove that were custom made for this study. All subjects had similar arm and hand sizes, and the fit of the arm sleeve and glove was appropriate for each endoscopist. A pocket in the sleeve held the Polhemus transmitter over the lateral epicondyle of the humerus, whereas a pocket in the glove (dorsum of the hand) held the Polhemus receiver (Fig. 1B). The transmitter was used
as the origin of the frame of reference to compute the angular excursions of the 3 wrist DoFs. Wrist angle data were collected through a serial port at a sampling frequency of 120 Hz. Measurements were made in the right wrist in different positions: (1) abduction/adduction, (2) flexion/extension, and (3) pronation/supination (Fig. 1C).

Endoscopic maneuvers were recorded while the endoscopists performed 2 GI lower endoscopies (colonoscopies) on a simulator (GI Mentor; Simbionix, Cleveland, Ohio) (Fig. 1A). Procedures 1 and 2 consisted of case numbers 1 and 7, respectively, in the second module of the Simbionix Mentor. Case 1 is considerably easier to perform than case 7 according to the simulator manual because of the anatomic and physiological differences involved in the 2 case studies. The order of procedures was counterbalanced across subjects. Before the actual recording of the maneuvers, we asked subjects to perform case 1 in the first module of the Simbionix GI Mentor as a practice session to be familiarized with the simulator. The simulator provided realistic visual and objective feedback to the user that aided in the complete survey of the entire lower GI tract with the forward-viewing scope.

Figure 1. A, The Simbionix GI Mentor Endoscopy simulator. B, Subject with sensors (red circles) in the custom-made arm and hand sleeve. C, Angle convention used for each wrist degree of freedom of the hand.
Experimental procedures

Data collection consisted of 2 phases: (1) estimation of wrist joint range of motion and (2) recording of wrist movements during simulated endoscopic procedures.

1. Estimation of wrist range of motion. We measured the extremes of the wrist joint range of motion by asking subjects to reach and keep the wrist at its maximum angle of pronation, supination, flexion, extension, adduction, and abduction (Fig. 1C). We also asked subjects to position the wrist in a neutral posture (Fig. 1C, top left) and defined it as the “center” of the wrist joint range of motion for all DoFs as follows: with the elbow flexed at 90° in the parasagittal plane and the hand in the “neutral” position and semipronated (thumb pointing toward the ceiling with little finger toward the floor), 0° at all joint angles, palm of the hand aligned with the forearm, and the midline of the forearm passing through the middle finger. These joint angles were used to define the full range of motion of each DoF and define boundaries of the joint range of motion (see Data Analysis section). One 5-second trial was recorded for the neutral wrist posture and each posture at the extremes of the range of motion.

2. Recording of wrist movements during simulated endoscopic procedures. Subjects wore the arm sleeve and glove with the magnetic tracker and were asked to perform 2 simulated endoscopic procedures. The recording person gave a “go” signal, after which the subject started the procedure at a self-selected pace. The endoscopist was instructed to perform a colonoscopy to the terminal ileum and then withdraw the endoscope, maximizing the percentage of mucosa visualized. The procedure was stopped once the endoscopist completed the examination or after 10 minutes had elapsed. Each procedure could last up to a maximum of 10 minutes but could be slightly shorter if the case was completed more quickly. We found that, on average, the duration of both endoscopic procedures lasted approximately 9 minutes (see Results section). Wrist movements were recorded throughout the entire procedure. Subjects were given a break of approximately 2 minutes between procedures. During both estimation of wrist range of motion and data recording during the simulated endoscopic procedures, the recording person verified that the arm sleeve and glove remained in place throughout the recording. Trials in which the sensors moved were stopped and immediately repeated.

Data processing

Wrist motion data were analyzed using custom-written software (Matlab; The MathWorks, Natick, Massachusetts). Figure 2A shows the time course (1 minute) of wrist pronation/supination recorded while 1 subject performed procedure 1. Before analysis, wrist movement data were filtered using a second-order low-pass Butterworth filter (cutoff frequency: 8 Hz; see comparison between raw and filtered data in Fig. 2A). The next stage of data processing consisted of defining the range of angular excursion and the center of joint range of motion for each DoF. We defined the entire joint excursion from one extreme to the opposite extreme as 100% range of motion. These procedures allowed us to compute the range of angular movements relative to the neutral position (0° flexion/extension, adduction/abduction, and pronation/supination) and the extreme positions of the wrist ranges of motion for each DoF as follows: (1) center range was ±10% relative to the neutral position; (2) mid range was ±20% relative to the neutral position; (3) extreme range was extreme wrist posture position minus 20% of the same angle; and (4) out of range was beyond the extreme range (The center range of the wrist joint range of motion corresponds to the Drury definition (i.e., ±10% of range of motion), whereas the other ranges were arbitrarily defined. Thus, we divided the entire time series of wrist movement, subdivided for each DoF, into a total of 4 ranges (center range, mid range, extreme range, and out of range) (Fig. 2B). Once the 4 ranges of wrist angular excursions were defined for each wrist DoF, we computed the time spent in each range. Of particular interest to this study was the time spent at the extreme range and out of range as these are likely to be associated with increasing risk of repetitive strain injury.

