MASTER THESIS

DETERMINING THE OPTIMAL ENDOSCOPY MOVEMENTS FOR TRAINING AND ASSESSING PSYCHOMOTOR SKILLS

E. van der Velden
26-01-2018

Faculty of Science and Technology
Technical Medicine – Medical Imaging & Interventions

Graduation committee:

Prof. dr. S. Perretta
Prof. dr. ir. S. Stramigioli
Dr. ir. N. Padoy
Drs. B. Hessink-Sweep
Dr. E. D. Rodijk-Rozeboom
Dr. Ir. M. Abayazid

EVEREST
Enseignement Virtuel International en Chirurgie par la Simulation et les Technologies web

ihu STRASBOURG
INSTITUT DE CHIRURGIE GUIDÉE PAR L'IMAGE

UNIVERSITY OF TWENTE.

Abstract

Introduction: Teaching flexible endoscopy to residents is still mostly based on the expert-apprentice relationship using a see one, do one, teach one approach. As only the highest standard of care becomes permissible, a shift is being observed to virtual and simulation based training. In flexible endoscopy, one of the biggest challenges is precisely explaining an elaborate choreography of psychomotor movements. A novice is thus confronted with a broad range of endoscope movements which should be trained sufficiently before participating in the clinical setting. Ideally, a simulation method able to develop these psychomotor skills, which are not taken into account by current simulators, should be developed. The here performed research was aimed at quantifying the required motoric skillset by observation and subsequent analysis. The end-goal being to develop a motion library that correlates the different movement possibilities of the endoscopist with the endoscopic response for developing a serious game to ease novice education in flexible endoscopy.

Materials and methods: Firstly, a motion dataset covering all movements that influence the resulting scope motion was acquired. This was done with a setup consisting of multiple tracking systems; a wireless motion sensor system to track the endoscopist's body (Awinda suit, Xsens Technologies), a magnetic probe inserted in the working channel of the endoscope to track the endoscope (Aurora, NDI) and a webcam to track the wheel's rotation. The endoscopic view and external view of the procedure were also recorded. Secondly, the acquired motion data was analysed in terms of similarity and motion parameters. To determine the optimal endoscopic procedure from more than two recorded experts, we had to synchronize motion trajectories of similar movements that vary speed. Dynamic time warping (DTW), was proposed to obtain synchronization. This technique was used to estimate an average motion trajectory and to determine a reference sequence among experts. Lastly, the different manoeuvres that influence endoscope manipulation (i.e. wheel rotation, scope torque & translation, upper body motion) were described and analysed individually.

Results: A motion library of 26 upper gastrointestinal procedures, simulating a clinical environment on animal models, performed by six experts and three beginners was recorded. DTW proved to be able to accurately align the motion data of multiple endoscopists, based on their intrinsic similarity. Original motion sequences correlates with computed average and reference sequence in terms of procedure time, path length and smoothness of motion parameters. Important additional results showed that there is a significant difference in path length between beginners and experts. Finally, endoscope manipulation manoeuvres analysis revealed the expert preferred manoeuvres. Insights in the similarity between the expert's and novice's manoeuvres can be achieved with the DTW comparison.

Conclusion: The study managed to create and analyse a comprehensive, multiple-view, motion library of surgical flexible endoscopy. This was used to estimate expert's optimal endoscopic movements. Furthermore, a motion-based visual comparison of novices' psychomotor skills was proposed. The work set the basis for the development of a serious game for an endoscopic training modality that could decrease expert's proctoring efforts and offer a platform for skill assessment.

Table of content

General introduction

The field of surgery continuously undergoes changes due to new technologies that should improve patient outcome. To be able to use these innovations, clinicians have to repeatedly educate themselves. Example changes due to the introduction of new technologies are the shift from open surgery to laparoscopy, followed by another ongoing shift from laparoscopic to endoscopic interventions. With the availability of new tools and the amplification of new endoscopic procedures, it enables surgeons to perform interventions in a more minimally invasive way. Yet, surgeons, residents and students need to acquire skills to perform surgical flexible endoscopy properly. Learning endoscopic skills requires additional training. However, it gives an extra workload on the time schedule of surgeons, residents and students due to teaching, practising and examination moments. In addition, to that it also leads to a higher impact on the hospitals' financial resources [1]–[3].

Known disadvantages in the widely used minimally invasive surgery is the new user interface. It provides less haptic feedback due to the length of the instruments. Besides this, it introduces a different instrument orientation related to the patient's anatomy. In endoscopy, this is related to the flexibility of the endoscope [4]. The endoscopic user interface requires a new set of psychomotor skills for the operators to acquire. Also interventional endoscopy requires extra training since it is technically challenging and has higher complication rates compared to diagnostic procedures [5], [6]. To ensure that surgeons and gastroenterologists spearhead the field of flexible endoscopy, new strategies must be developed and implemented for teaching interventional endoscopy to students, residents and surgeons. Because today experts are facing the challenge of explaining precisely an elaborate choreography of movements performed during the procedure, while novices are confronted with a broad range of hand, wrist and shoulder movements each resulting in different scope responses. In addition to this, it would be desirable to offer the majority of students the possibility to learn from the best international expert in the field.

There is good evidence for the use of virtual reality simulation in endoscopy training programs to enhance psychomotor skills competency, as well as assessing them [3]. Most benefits are shown in the initial phase of learning, evaluating early stages of patient-based endoscopy [7]–[9]. The systemic review of *Dawe et al.* showed that participants who reached simulation-based skills proficiency before undergoing patient-based assessment performed with higher global assessment scores and fewer errors in the operation room than their counterparts who did not receive simulation training [10]. It has been demonstrated that skills gained by simulator training can be transferred effectively in a patient-based situation [10]–[13]. This supports the transfer of teaching technical skills in a simulator-based environment in a safe, effective and ethical way before entering the operating room. Yet, these skills obtained in a virtual reality environment with a simulated anatomical environment, can also be learned in a video game environment [14], [15]. In a serious game, an enjoyable interface and didactic intentions are combined [16]. They provide a balanced combination between challenge and learning. Serious games are applied already to train technical and non-technical skills relevant to the surgical field, like team training in acute care, triage and surgical skills [17]. *El-Beheiry et al.* demonstrated that the competition aspect of a simple serious game increased voluntary usage and performance on a laparoscopic simulator [18].

Currently there are several flexible endoscopy simulators available to practice technical skills outside the operating room, such as; GI MENTOR of Simbionix, EndoSim of surgicalscience and ENDOVR of CAE. Although some are useful, these simulators are also bulky, expensive and difficult to operate. Above this, trainees need to take time of their busy work schedule to go to a specific simulation training centre to practice.

Cost is one of the major limiting factors preventing the extensive implementation of endoscopic simulation programs [3], [12]. Prolonged endoscopic procedure times due to resident training in the operation room also has a high financial impact. More importantly the use of simulation training could reduce the potential complications of training directly on patients. The financial burden and some of the safety issues may be lessened with the appropriate use of simulator based endoscopic training [3]. Apart from the reduction in time and costs, an effective endoscopic simulator can also have direct clinical effects. When students are able to train the psychomotor skills needed to interact with the unintuitive interface of a flexible endoscope, they have more attention for medical aspects during the clinical procedure.

Many of the existing simulators define and assess an operator experience in endoscopy with parameters such as; (independent) procedure completion time [9], [13], [19], required assistance [9], percentage of time of mucosal visualization [7], path length [19], [20]. Instead of only focussing on such outcome parameters and the number of cases performed, it would be interesting to look at how the procedure must or should be performed, the input parameters. Because the teaching strategy of endoscopy could benefit from a dedicated motion library that deciphers the operator's motions and the consequent endoscope response. To this aim objective parameters that actually correlate performance directly to the end-result must be defined. To increase the effectiveness of the training, as time and money is limited. Research has shown that there is a significant difference between posture and movement during an endoscopic procedure between trained and experience clinicians and untrained students [21]. To create a valid tool for endoscopy training, psychomotor skills must be registered to define procedure competence for a specific procedure. Literature describes multiple criteria and measurable parameters on posture and motion during flexible endoscopy. *Arnold et al.* based their parameters upon the hypotheses that for an optimal stance a gentle curve of the scope should be obtained and therefore, the endoscopist's hands must be wide apart and the hand holding the scope must be held high. Next to that the scope hand should be moved in an ergonomic fashion with precise movements [21]. Next to this, other literature suggests that the amount of scope torque used for steering, smooth and fluent motion, expression of the upper body movements and usage of right hand for wheel rotation are parameters to define optimal posture and motion for endoscopy [22]–[25].

Framework

To improve training of endoscopic skills and to decrease the supervision time, a serious game designed for endoscopy is being developed within the context of the Everest project at IHU (Strasbourg, France). The Everest project is performed in a consortium with the University of Twente and aims at developing three strategic aspects of modern invasive surgery. Namely, surgical endoscopy, percutaneous image guided surgery and surgical innovation. In this framework a series of three European master programs will be created. For the surgical endoscopy master a low-cost endoscopy simulator is being designed, with a serious game to teach basic endoscopic skills. The game will focus on the performance of a predetermined task with different steps, reproducing the psychomotor skills required for the performance of a good endoscopic procedure. The simulator should have a user interface that tracks the motion of the student and give feedback based on the recorded movements. So it allows feedback based on input parameters, instead of only game or output parameters, allowing an adaptive storyline that further increases engagement and learning efficiency. This serious game will make it possible for students to practice their surgical skills in their own time. The game adds a competition element, resulting in more voluntary willingness to play. The skill training will decrease supervision time and financial resources.

This master thesis, will focus on the first step towards developing the serious game simulator. To reproduce the psychomotor skills required for the achievement of an expert endoscopic procedure, a dedicated motion library with key movements is needed. Therefore, this work focuses on identifying endoscopist's and endoscope's motions during the different phases of a basic endoscopic procedure.

The surgical innovation master of the Everest project is based on an already existing course, namely the Business Engineering and Surgical Technologies (BEST) innovation course. During my graduation internship, I had the opportunity to also work on this part of the Everest project. These extra activities, including obtained experiences and insights, are outlined in the first section of the appendix.

Research questions and goals

The main question being investigated is:

> *Can an average procedure of an endoscopic procedure be constructed and used for psychomotor skill instruction?*

This is described in multiple chapters, each with its own research questions and goals listed in table 1.

Table 1: List of research questions and goals

Research question	Goal	Chapter
What are the relevant endoscopy movements and how can these movements, of the endoscopist and the endoscope, be acquired during an endoscopic procedure?	To acquire raw measurement data from different movement tracking sources, to track all relevant endoscopy movements, during an endoscopic procedure with a standardized workflow.	1
How can the recorded motion data be compared based on their dynamic features?	To standardize and synchronize the recordings, independent of the time needed to perform the endoscopy procedure.	2
What approach can be used to determine the optimal endoscopic movements of multiple expert endoscopists for comparison and evaluation?	To propose and perform different methods for the calculation of the optimal movements during an endoscopic procedure.	3
What results shows the computed optimal procedure (average and reference), when evaluated based on motion efficiency?	To evaluate the results of chapter 3 based on three defined motion parameters.	4
Can the different manoeuvres, that influence the endoscope manipulation, be described and analysed individually?	To describe and analyse the different manoeuvres that influence endoscope manipulation, by evaluating their change over time.	5

The results of this study will be used to create an objective means to evaluate endoscopic skills, to determine if the learning goal has been met and to deliver appropriate training. The expert movements can be used to create movement references for a serious game, designed for flexible endoscopy. This way each student can learn and compare their performance with the best expert in the field, while receiving direct feedback.

Chapter 1: Endoscopy motions: parameters and measurement techniques

Research question	Goal
What are the relevant endoscopy movements and how can these movements, of the endoscopist and the endoscope, be acquired during an endoscopic procedure?	To acquire raw measurement data from different movement tracking sources, to track all relevant endoscopy movements, during an endoscopic procedure with a standardized workflow.