Statistical analysis

Statistical analysis was designed to quantify the extent to which the time spent (in minutes) by our subject group within each of the above-defined wrist motion ranges differed across wrist DoFs, procedure difficulty, or subjects characterized by different levels of experience with endoscopic maneuvers. We used a mixed-effect model including 4 ranges (out vs extreme vs mid vs center), 2 procedures (easy [procedure 1] vs difficult [procedure 2]), 3 orientations (pronation/supination vs flexion/extension vs abduction/adduction), 2 previous injuries (yes vs no), 2 experience levels (less experienced vs more experienced) and interactions between (a) range and orientation, and (b) range and experience as fixed effects. Other nonsignificant pairwise interaction terms, such as procedure × orientation, were removed from final models. The random effects allow covariance to vary across subjects. Post hoc pairwise comparisons were conducted for subgroups of range and experience combination and range and orientation combination (we used Tukey’s method to adjust for multiple testing). \( P \) values < .05 were considered statistically significant. All statistical analyses were performed by using SAS software version 9.2 (SAS Institute Inc, Cary, NC). Values are reported in the text and figures as mean ± standard deviation of the mean.
RESULTS

Wrist motion patterns during endoscopic maneuvers

Wrist motion data were collected from 12 right-handed endoscopists. The mean age ± standard deviation (SD) of the subjects was 43.4 ± 10.9 years; range 32-65. The average number of years of endoscopic experience was 12.5 ± 10.7; range 1-35. Each endoscopist reported performing an average of 5.2 ± 2.2 procedures a day, 21.6 ± 7.1 hours per week on endoscopic procedures. Endoscopists were asked to report whether they had ever experienced pain, discomfort, rheumatological, orthopedic, or neurological problems from performing endoscopic procedures. Most of the endoscopists (8 of 12) reported positively to this question. Five of these 8 endoscopists also reported having altered their technique because of pain, with 3 endoscopists reporting having to miss work because of injury or treatment for pain. Three endoscopists responded to pain symptoms by wearing a wrist or a back brace to avoid further injuries in the respective areas. Those who had performed endoscopy for 10 years or less were defined less experienced (n = 7; 4 men, 3 women), and those who had more than 10 years of experience (n = 5; 4 men, 1 women) were considered more experienced. The 10-year cutoff to separate endoscopists based on experience allowed a more even distribution of subjects for statistical analysis.

The mean time spent performing the simulation procedures averaged across all subjects, DoFs, and procedures was 8.97 ± 1.21 minutes. Figure 3 shows the time spent by all subjects during each endoscopic procedure for each of the 4 wrist ranges of motion and DoF. Several observations can be made. First, no clear difference was seen when comparing the time spent within each range of motion as a function of wrist DoF. Therefore, no tendency for spending more time in a given motion pattern (eg, flexion/extension vs adduction/abduction) was evident. Second, the time spent during each procedure was not uniformly distributed across the 4 wrist ranges of motion. Specifically, Figure 3 suggests a tendency for the greatest amount of time in the center and mid range, followed by extreme and out of range, irrespective of the difficulty of the procedure and wrist DoF. An important observation is that subjects spent, on average, up to approximately 30% of the duration of the endoscopic procedures in both the extreme and out of range portions of the wrist range of motion (1.75 and 1.01 minutes, respectively, averaged across procedures 1 and 2). Table 1 shows the average time spent at each of the 4 motion ranges of interest and for each wrist DoF.

Statistical analysis supported these observations. Specifically, we found no main effect of wrist DoF, procedure, injury, or experience level (all P > .05). However, our analysis revealed important main effects and interactions among some of the above factors. Specifically, wrist range of motion was a significant term in the mixed-effect model (P < .0001), thus confirming the nonuniform distribution of time spent across motion ranges. We also found significant interactions between wrist DoF and range of motion (P = .02) as well as between endoscopy experience and range of motion (P = .03). Because of these 2 significant
interactions, individual levels of range of motion, experience, and wrist DoF were not compared overall.

The interaction between wrist DoF and ranges of motion is a very important result to establish a particular DoF’s tendency to drift into the extreme range of joint motion. This interaction caused insignificant differences in the time spent between mid versus center and mid versus extreme ranges in most wrist DoFs (Fig. 4A; Table 2). For instance, the more experienced endoscopists seemed to spend more time in the center and mid ranges than the less experienced, and the latter spent more time in the other ranges (Table 3). Figure 4C represents this graphically.