Introduction

Each flexible endoscopic procedure, from a simple diagnostic procedure to more complex procedures like an endoscopic sleeve gastroplasty, consists of a serie of body movements that result in a certain scope position. Most evident are the movements that manipulate the scope wheels and the right hand movements that influence the translation and rotation of the scope where it enters the patient's body. The wheels control the steering of the distal tip of the endoscope, the tip can move up and down (movement *a* in figure 1.1) and left and right (movement *b* in figure 1.1). The endoscope tube that enters the patient body is hold by the endoscopist, this way the amount of scope tube inserted into the patient's body (movement *c* in figure 1.1) and the rotation of the scope (movement *d* in figure 1.1) is influenced. Nevertheless, these are not the only body movements influencing the position and orientation of the endoscope. Upper body motion and posture also influence scope motion. Research has shown there is a significant difference of body posture and movement between experienced clinicians and untrained students. [21]

Figure 1.1: Manipulation possibilities of a flexible endoscope

Adding up all scope manipulation possibilities, there are three different movement elements; the wheel rotation, torque and translation of the scope and movement of the upper body. To record the different motion parameters, the movements of the endoscope as well as the endoscopist have to be tracked.

The feasibility of recording all endoscopic movements is tested with a simple endoscopic procedure. In figure 1.2 the diagnostic esophagogastroduodenoscopy (EGD), which is an upper gastrointestinal (GI) procedure is illustrated. This endoscopic procedure is simple, fast and the upper GI tract shows less anatomical variation, compared to the lower GI tract. Above this, it is relatively easy to define a standardized workflow for EGD procedure.

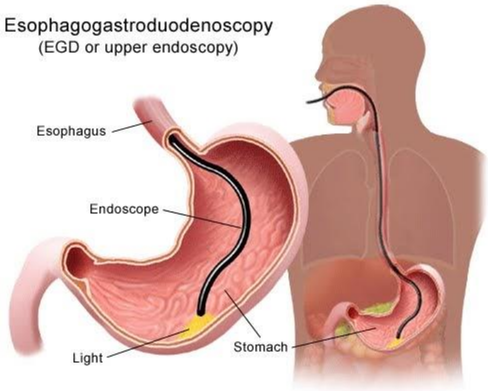


Figure 1.2: Animated overview of an EGD procedure

Methods and materials

Endoscopist motion

To track the body motion of the endoscopist, the Awinda suit provided by Xsens Technologies is used. The suit consists of 17 motion trackers (MTw). These trackers contain 3D linear accelerometers, 3D rate gyroscopes, 3D magnetometers and a barometer [26]. The angular velocity is defined as the velocity that is used to move an object around a line which is referred to as the axis of a rotation. The movement of a specific object is described with an angle in radians. The acceleration is used to determine the velocity and the changing velocity during a movement. The magnetic field is a 3D space that has the ability to measure the position of a sensor.

A biomechanical model is used to translate the kinematics to the body segments. This model assumes that the body consists of segments which are in turn connected by joints and that the sensors are attached to these body segments. Joints origins are determined by the anatomical frame, with the use of premeasured body measurements. They are defined in the centre of the functional axes with the X, Y and Z planes being related to functional movements.

The biomechanical model consists of 23 segments: pelvis, L5, L3, T12, T8, neck, head, right and left shoulder, upper arm, fore arm, hand, upper leg, lower leg, foot and toe. For the segments on which no sensor is attached, the kinematics are estimated based on the biomechanical model taking into account stiffness parameters between linked segments [27].

The trackers are placed at strategic and standard locations on the body to measure motion on each body segment (figure 1.3). Before measuring, the system has to be calibrated. Extra focus is put on an accurate calibration for the hand movements, since these are important for endoscopy [26].

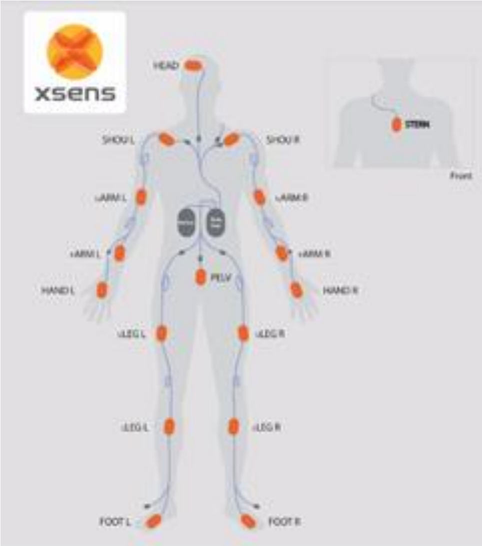


Figure 1.3: Placement of the Xsens segment motion trackers

Flexible endoscope motion

The scope movements are tracked by the electromagnetic Aurora system, produced by NDI. It consists of a 1.20 meter long fibre probe, with seven miniature electromagnetic coils, that can be localized by the Aurora system. The probe is inserted in the scope through the working channel and it is fixed with a transparent endoscopic cap at the top. Rotation of the endoscope over its longitudinal axis can also be tracked.

Electromagnetic field tracking systems determine the location of objects that are embedded with sensor coils. By placing the object inside a varying magnetic field, produced by a field generator, the position and orientation of the object can be calculated. This can be calculated, since the electromagnetic field is distorted through the induction of voltages in the sensor coils. The benefit of using this kind of tracking is that it does not suffer from the line-of-sight constraints as with optical tracking systems. Problems may occur by distorting the electromagnetic field, which is not solely due by the sensor coils in the probe, but also through other ferromagnetic objects. Fortunately, the tracking system is compatible with most surgical instruments and research has shown that tracking endoscopes during an intervention is a feasible application for electromagnetic tracking of the current technology [28], [29]. Most importantly, motion analysis with electromagnetic trackers has been shown to be an objective method for measuring surgical dexterity [30].

Wheels rotation

The wheel rotation of the endoscope is being tracked by an external camera mounted on the endoscope handle (figure 1.4). To track the angle of the wheels, a special colour band is designed for the identification of the wheel angle. The band, visualized in figure 1.4, is fixed on the endoscope wheels like a sticker to not disturb the endoscopist's hand.


Figure 1.4: Colour band and wheel tracking setup with the external camera mounted on the endoscope handle

The camera footage will be processed by an in-house developed optical tracking system to detect both wheel angles, based on a colour-coded algorithm. The colours on the wheel band are chosen so that the hue values are equally scaled on the HSV colour range to have a maximum difference from each other. HSV colour range is chosen, due to its independence of lighting. The order of the colours is determined by the requirement of the robustness against occlusion and confusion. Robustness for occlusions means, in case a colour gets occluded by the endoscopist's hand, the detected colour pattern is still unique. Robustness for confusion means that if a colour is detected as the next colour in the hue scale, the detected colour pattern is still unique. The detected colour pattern refers to the colours visualized by the camera. The fixation of the colour band is standardized and the order of the colours is known. Due to this, a standard configuration is made that correlates each detected colour pattern with a wheel angle.

Tracking setup

The final data acquisition setup contains different tracking sources, described in the previous paragraphs. The two commercial tracking systems used to record the endoscopist's body motion and endoscope motion and the webcam to track the endoscope wheel rotation. Next to this the endoscopic view is recorded and an external camera, the Kinect 2 system from Microsoft, records the procedure. The combination of the different recording sources is shown in figure 1.5.

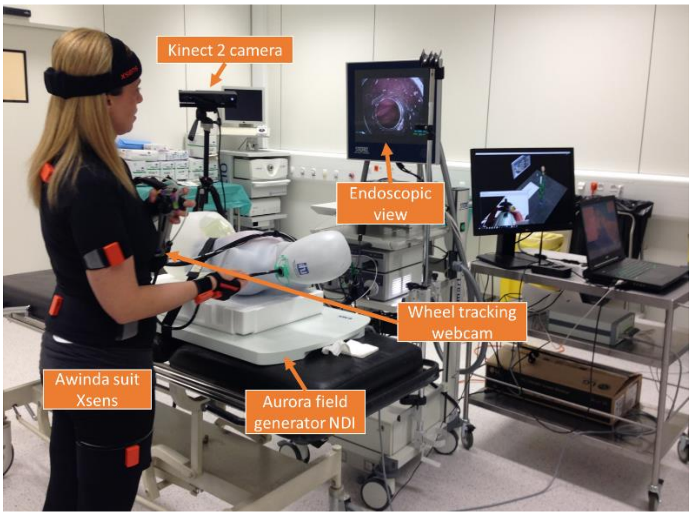


Figure 1.5: Different tracking sources of the final setup at the experimental platform of IHU.

The positioning of the setup is chosen so that it resembles clinical practice. Since the final goal, after testing the feasibility of the setup, is to acquire motion data while performing flexible endoscopy on patients.

Data acquisition software

During preliminary experiments performed on pigs, the importance of a software that synchronously records all motion data became apparent. Therefore, a C based in-house software program has been created for the acquisition of the motion data extracted from the three different data resources described in the previous section (body motion, scope motion and wheel rotation). The different tracking sources have different update frequencies; the Aurora system has an update frequency of approximately 15 Hz, the Xsens system mostly reached 60 Hz and the external camera updates with 20 Hz approximately. Eventually the data is resampled to 20 Hz, with the same timestamp for each source. Wherefore the nearest data point at each time stamp is selected.

The recording software does not only record the motion data synchronously, but it also operates as an interface for registration between the different tracking sources. For registration an electromagnetic probe fixed on a checkboard-like surface, at known location, is used (figure 1.6). By capturing this checkboard in minimal 10 different poses, the software configures a registration between the Aurora system and an external camera, a Kinect 2 system from Microsoft. For the first experiment, the most optimal registration had a residual error of 8.317 mm and 1.895 degrees. For the second experiment, the residual error remained 6.236 mm and 0.875 degrees. The Kinect camera, in its turn, configures a registration with the Xsens system, by detecting the head of the endoscopist and linking this to the head of the kinematical model of the Xsens. The raw position and orientation of the Xsens source, used for further analysis, is defined in the Aurora coordinate system. This is done with the use of the transformation matrices resulting from both performed registrations.

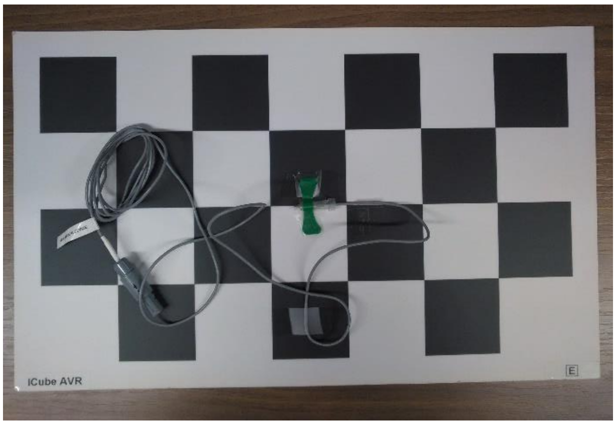


Figure 1.6: Checkboard-like surface with fixed electromagnetic probe

There has been no quantitative analysis of the synchronization between the different sources. Yet, a qualitative judgement can be made by evaluating the accuracy of the superimposed endoscope reconstructed from the recording on the video. The augmented scope is able to follow the real scope and has a precise overlay. This indicates a low time latency and acceptable registration error. The maximum registration error is set at the outer sheath diameter of the endoscope, which is 9,3 mm for the Karl Storz Silver scope. The registration errors of both experiments meet this requirement.

Lastly, the software also serves as a replay tool where recording can be reviewed and recorded motion data can be reconstructed and superimposed on the footage. Multiple viewing options are available and it is possible to navigate through all recordings.