**DISCUSSION**

The American Society for Gastrointestinal Endoscopy Technology Committee prepared a status evaluation report addressing the way to minimize occupational hazards in endoscopy. One of the concerns was the “ergonomics of

![Figure 3. Time spent within each range of motion for each wrist degree of freedom. Each plot shows mean time (± standard deviation) spent by all endoscopists during procedures 1 and 2 (light and dark bars, respectively) for each wrist degree of freedom within each of the 4 ranges of motion (see text for more details). Abd/Add, abduction/adduction; Fle/Ext, flexion/extension; Pro/Sup, pronation/supination.](image-url)
endoscopic procedures. The Committee emphasized that gastroenterologists spend more than 40% of their time performing procedures and stated that there is a need for ergonomic evaluation because of the high prevalence of musculoskeletal injuries among endoscopists.

Our review of the literature revealed a paucity of scientific information measuring musculoskeletal activity during endoscopic procedures. Outside of GI endoscopy and other areas of procedural medicine, the use of kinematics is commonplace to identify movement patterns that subjects choose to attain specific task goals, e.g., changing where an object is grasped to reduce how much force they exert to balance an object during manipulation or whether a grasped bottle is lifted or rotated to pour liquid in a cup. One of the goals of this project was to apply techniques of kinematics to a common endoscopic procedure to make clinicians aware of the sophistication that can be used to study this important topic.

The use of simulators provided a way to help standardize the investigation. Simulators have been used to study performance during colonoscopy. Studies have validated the use of simulators for evaluating colonoscopy technique. Endoscopic simulators are able to differentiate experienced from novice endoscopists on particular criteria such as total procedure time, cecal intubation time, efficiency of examination, and percentage of mucosa

Figure 4. Time spent within each range of motion. The mean time spent (± standard deviation) by all endoscopists within each range of motion is plotted A, for each wrist degree of freedom and B, as a function of endoscopy experience. C, Overall effect analysis in a mixed model. Abd/Add, abduction/adduction; Fle/Ext, flexion/extension; Pro/Sup, pronation/supination.
The realism of the colonoscope and difficulty of the procedure, 2 important aspects of simulated endoscopy, are also representative of actual endoscopy. To the best of our knowledge, this work is the first attempt to quantify upper limb kinematics during full endoscopic procedures and lays the foundations for future studies addressing the link between upper limb movement patterns and overuse injury. Factors such as years of endoscopic experience and history of musculoskeletal injury do not appear to affect the amount of time spent across the different ranges of wrist motion. Specifically, we found that endoscopists spend similar amount of time across 3 different types of wrist motion. However, there does appear to be a tendency of experience leading to differences in how much time is spent at specific segments of the wrist range of motion, even

### TABLE 2. Statistically significant pairwise comparisons between the factors wrist degree of freedom by wrist range of motion subgroups

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<th>Range of motion (1)</th>
<th>Wrist DoF (2)</th>
<th>Range of motion (2)</th>
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DoF, Degree of freedom; Abd/Add, abduction/adduction; Flex/Ext, flexion/extension; Pro/Sup, pronation/supination.

Based on a mixed model; the last column includes an adjustment for multiple testing based on Tukey.
if not statistically significant. Experience with endoscopic procedures led to more time being spent in the extreme and out of range of motion than the less experienced in the mid range (Table 3). A key observation is the lack of a significant difference in the time spent at the extreme and out of range of motion when comparing more-experienced and less-experienced endoscopists. Because our definitions of more-experienced and less-experienced endoscopists were arbitrary, it is uncertain that this finding is important. We also found that endoscopists spent up to 30% of the duration of endoscopic procedures at the extremes of wrist joint range of motion, thus straining muscle, tendon, and joint tissues in a repetitive fashion. Although these observations are not sufficient to establish a conclusive link between wrist movement patterns and overuse injury, it is likely that they are a contributing factor.

We believe that it is important to link upper limb motion patterns to the risk of overuse injury caused by endoscopic maneuvers, but the current work is limited by the relatively small sample of subjects, the focus on only 1 joint, and no measurement of interaction forces with endoscopic tools. The small sample of subjects prevents making inferences about whether experience with endoscopic procedures does not change wrist motion patterns as described here. As endoscopic procedures lead to a host of musculoskeletal injuries that affect several joints of the upper limb and the trunk, it will be important to extend this approach to a more complete kinematic analysis of the upper body. Last, it is likely that excessive muscle forces contribute, along with the repetitiveness of specific movement patterns, in causing musculoskeletal injuries. Future work should address these limitations, by studying a larger number of subjects by directly examining the effect of endoscopic practice in a longitudinal fashion, by extending the kinematic analysis to more upper limb joints, and by including force measurements. Even though it was not a focus of this study, this raises the question as to whether the fact that endoscopists spend approximately 30% of the duration of endoscopic procedures at the extreme of wrist joint motion is related to endoscope design, and, if so, it provides an opportunity for endoscopic manufacturers to review the subject. To the best of our knowledge, no standard exists for what undesirable deviations of wrist posture are from neutral. Ongoing research aims at defining musculoskeletal injury risk thresholds to improve training guidelines for endoscopists and design guidelines for endoscope manufacturers.

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REFERENCES


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