Experiments

The first experiments were conducted in an office room with a plastic upper gastrointestinal model. Followed by experiments at the experimental platform at IHU. At this platform, the setting consisted of a standard endoscopic console, a decommissioned patient bed and an ex-vivo upper gastrointestinal model. Only the measurements performed with the final setup will be used for analysis in the next chapters.

With the final setup nine different endoscopists are recorded. From these nine endoscopists three were beginner endoscopists with less than 100 practises of upper GI endoscopy in human patients. The other six endoscopists were experts with at least more than 500 procedures. According to literature, a minimum of 100 – 300 EGD procedures is needed to become competent in upper GI endoscopy [31], [32].

Phase annotation

Based on the clinical workflow of an EGD procedure [33], a set of key time points is defined to divide the recording into different phases. Figure 1.7, shows an overview of the key time points and clinical phases that have been defined for the experiments in order to cut the recorded procedures. The key time point are manually annotated during an experiment with the use of the acquisition software.

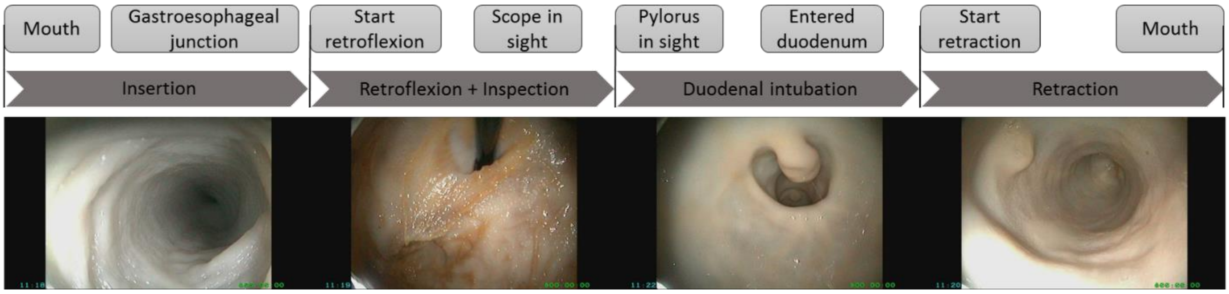


Figure 1.7: The key time points and clinical phases defined for data acquisition of and EGD procedure.

The clinical phases of the recorded EGD procedure:

1. **Insertion:** this first phase starts at the mouth, through the esophagus and passes the gastroesophageal junction. The end of the phase is the moment when the scope enters the stomach, before retro flexion is initiated.
2. **Retroflexion and inspection:** retroflexion is the bending of the endoscope by approximately 180 degrees in order to inspect the gastroesophageal junction from the inside and inspect the fundus of the stomach. This second phase ends when the pylorus is visualized by the endoscope.
3. **Duodenal intubation:** after visualization of the pylorus the endoscopist will intubate it, sometimes after multiple attempts.
4. **Retraction:** the last phase is the retraction of the scope from the duodenum back to the stomach, esophagus and out the mouth again. During retraction the endoscopist inspects the mucosa of the stomach and esophagus, which is the main goal of the clinical procedure.

During the experiments an observer who follows the endoscopic procedure will annotate the defined key time points. Each endoscopists repeats the experiment at least three times.

Results

The first measurements were performed to test and improve the technical setup and the experimental workflow. With the final setup, nine endoscopists were recorded. The recordings were divided into two datasets, see table 1.1.

Table 1.1: Overview of acquired recordings

Endoscopist	Level	Number of successful recordings	Endoscope tracking	Body tracking	Dataset
1	Beginner	1	√	√	1
2	Expert	8	√	√	1
3	Beginner	4	√	√	1
4	Beginner	2	√	√	1
5	Expert	2		√	2
6	Expert	2		√	2
7	Expert	2		√	2
8	Expert	1		√	2
9	Expert	4		√	2

In total, the current dataset consists of seven beginner and 19 expert recordings.

Unfortunately, a part of the recordings does not have reliable endoscope motion data recorded, due to the Aurora probe being suddenly defective. For those recordings, only body motions can be analysed. For the data analysis, the recordings are split up into two datasets; one including endoscope motion and one without.

As described in the method section, the developed acquisition software also serves as a replay tool for the recordings. The tracked motion data can be reconstructed and superimposed on the video. An example in shown in figure 1.8.

Figure 1.8: Snapshot of a superimposed replay recording.

In the top left corner of the image, the endoscopic view, synchronously recorded during experiments, is projected. At the lower right corner, the amount of scope insertion, torque and wheel angles are displayed. The position and orientation of the scope is projected on the image, since the real endoscope is actually inserted inside the model. Lastly, the kinematic model of the tracked body motions is superimposed on the endoscopist and displayed semi-transparently. Since all the sources are synchronously recorded, all projections follow when navigating through the video.

Discussion

The different endoscopists recorded for this research have all followed a different medical education before performing endoscopies. Some were trained as surgeons, some as endoscopists. Two experts followed their medical training in Europe, two in North America and the other two in Asia. Opposed to Europa and North America, surgeons in Asia also receive full endoscopy training. Therefore, it is clear that the population sample has a significant amount of variation due to the different backgrounds of the subjects. Above this, the expert sample size is small, therefore it might be difficult to find a reference or average movement that represents all experts or an average movement that is still interpretable.

One of the challenges for this technical setup in a patient setting is the need for a fixed position of the Aurora system, relative to the Kinect camera. The fixed position is required for registration between the tracking sources. The registration is needed to be able to replay the recording afterwards and superimpose the reconstruction of the recorded motion data. A fixed position of the Aurora system in relation with the Kinect camera means that the patient's bed should not be moved after registration, since the Aurora detection board in placed under the matrass of the patient's bed. This might cause difficulties when preparing the patient for endoscopy. Three options can be imagined; the patient is transferred on the bed without moving the bed, the registration is performed while the patient is already on the bed or a system is put in place that tracks the displacement of the bed. The latter could be done by fixing a small checkboard surface on the bed. A last option is to record motion data from the different sources without registration, discarding the possibility to superimpose and replay the reconstruction of the recorded data. Nonetheless, it might make the analysis more difficult when comparing different recordings. This option should therefore be investigated in more detail.

Even though each endoscopist is recorded at least three times and sometimes more, the amount of successful recordings can be less than three. This is feasible since it was not yet possible to check, in detail, if the data was complete, during the experiments. In retrospect, missing values were detected for some recordings, over a certain time period. Most likely, this is caused by the processor not able to manage the high calculation load that is required for this experiment to succeed smoothly. Unfortunately, due to this, these recordings were unfit for further analysis.

Conclusion

The technical setup built to track endoscope and endoscopist motion proves feasible for the acquisition a complete motion dataset, providing a motion library to use for education purposes. For this thesis the experiments were performed in a pre-clinical setting and limitations for the clinical setting, like a fixed patient bed position, need to be investigated for future advancements.

Chapter 2: Sequence synchronization

Research question	Goal
How can the recorded motion data be compared based on their dynamic features?	To standardize and synchronize the recordings, independent of the time needed to perform the endoscopy procedure.

Introduction

In this study, the similarity between different motion time series, either of the same endoscopist or between two different subjects, is investigated. However, simple point-to-point comparison gives unrealistic results, because a time series can be different in time but similar in 'shape'. This principle is demonstrated in figure 2.1.

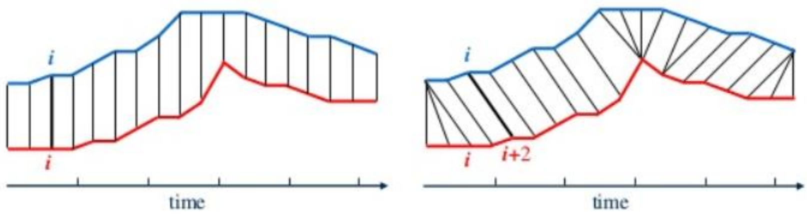


Figure 2.1 Point-to-point comparison (left) vs alignment based on similarity of shape (right) ***[34]***

With a component-wise Euclidean distance comparison, point i on one time series would be compared with point i on the other resulting in a poor similarity outcome. A non-linear synchronization method, like dynamic time warping (DTW), is capable of aligning two sequences based on their 'shape'; a feature-wise comparison independent of time.

During the experiments, described in chapter 1, the recording is annotated with key time points. Based on these annotations the recordings could be aligned, by linear interpolation in each phase. Nonetheless, this is still not optimal when looking for intrinsic similarity between time series and is only possible when phases are annotated. Next to this, the key time points are annotated manually and might therefore be inaccurate, due to reaction time. Correcting the annotations afterwards is a time consuming process. Therefore, a synchronization method is needed that reflects the intrinsic similarity between time series and also quantifies the similarity features. The latter is of importance in order to compare the automatic synchronization with the annotated phases.

Among the methods commonly used for similarity measurement, DTW is the most widely used [35]–[38]. Originally, DTW has been used to compare different speech patterns for automatic speech recognition [39]. Nowadays, it has been successfully applied in many domains. It allows for synchronization of temporal data independent of time and intuitively warps sequences in a nonlinear fashion to match each other. In this chapter, a method is presented which allows for the synchronization and comparison of 3D captured movements.

Basic principle of dynamic time warping

Dynamic time warping allows a sequence to be 'squeezed' or 'stretched' in comparison with another sequence in order to find the minimum distance between data points. It then uses these distances to calculate a cumulative distance matrix and finds the least expensive path through this matrix (figure 2.2). This path represents the ideal warp; the synchronization of the two sequences where the distance between the synchronized points is minimal [36]–[38], [40].

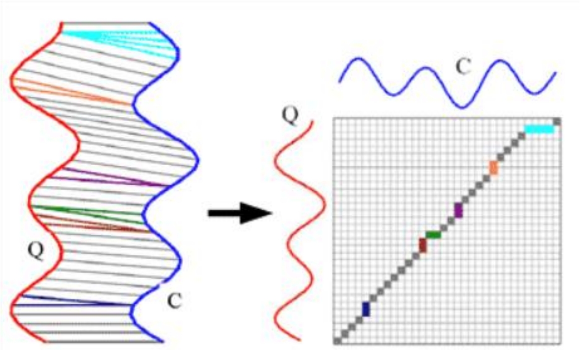


Figure 2.2: Optimal warping path in cumulative distance matrix ***[41]***

The distance is based on the Euclidian metric:

$$d(x, y) = |x - y|$$

Then the two given sequences $X(x_1, x_2, \dots x_m)$ with length m and $Y(x_1, x_2, \dots x_m)$ with length n can be compared by calculating local distances. For the motion recordings the arrays X and Y consist of 3D position and orientation information. A m x n matrix M can be defined to represent the point-t-point correspondence relationship between X and Y, as demonstrated in figure 2.2. Consequently, the point alignment and matching can be represented by a time warping path W. The total cost $W(X, Y)$ of warping path W between X and Y with respect to local cost measures w is defined as:

$$W(X, Y) = \sum_{k=1}^{K} w(x_{m_k}, y_{n_k})$$

Here K is the dimension of the sequence. For the recorded motion data this can mean the amount of position and orientation data, depending on how many body segments or endoscope probe sensors are taken into account. To be able to optimize the warping path, the sum of the local comparison needs to be minimized, this optimal value is denoted as $DTW(X, Y)$:

$$DTW(X, Y) = d(X, Y) + min \begin{cases} DTW(X, Y[2:-]), \\ DTW(X[2:-], Y), \\ DTW(X[2:-], Y[2:-]), \end{cases}$$

Here $[2:-]$ indicates a subarray that starts at the second element and ends at the final element in a one-dimensional array. $d(X, Y)$ represents the distance between point x_i and y_j by a distance measurement, for example the Euclidean distance.

For this research, the DTW algorithm of the MATLAB software, created by MathWorks, is used. In this algorithm, the first sequence input is taken as the source sequence and the second sequence as the measurement that will be warped. The second sequence will be ‘stretched’ and ‘squeezed’ until the dynamic features are aligned to those of the source sequence.

Methods

Dataset 1 is used for the analysis described in the next section, in order to keep an equal number between endoscope and endoscopist data.

Preparation of the recorded data

Firstly, the recorded motion data is exported from the acquisition software and loaded into MATLAB for further analysis. Before synchronization, the raw position and orientation data needs to be prepared and filtered. Since the lower body of the endoscopist is considered irrelevant for manipulation of the scope, only the upper body segments are selected. The upper body consists of the shoulders, upper arms, lower arms, hands and pelvis.

Standardization of the data is performed by rescaling the data to have a mean (μ) of 0 and a standard deviation (σ) of 1 (unit variance), in order to compare different sequences. A sequence is here defined as a time series of recorded position data of one procedure. One endoscopist has multiple sequences recorded. Standardization is needed to remove biases and the influence of for example differences in body dimensions of the endoscopists. Thus, the Z-score is calculated for each position or orientation dataset over time, for example all x-coordinate observation time points of the left hand.

$$\mathrm{Z} = \frac{X - \mu}{\sigma}$$

In this formula, Z represents the distance between the raw score X and the population mean in units of the standard deviation.

The occurrence of short time periods, where a sensor in the Aurora probe is not detected and consequently not recorded, is solved by performing spatial and temporal linear interpolation when possible.

After preparation of the recorded data, the DTW built-in function from Matlab is used to synchronize the recordings.

Similarity metrics for assessment

The outcome of the automatic DTW synchronization can be evaluated with the annotations of the phases that were set during the experiments and manually checked afterwards. In order to do this, metrics are needed to quantify the similarity after automatic synchronization. This requires a more interpretable metric than the DTW distance. With the information of the annotated phases, new similarity metrics are proposed.

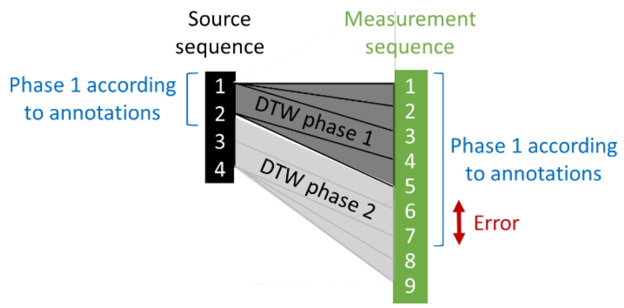
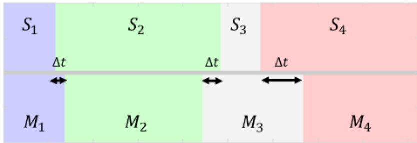


Figure 2.3: Schematic illustration of the possible misalignment between DTW synchronization and annotated phases

In figure 2.3, it can be seen that DTW may have synchronized the first two data points in the source sequence with the first five data points in the measurement sequence. However, according to the annotations, this should be up to the seventh data point. This misalignment between the DTW synchronization and the phase annotations determines the synchronization error. This metric gives information about how well DTW synchronized the sequences and can be expressed in time units or percentage of the total sequence length. Despite the partial misalignment, five data points were actually correctly synchronized. To also take this into account, the accuracy of the synchronization is also computed. In table 2.1 these similarity metrics are defined.

Table 2.1: Similarity metrics

Metric	Formula	Unit
Synchronization error	$\frac{\sum_{p=1}^{P}\lVert S_p - M_p \rVert}{frame\ rate}$	seconds
	$\frac{\sum_{p=1}^{P}\lVert S_p - M_p \rVert}{T_S}$	%
Accuracy	$\frac{\sum_{p=1}^{P}(M_p == S_p)}{T_S}$	%



With DTW, a source sequence '*S*' is passed as an input to synchronize with the measurement '*M*' for each procedural phase '*p*' defined by the clinical workflow. The illustration in the table shows how a DTW synchronization might show some misalignment according to the annotated phase. T_S is the total time of the source sequence. The synchronization error metric represents the misalignment of the phases after performing DTW. The accuracy metric shows the percentage of time points that overlay in each phase after DTW synchronization.

The recorded motion data consists of different information; 3D position and orientation observations for the sensor's location of the endoscope and the segments of the endoscopist. One or multiple of these parameters could serve as input for the DTW algorithm. When the DTW synchronization can be quantified with similarity metrics, an optimal parameter configuration can be determined. The configuration is determined by the nine different sets of input parameters for the DTW algorithm. The optimal configuration will have the lowest synchronization error and the highest accuracy.

Table 2.2: The ID's of the nine tested configurations

	Endoscope	Endoscopist	Both
Position	1	4	7
Orientation	2	5	8
Both	3	6	9

Results

Figure 2.4 shows a 3D visualization of two synchronized recorded sequences from different subjects. The visualization shows the warping based on the different shape characteristics by matching one data point of a faster subject with multiple data points of a slower subject.

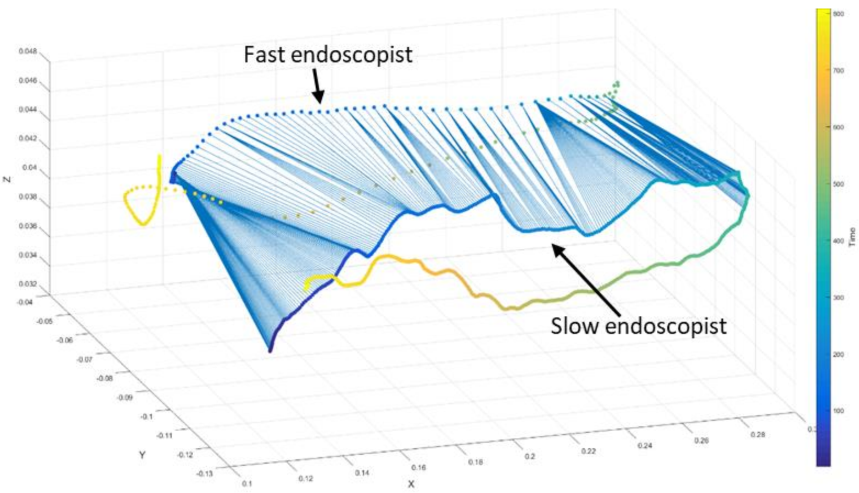


Figure 2.4: 3D visualization of two scope position sequences during the insertion phase, synchronized with DTW. The blue lines show the matched data points, based on their dynamic features.

Figure 2.4 demonstrates the functionality of the DTW algorithm. Two sequences of a fast and slow endoscopist are visualized over time (demonstrated by the vertical colour bar). The synchronization lines between the two sequences, which refers to a point in time, show that based on the dynamic properties of the data, the fast endoscopist can be aligned with multiple time points of the slower endoscopist. Notice that, for visualization purposes, only a part of the synchronization match lines are shown.

With the proposed similarity metrics defined in the method section, the optimal configuration for the synchronization can be determined. In order to select the optimal configuration, the metrics have been computed by selecting each sequence as source sequence and are then compared to all the other sequences recorded. This is done for each configuration. In the end, the average of each metric per configuration is evaluated in table 2.3

Table 2.3: Average outcomes of similarity metrics for all nine configurations

	Synchronization Error [sec]	Synchronization Error Percentage of sequence length [%]	Accuracy [%]
1) Scope position	65,80	35%	84%
2) Scope orientation	77,55	43%	82%
3) Scope position & orientation	72,23	40%	82%
4) Endoscopist position	155,95	90%	69%
5) Endoscopist orientation	185,91	109%	64%
6) Endoscopist position & orientation	167,22	98%	66%
7)All position data	86,55	49%	79%
8) All orientation data	128,18	74%	72%
9) All data	105,79	61%	76%

From the results shown in table 2.3 can be concluded that the optimal configuration of input parameters for DTW is composed of the scope position data. The endoscope position data is most accurate to use for analysis.

Inter- and intra-observer results of the least and most accurate DTW synchronization, according to the annotated phases, can be seen in figure 2.5. The different colours correspond to the four defined phases of the gastroscopy experiments (see phase legend).

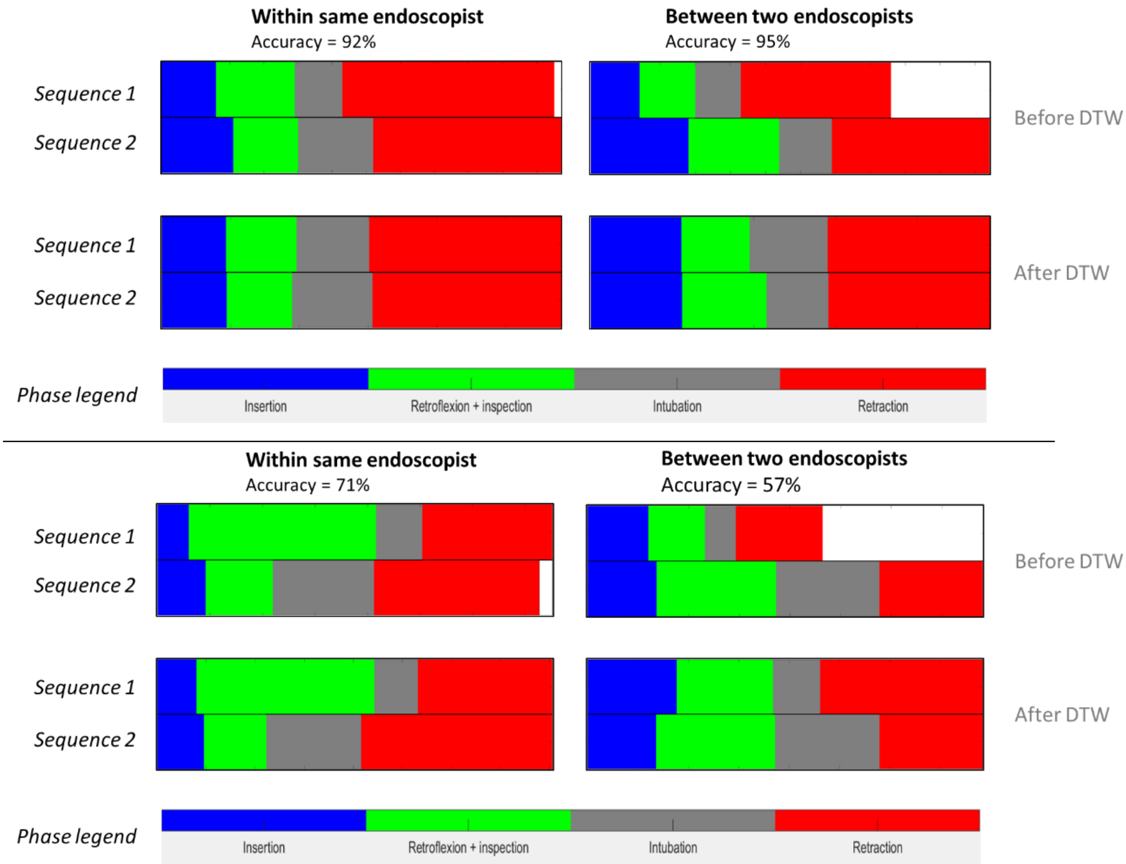


Figure 2.5: The most (upper) and least (lower) accurate DTW synchronization results within and between endoscopists showing the annotated phases represented in different colours.

The colour-bar-representation of the phases before and after DTW synchronization shows the effectiveness of the algorithm. Especially when comparing different endoscopists, the synchronization has a high impact.

Figure 2.6 gives a boxplot overview of the similarity metric outcomes when DTW synchronization is performed with endoscope position data, the optimal configuration. Each sequence from dataset 1 is selected as source sequence and compared to all the other sequences from the whole dataset. Hereafter, each other sequence is selected as the source sequence and synchronized with DTW to all the other sequences. All metrics outcomes of the individual comparisons can be examined in the boxplot.

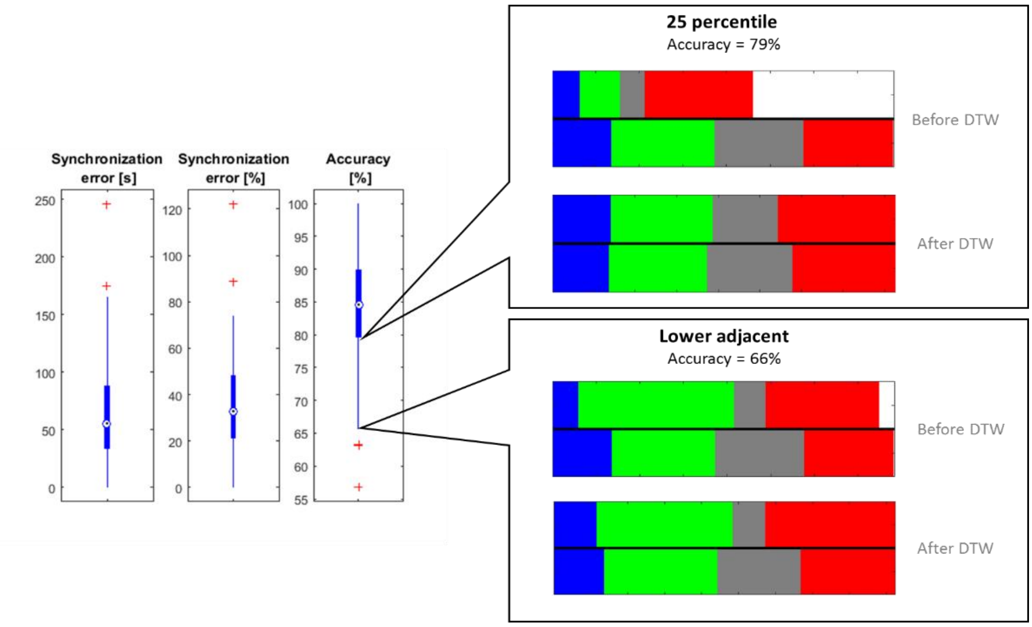


Figure 2.6: Left: boxplot results of similarity metrics averages after DTW synchronization endoscope position input data. Right: synchronization results of the boundaries of the interquartile ranges.

The boxplot in figure 2.6, shows that the least accurate synchronizations in figure 2.5 were outliers. In order to evaluate what amount of sequences can be accurately synchronized, the boundaries of the interquartile ranges are inspected. The synchronization results on the right in figure 2.6 show the least accurate alignment of the lower adjacent and the 25-percentile range. The least accurate synchronization in the 25-percentile range of the accuracy metric is accurately aligned, looking at the phase annotations. Which means that at least 75% of all the sequences in dataset 1 can be accurately synchronized with dynamic time warping, using the endoscopic position as input.

Discussion

Using scope position data as the optimal configuration seems logical, since the position of the scope is more directed and fixed with the endoscopic procedure and therefore more similar between all recordings. In order to follow the workflow of a standard gastroscopy and succeed, the position of the scope has limited options. Yet, for the body movements of the endoscopist this is not the case. Multiple movements might result in the same scope position and are therefore less suitable as input data for the DTW algorithm. This means that the scope position data is most applicable for computing the warping path, after which the whole sequence, including orientation data and endoscope information, can be warped.

The high impact of the DTW synchronization is especially seen when aligning sequences of different endoscopists. Focusing on the dynamic properties of these sequences and making a comparison independent of both timelines, it was possible to align both time series. Realizing the different backgrounds of the recorded endoscopists this is an essential step in the data analysis of this thesis.

Conclusion

Judged by the defined similarity metrics, dynamic time warping performed with endoscopic position parameters, showed to be a valuable technique to synchronize time series based upon intrinsic similarity. DTW proved to be able to synchronize the majority of the sequences in agreement with the annotated phases.

Chapter 3: Reference and average sequence

Research question	**Goal**
What approach can be used to determine the optimal endoscopic movements of multiple expert endoscopists for comparison and evaluation?	To propose and perform different methods for the calculation of the optimal movements during an endoscopic procedure.

Introduction

Synchronization between two recordings proves to be successful, though, for the serious game the optimal expert procedure that describes the different phases of an endoscopic procedure is researched. Therefore, in this chapter, the methodology for computing an average or reference endoscopic procedure or phase is proposed. The outcome will provide a motion data set that can be used for comparison and evaluation during training and assessment.
The optimal endoscopic procedure or phase can be derived as a real average and therefore consists of virtual data, no expert performed the movements. Another option is to determine a reference sequence from the expert recordings, based on the similarity metrics. Depending on the amount of variance between experts, an average sequence might lose its reality and become less intuitive. An average of the recordings of the same endoscopists could however filter small differences between the recordings. A reference endoscopist has the benefit of real recorded data, including optical data, but might favour a specific expert or specific tricks.

The DTW algorithm is a well-known time series analysis that aligns two time series based on similarity, independent of time. Several attempts have been made to configure an averaging method for DTW, that handles multiple time series, yet they provide an inaccurate notion of average [40]. For this study, an averaging algorithm based on the work of *Wang and Gasser* and *Padoy et al.* is used [37], [42]. They propose a method where an average is created when all sequences are aligned using the DTW algorithm, in order to generate an average timeline, while the average length of the original sequences and the phases is maintained.

Methods

Dataset 1 is used for the analysis described in the next section, since it consists of reliable endoscopic motion data. According to the results of chapter 2, endoscopic motion data is most accurate for analyses using the DTW algorithm.

Reference

Figure 3.1 shows the schematic overview of the system built to find a reference sequence. A sequence is here defined as a time series of recorded position data of one whole EGD procedure. One endoscopist has multiple sequences recorded. A first source sequence is selected and synchronized with all other sequences, hereafter all sequences serve as source input for the DTW algorithm. With the computed similarity metrics the sequence with the smallest error and therefore shares the highest similarity with all other sequences is determined as reference.

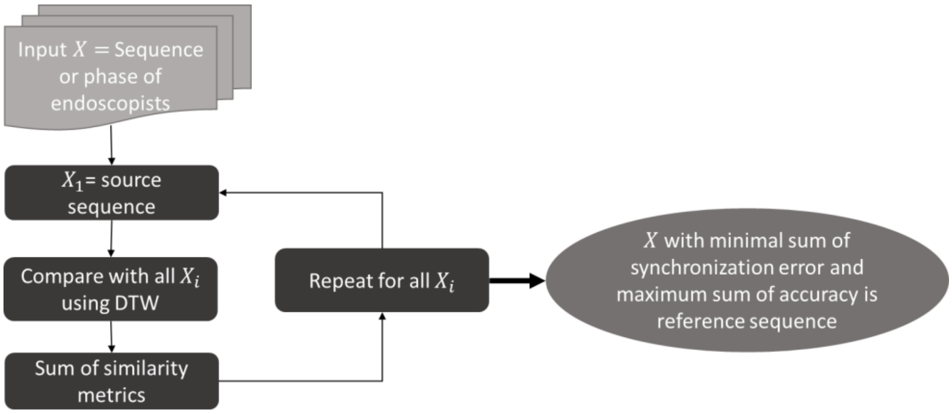


Figure 3.1: Schematic overview of the algorithm created to determine a reference sequence.

Average

Opposed to a standard average computation, where a cross sectional computation is performed, a structural analysis is suggested in this thesis. Which means that for each input sequence, individual structural points are identified. These points are features, common in all or most input sequences. Subsequently, shift functions are constructed so that the individual features are shifted to the average timeline. In between the feature points, linear interpolation is used. This way a structural average, S_0, is constructed by averaging synchronized sequences:

$$S_0 = \frac{1}{n}\sum_{i=1}^{n} S_i(\hat{u}_i)$$

In this formula, S_i is one of the input sequences, shifted by its shift function $\hat{u}_i$. Which is done for all $i = 1, \dots, m$ endoscopists.

The average algorithm, based on the described principle of a structural average, follows similar steps as proposed by *Padoy et al.*:

1. Pairwise average computation.
2. Compute first final average.
3. Iterate average sequence computation using previous original sequences as reference.

A schematic overview of this general process is given in figure 3.2.

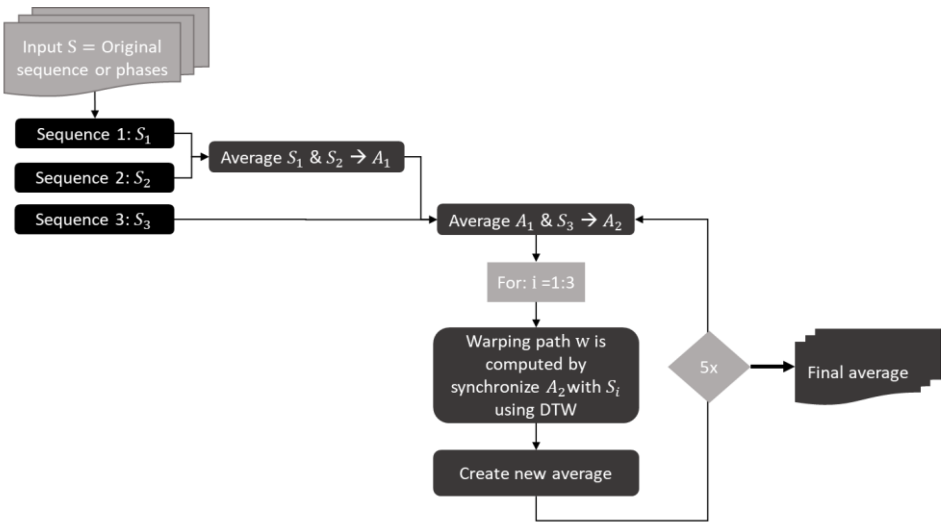


Figure 3.2: schematic overview of the averaging algorithm

As shown in figure 3.2, the first step is to create average sequences of all sequences in a pairwise manner, using the Euclidean distance. From these average sequences, again new average sequences are created in a pairwise manner. This process iterates until the first final average is computed. To make this average more robust, the last step consists of iterating five times and comparing the first final average to all original sequences again, using DTW to create the optimal warping path. This result gives discrete correspondences between the timelines of the average and the other sequences, based on their common features. With these correspondences, using linear interpolation, a final average timeline can be created.

Average sequence phase annotation

Logically an average sequence is not annotated with key time stamps, since the sequence is not actually recorded. However, these phases can be annotated afterwards, by again comparing the average to all original sequences using DTW. This will result in original sequences with phase annotations, warped to the average timeline. For each point on the average timeline, a majority vote calculation can determine which phase it belongs to, as described in table 3.1.

Table 3.1: Phase annotation algorithm for the created average sequences.

Algorithm Annotate average sequences

Input: A_n = average measurements & O_m = original sequences

1) **For** $i = 1:n$

    2) **For** $j = 1:m$
    [warpingpath(A_i), warpingpath(O_j)]=dtw(A_i, O_j)
    WarpedPhases(j)= O_j (warpingpath(O_j) , PhaseAnnotation)

    3) **For** length WarpedPhases
    Phase(i) = Majority of votes (WarpedPhases)

With the annotated phases, the average sequences can be used for further analysis, such as with the computation of the reference sequence with similarity metrics.

Workflow

Multiple ways of creating an optimal procedure are proposed with the *average* and *reference* method. Figure 3.3 gives an overview of the different implementations.

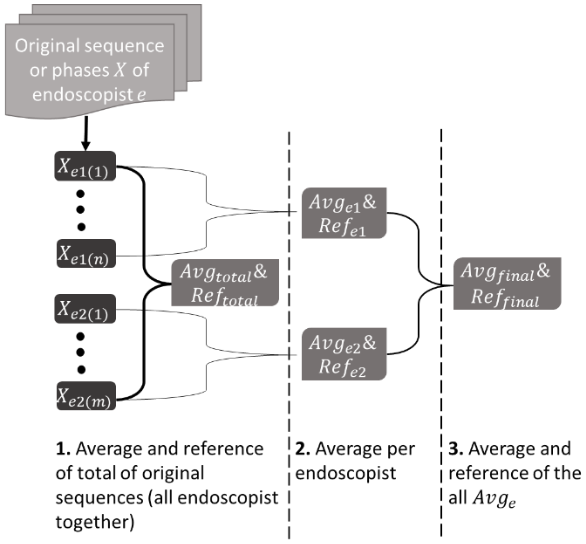


Figure 3.3: Schematic overview of implementations for computing a standard expert sequence

First, an average sequence is derived from all original sequences together. Secondly, an average and reference can be computed per endoscopist, to remove the bias when the amount of sequences per expert in unequal. Finally, a final reference and average sequence is computed.

Results

In figure 3.4, the visualization of the computed reference (Ref_{total}) and average (Avg_{total}) of the endoscope position, is shown. The 3D path shown is the positon of the tip of the endoscope during insertion into the stomach.

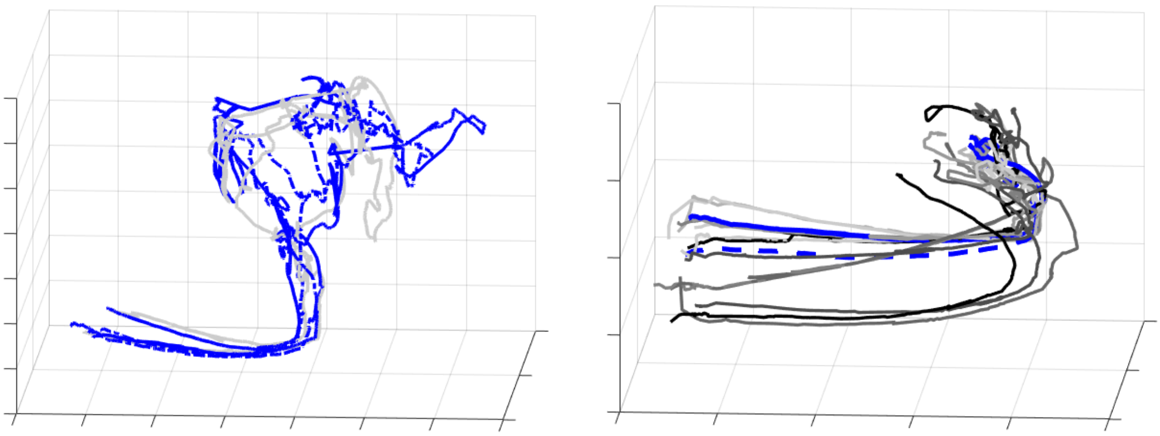


Figure 3.4: Computed average (Avg_{total} in blue interrupted line) and reference (Ref_{total} in blue continuous line) of 3D scope position during the whole procedure (left) and only during the insertion phase (right). In different shades of grey 1 or more of the original scope positions are visualized.

This result is after averaging or computing the reference directly from the original sequences. The resulting average and reference are similar. Hereafter, only the graphs of the first phase, insertion into the stomach, will be shown since this graphs is easy to interpret. The average of the endoscopist position are visualized in appendix section 2.

Next, the average (Avg_e) and reference (Ref_e) sequences per endoscopist are computed. This way the bias caused by endoscopists with more sequences, compared to the others, is neutralized (figure 3.5). Subsequently, a final reference (Ref_{final}) and average (Avg_{final}) sequence can be determined (figure 3.6).

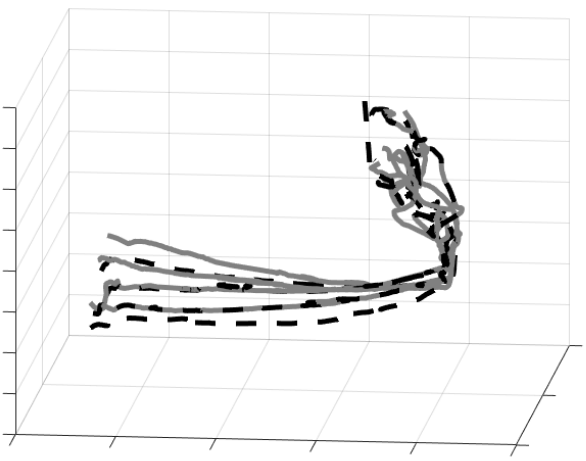


Figure 3.5: Average and reference results of endoscope tip position during the insertion phase. Continuous lines: reference sequences per endoscopist. Interrupted lines: average sequences per endoscopist.

In figure 3.5, one of the average sequences overlays one of the reference sequences. This is possible since from one of the endoscopists in dataset 1, only one recording was successful in the end. Therefore, the original sequence is kept as reference and average.

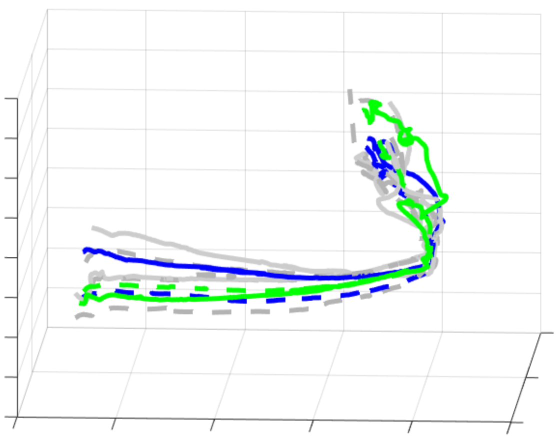


Figure 3.6: Average and reference results of endoscope tip position during the insertion phase. Blue line: Ref_{total}. Blue dotted line: Avg_{total}. Green line: Ref_{final}. Green dotted line: Avg_{final}. In different shades of grey the other reference and average sequences per endoscopist.

On figure 3.5 and 3.6, it can be seen that after using an averaging method, the difference between sequences becomes smaller, while the general shape is maintained. There is not much difference between an average or reference derived from the original sequences, compared to an average or reference from the initial average of references.

Discussion

One can argue whether it is better to look for a reference or an average movement. An average movement will consist out of newly derived data because the algorithm generates an average surgery on an average timeline, thus no endoscopist or endoscope will have made those exact movements. A reference movement, on the other hand, is a movement performed by one of the endoscopists, with the highest similarity to the other sequences. If the expressed motions by endoscopists resemble each other significantly, an average sequence might turn out to be a good representation. If comparing sequences with deviant motion patterns or unique tricks, a reference motion might be in favour, since an average sequence in this case becomes less intuitive. Another drawback of the computed average sequences is that these sequences naturally do not contain annotated phases or information about the insertion point. The latter is the moment and location where the endoscope enters the body. This information is needed in order to calculate the translation and rotation of the scope into the body, which is used for analysis in chapter five. It is possible to annotate the sequence using DTW synchronization, it might be possible to be verify this by replaying the motion data.

One may agree that the process of computing an average and subsequently derive the phase's time stamps, in order to compute a reference sequence again, is a detour to calculate an average motion. A simple computational process might keep the result closer to the original recordings. Above this, the results show little difference between an average or reference derived from the original sequences, compared to an average or reference from the initial averages or references. Although, here the endoscopic position data is analysed, where sequences highly resemble each other. For more deviant data, like the endoscopist's motion data, the initial averages per endoscopist might be needed, before computing the final average. Next to this, one average per endoscopist, makes sure all endoscopists have an equal influence on the final average.

As can be seen in the left graph of figure 3.4, the middle part of the endoscopic procedure has a chaotic trajectory. The same holds for some body segments trajectories. Creating an average sequence from these chaotic trajectories proves to be less realistic. Next to this, replaying the average sequences revealed an issue considering the physical reality of the data. The representation of the data should be adjusted, to take into account the physical constrains of the body as well as the endoscope when estimating the average motion.

Conclusion

The results of the different methods to determine the optimal endoscopic motion trajectory show that an average or reference computation delivers promising results. The 3D graphical visualizations show that the average and reference sequence could represent the original expert data and provide a dataset to compare student's performance with.

Chapter 4: Motion parameters

Research question	Goal
What results shows the computed optimal procedure (average and reference), when evaluated based on motion efficiency?	To evaluate the results of chapter 3 based on three defined motion parameters.

Introduction

The composed average and reference sequences in in the previous chapter are based on their similarity with the other sequences. It would be interesting to evaluate how these sequences behave looking at the efficiency of motion. As discussed in the introduction, multiple output performance measures, to assess endoscopic skills, exist, for example procedure time, path length and smoothness of motion. Despite this, these measures have no 'gold standard' known for flexible endoscopy competency. Moreover, one performance measure alone does not adequately measure proficiency [43]. For laparoscopy, procedure time, path length of the instrument and motion smoothness were positively correlated and showed significant differences between beginner and experts [44]. In this chapter, the computed reference and average sequences, as well as the original recordings, will be analysed for these three measures.

Methods

Firstly, dataset 1 is used for analysis, since the results of the previous chapter will be evaluated. Secondly, dataset 2 will be examined to study a bigger data sample and additionally dataset 2 will be investigated for differences between beginners and expert endoscopists.

Motion parameters

It would be most efficient to perform the procedure with the shortest path length within an acceptable time period. Procedure time is defined as the duration of a procedure in seconds, starting with the first phase (insertion) until the end of the last phase (retraction). Path length P, of the endoscope tip in 3D space, is defined as:

$$P = \sqrt{\left|\frac{dx}{dt}\right|^2 + \left|\frac{dy}{dt}\right|^2 + \left|\frac{dz}{dt}\right|^2}$$

Smooth motion is expected to express motion efficiency as well. This parameter also depends on the precision and the accuracy of the measurement. Motion smoothness can be defined as the change in acceleration [44]. The change in acceleration for a position in 3D space is calculated as follows:

$$Smoothness = \sqrt{\left(\frac{d^3x}{dt^3}\right)^2 + \left(\frac{d^3y}{dt^3}\right)^2 + \left(\frac{d^3z}{dt^3}\right)^2}$$

A smoothness rate is calculated by putting the endoscopist with the smoothest moved body segments, or smoothest moved endoscope at a 100%.

To compute the smoothness of motion of the upper body of the endoscopist, a normalization is applied on the original data, to correct for differences in body dimensions. This is done by computing the mean and standard deviation for all subjects. Subsequently, all values are subtracted by the mean and divided by the standard deviation.

Results

Procedure time, path length and smoothness of motion serve as parameters to analyse efficiency of motion. The *time* and *path* parameter are displayed as a total, as well as the difference with the mean value, to demonstrate the variation. Table 4.1 presents the efficiency of motion metrics for the average and reference sequences, composed in chapter 3.

Table 4.1 Motion parameters results of the average and reference sequences (endoscope position, phase 1)

		Time [s]		Path endoscope tip [cm]		Smoothness rate endoscope[%]
Type		T	$T-\bar{T}$	P	$P-\bar{P}$	
Average	endoscopist 1	30,0	4,9	73,2	1,1	77%
	endoscopist 2	17,8	-7,3	56,1	-15,9	54%
	endoscopist 3	34,1	9,0	97,7	25,7	94%
	endoscopist 4	29,6	4,5	99,0	27,0	8%
	all endoscopists	27,9	2,8	75,1	3,0	64%
	all sequences	24,4	-0,7	62,6	-9,4	100%
Reference	endoscopist 1	30,0	4,9	73,2	1,1	77%
	endoscopist 2	21,1	-4,0	53,7	-18,4	98%
	endoscopist 3	29,1	4,0	95,9	23,9	100%
	endoscopist 4	16,0	-9,1	55,3	-16,7	94%
	all endoscopists	30,0	4,9	73,2	1,1	97%
	all sequences	30,0	4,9	73,2	1,1	77%
Original	endoscopist 1	30,0	5,2	73,2	5,8	77%
	endoscopist 2	15,0	-9,9	56,6	-10,7	94%
		20,0	-4,8	56,1	-11,2	0%
		16,1	-8,8	50,6	-16,7	97%
		21,1	-3,8	53,7	-13,7	98%
		14,0	-10,8	52,1	-15,2	94%
		23,0	-1,9	45,1	-22,3	95%
		15,0	-9,8	51,8	-15,5	100%
		14,9	-9,9	51,1	-16,3	100%
	endoscopist 3	34,1	9,2	70,1	2,8	99%
		45,9	21,1	57,6	-9,7	94%
		29,1	4,3	95,9	28,6	100%
		28,0	3,2	64,3	-3,1	85%
	endoscopist 4	43,0	18,2	118,8	51,5	86%
		16,0	-8,9	55,3	-12,0	94%

The results, in table 4.1, show that the average and reference sequences give similar results as the original sequences, when looking at the motion parameters. A better overview is given with the boxplots in figure 4.1.

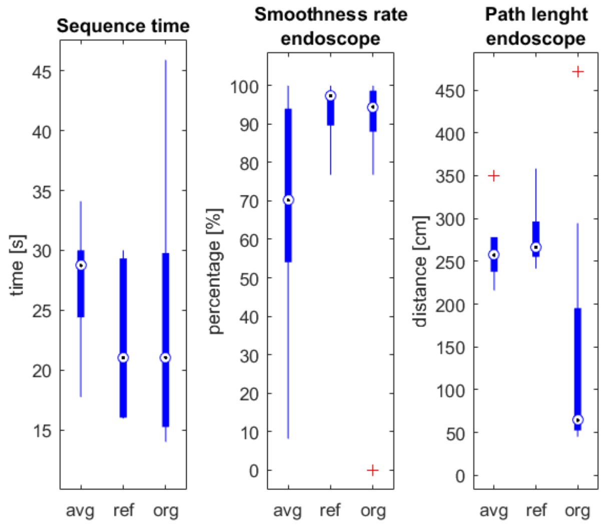


Figure 4.1: Boxplots of the motion parameters for the average, reference and original sequences

Figure 4.1 shows that considering sequence time, the reference sequences represent a part of the original sequences. The average sequences indeed average the total time range of the original sequences. For the smoothness rate and path length, it is clear to see how outliers might influence the range of the reference or average sequences.

The motion parameters are also computed for the whole procedure of all original sequences from dataset 2 (table 4.2). Here, the motion smoothness of the upper body was also analysed. Both the beginner and expert endoscopists' reference sequences, calculated from the original sequences in the previous chapter, are marked.

Table 4.2: Parameters for all sequences

Recording	Level	Time [s]		Path tip [cm]		Smoothness rate upper body [%]	Smoothness rate endoscope [%]
		T	$T-\bar{T}$	P	$P-\bar{P}$		
1	beginner	117,0	-23,3	278,2	-5,1	93%	38%
2	expert	188,0	47,7	350,4	67,0	63%	71%
3	expert	114,0	-26,3	256,9	-26,4	43%	0%
4	expert	116,0	-24,3	257,5	-25,9	73%	85%
5	expert	118,0	-22,3	237,8	-45,6	0%	76%
6	expert	87,1	-53,2	216,0	-67,3	59%	38%
7	expert	182,0	41,7	259,7	-23,7	89%	0%
8	expert	128,9	-11,4	241,5	-41,8	67%	100%
9	expert	181,0	40,7	275,9	-7,5	11%	73%
10	beginner	196,0	55,7	358,2	74,9	79%	83%
11	beginner	178,1	37,8	266,5	-16,9	88%	77%
12	beginner	123,0	-17,3	265,5	-17,8	77%	54%
13	beginner	115,0	-25,3	220,7	-62,6	70%	82%
14	beginner	185,0	44,7	471,1	187,7	37%	63%
15	beginner	95,1	-45,2	294,4	11,1	14%	85%
16	expert	223,0	82,7			93%	38%
17	expert	161,0	20,7			83%	
18	expert	109,0	-31,3			68%	
19	expert	96,0	-44,3			88%	
20	expert	228,0	87,7			86%	
21	expert	118,0	-22,3			69%	
22	expert	186,5	46,2			88%	
23	expert	113,0	-27,3			77%	
24	expert	101,0	-39,3			95%	
25	expert	95,0	-45,3			54%	
26	expert	93,0	-47,3			68%	

Both marked reference endoscopists are relatively fast and their scope paths are relatively short.
An extra result can be derived by comparing the efficiency of motion metrics for the beginner and expert endoscopists.

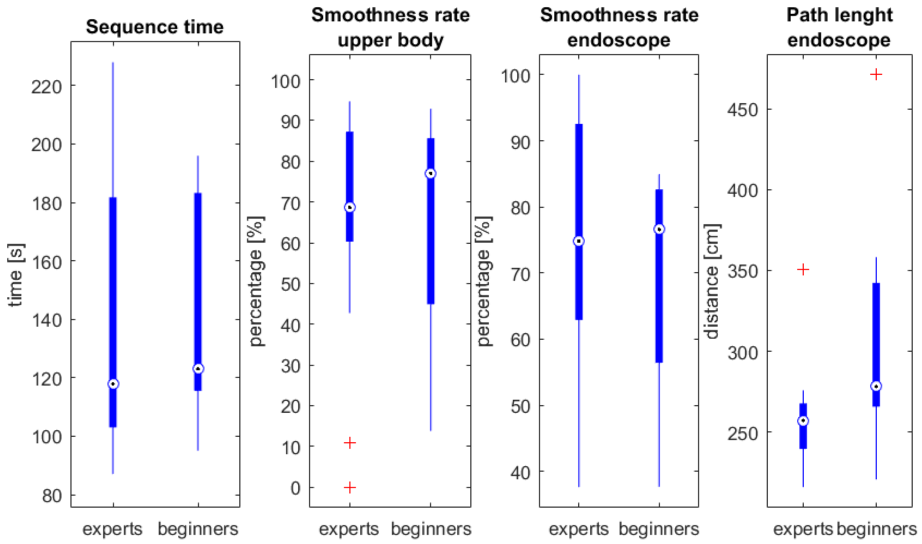


Figure 4.2: Boxplot results of sequence time, smoothness rate and endoscopy path length; experts compared with beginners.

Figure 4.2 shows the differences in the proposed efficiency of motion parameters between experts and beginners. Most obvious is the difference in path length between experts and beginners. Experts manage to complete the endoscopic procedure with a more optimal path. Due to the small sample of beginner sequences and high variance between observations, only the difference in path length is significant for $p < 0.05$.

Discussion

The outlier results from the motion parameters can have a high influence on the average or reference sequence. In the dataset used for analysis in this work, this might be caused by the variance in endoscopists, when considering their level and training background. It shows that it might be important to put thought in which expert is recorded for which procedure, in order to get the best average or reference procedure.

The comparisons between beginner and expert endoscopists, considering the efficiency metrics, were secondary findings. The performed experiments were executed with the goal of acquiring an expert dataset, but after all, while validating the technical set up, beginner endoscopists were recorded and therefore these secondary results seemed interesting. It has to be noted that the sample size of the beginner sequences is rather small. In combination with the high variance, the found differences show little significance. Nonetheless, these comparisons are interesting for a later stage of the Everest project, when the level of motion input will be evaluated. Feedback can be based on these criteria.

Conclusion

The average and reference sequences computed in the previous chapter represent the original sequences, when looking at the motion parameter sequences time, path length and motion smoothness. Additional results show that, with these datasets, only a significant difference in path length is detected when comparing experts and beginners.

Chapter 5: Analysis of movement elements

Research question	Goal
Can the different manoeuvres, that influence the endoscope manipulation, be described and analysed individually?	To describe and analyse the different manoeuvres that influence endoscope manipulation, by evaluating their change over time.

Introduction

As explained in the first chapter, the resulting movement or position of the endoscope is the outcome of mainly three different elements manipulating the endoscope; the wheel rotation, torque and translation of the scope and movement of the upper body segments. The final goal of this study is to characterize the identified key movements for flexible endoscopy, based on these three elements for psychomotor skill training and assessment. This results in a formula for a certain endoscopic manoeuvre:

$$Wheel\ rotation + Scope\ torque\ \&\ Translation + Upper\ body\ movement = Endoscope\ position$$

The experiments were annotated with key time points, which were used to create four clinical phases of the endoscopic procedure. Duodenal intubation of the pylorus is considered to be most relevant for motion analysis, since it is the most challenging phase of the procedure and requires specific movements and positions. In the method section of this chapter, the variance in movement is calculated per phase. A high variance might indicate there is no straightforward way to manoeuvre the scope, which indicates that the phase is more interesting for analysis.

Methods

For this chapter, a single expert's sequence is selected for analysis. In order to perform the element-wise analysis, as defined in the introduction of this chapter, a real recorded sequence is needed. Only then will the information of all the elements be available. As example, to present the elementary analysis, the expert reference sequence, determined in chapter 3, is selected.

Phase variation

The variance in 3D position between endoscopists and endoscopes for each clinical phase is calculated. First normalization is applied to the position data of the endoscopists, in order to correct for the difference in body dimensions. This is done by computing the mean and standard deviation for all subjects. Subsequently, all position time series values are subtracted by the mean and divided by the standard deviation. For the endoscope, no normalization is applied, since the same endoscope is used for all experiments.

The standard deviation between the mean position of each segment and sensor, is computed per phase. The standard deviation is summed for all recordings to find the overall variance in 3D position per phase.

Wheel angles

The designed colour bands, for wheel angle detection, are fixed on the endoscope wheels in a known and standard manner. Due to this, a standard configuration is pre-computed that correlates each detected colour pattern with a wheel's angle. The wheel computation process is demonstrated in figure 5.1. Each colour pattern is unique and correlates with a specific wheel angle.

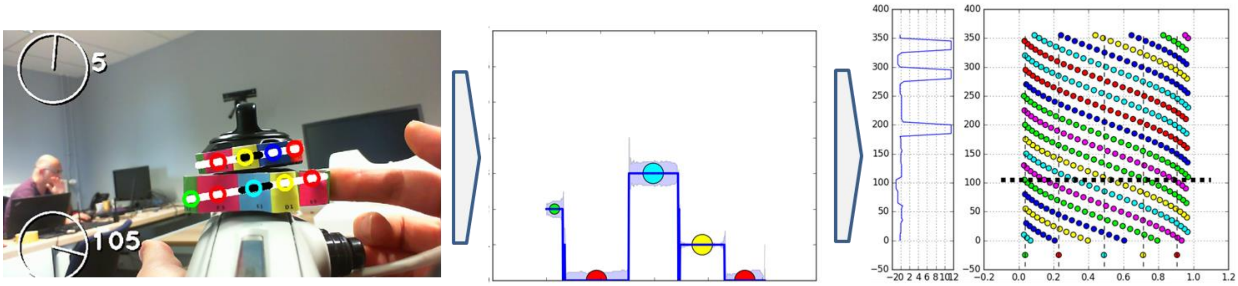


Figure 5.1: Colour band encoding for angle detection of the endoscope wheel.

The scan lines on the most left image of figure 5.1, where the colours are detected, are set manually. The lines are assumed to be set once per experiment, since the camera position on the scope is fixed. In the middle image, the hue values of the colours are plotted, in respect to the location on the scan line (in the case of figure 6.1 the hue values of the bottom scan line is shown). Finally, the detected colour pattern is compared to the pre-computed table of all configurations that corresponds to a unique wheel angle. The pre-computed table is set with steps of five degrees. The step size determines the maximum accuracy of the algorithm.

In clinical practise, an endoscopist wears gloves for hygiene reasons. At IHU Strasbourg, the colour of the worn gloves is blue. The hand of the endoscopist is used to rotate the scope's wheel and might therefore occlude the colour band and interfere with the colour detection. Because of this, the colours on the band are selected while taking into account the colour of the gloves as the exclusion colour. The algorithm is developed to detect the glove with the following constraints; of the colour of the glove, the uniformity of the colour and the knowledge that the hand of the endoscopist enters the scope of the camera from outside. This way the algorithm keeps track of which colour to exclude, as demonstrated in figure 5.2.

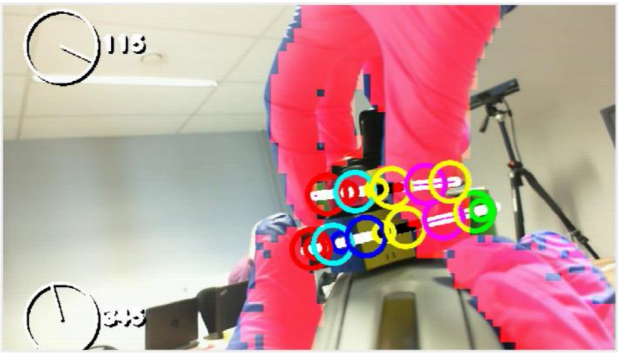


Figure 5.2: Glove colour exclusion

Scope torque and translation

At the point where the endoscope inserts the body, there are two movement options; torque (rotation of the scope) and translation (back and forth into the body). Scope torque and translation is tracked, in case of reliable recorded scope data, with the Aurora tracking system. Taking the point of insertion as beginning, the start of the oesophagus, the amount of scope length inserted into the body is computed. The rotation of the scope, at the insertion point, is derived from the sensor in the tip of the scope. Only this sensor detects information from all six degrees of freedom (DOF), the other sensors in the rest of the scope detect five DOF, which exclude the scope rotation over its longitudinal axis. To solve this, taking into account the shape of the scope, the torque rotation at the insertion point is derived from the six DOF tip sensor. After obtaining 5 DOF information from each sensor in the endoscope, the shape of the endoscope is parameterized with a cubic Bezier curve [45]. This parameterization is done with the following known parameters; the distance between adjacent sensors, the 3D position and tangent of each sensor. As demonstrated in figure 5.3, the rotation at the insertion point can then be calculated as follows; 6 DOF position and orientation is known in the global frame e_1, e_2, e_3. At a certain different location on the scope, local frame d_1, d_2, d_3, the torque rotation r can be derived. This is calculated by the transformation matrix between the cross section of both frames, derived using the Bezier parameterization.

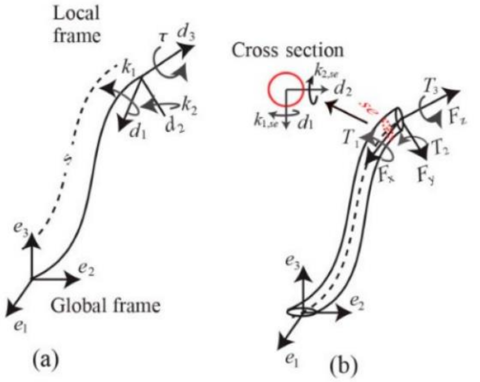


Figure 5.3: Schematic overview of torque derivation between different frames

Upper body motion

Lastly the endoscopists use their upper body to manipulate the scope's position. The segments with the highest displacement are found by calculating the standard deviation of the position, this is done for each segment and the plane in which direction it moved. An expression rate is calculated by ranging between the most expressed and least expressed segment. For the analysis, only the top 25% of most expressed body segments in a certain directional plane is considered. An expression rate is calculated to represent the amount of movement made by the top 25% segments which is done by setting the most moved segment to a 100%.

Results

Phase variation

The variation in 3D position of the endoscopist's upper body and endoscope is calculated and shown in table 5.1

Table 5.1: Mean of variation between all endoscopist and endoscope positions

	Variation (standard deviation) [cm]	
Phase	Endoscopist	Endoscope
1: insertion	43,1	19,7
2: retroflexion & inspection	43,1	21,2
3: duodenal intubation	42,9	25,2
4: retraction	43,1	19,0

The table of position's variance shows that there is little to no variation in the endoscopist’s position when comparing between the different phases. On the contrary, the endoscope's position clearly shows more variation in phase two and three, with emphasis on phase three called "duodenal intubation". This makes the phase most interesting for the element-wise analysis:

$$Wheel\ rotation + Scope\ torque\ \&\ Translation + Upper\ body\ movement = Endoscope\ position$$

The rest of this result section, will therefore present the results of the duodenal intubation phase.

Wheel rotation

The big and small wheel angels are defined from 0 to 360 degrees. In this range, 0 degrees is the neutral position of the wheels for a straight endoscope. In figure 5.4, the results of the wheel rotations, during the duodenal intubation phase, are visualized.

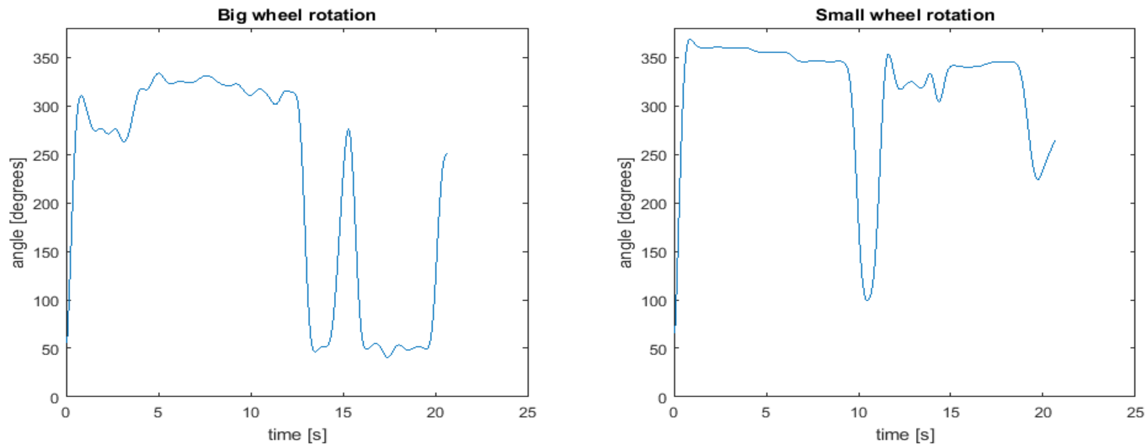


Figure 5.4: Big and small wheel angels during the duodenal intubation phase

The big wheel is turned from its maximum, to an almost neutral position, with a quick change around 15 seconds. The high rotation could be explained by the fact that the pylorus, in the pig stomach, is often visualized in retroflexion. After visualization the scope turns back to a more neutral position, approaching the pylorus for intubation. The small wheel mainly remains in the same angle.

Scope torque and translation

At the insertion point, the point where the endoscope enters the body, there are two movement options; rotation of the scope and translation in or out of the body. The derived torque information at the insertion point of the scope ranges from -180 to 180 degrees. In figure 5.5, torque and translation of the scope are visualized over time, during the duodenal intubation phase.

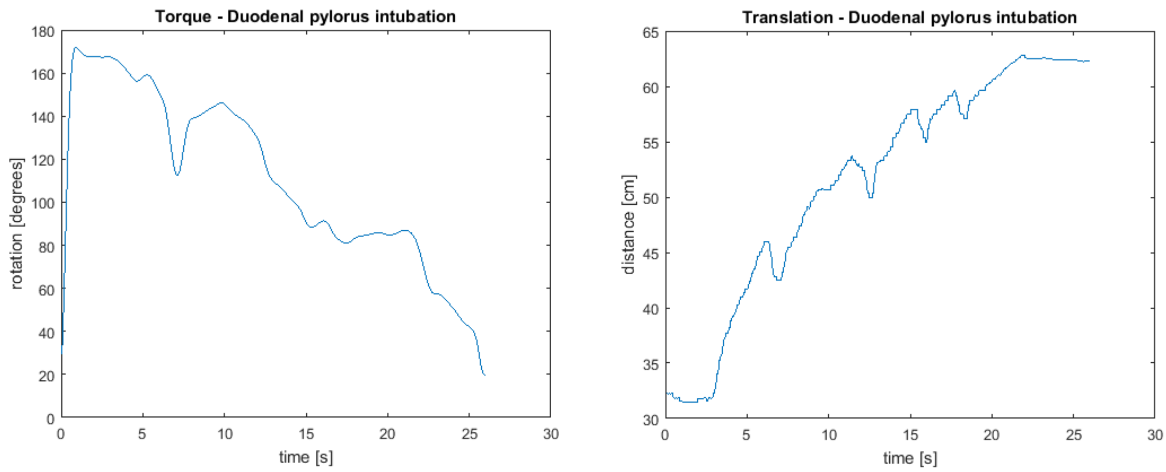


Figure 5.5: Scope torque and translation at the insertion point during the duodenal intubation phase of the reference sequence.

The visualized course of degrees in torque starts with a steep rise, after which the torque gradually decreases, with the exception of one trough around seven seconds. An increase or decrease of torque during the intubation phase is seen in nine out of 12 sequences. The insertion of the scope into the body increases over the whole time period of the intubation phase. Short retraction periods are seen as a consequence of the right hand letting go of the scope, in order to grasp it again more distally from the mouth. This is seen in all sequences.

The graphs in figure 5.5 can be used to compare performance of a novice with the reference expert. Using DTW synchronization on the two sequences can show the similarity between the novice's and expert's movement. Figure 5.6 shows the expert (blue) and novice (red) torque motion, for comparison, some of the DTW synchronization lines are drawn.

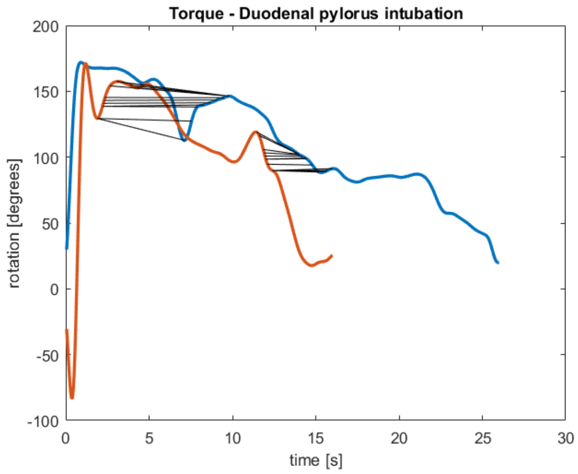


Figure 5.6: Torque motion of reference expert (blue) and novice (red) with DTW synchronization lines.

This figure illustrates that a time independent comparison of motion data, for example scope torque, could help with assessing performance psychomotor skills. Which in its case could be used for feedback given to the novice.

Studying the torque and translation information from all the sequences from dataset 1, a difference between experts and beginners was detected. An example in shown in figure 5.6.

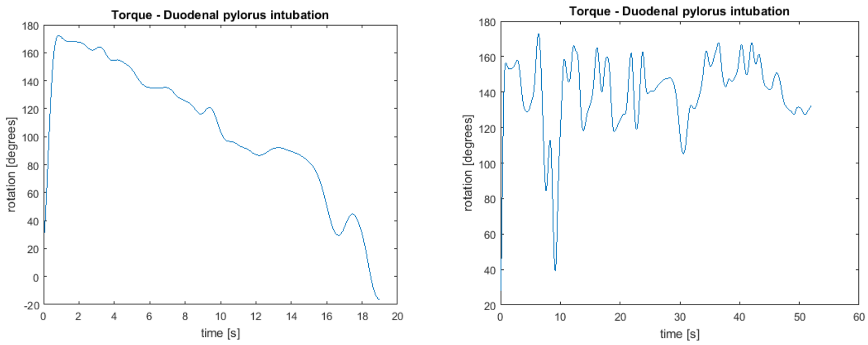


Figure 5.7: Difference in motion smoothness for torque between an expert (left) and beginner (right) endoscopist.

Figure 5.7 shows that an expert endoscopist tends to rotate the scope in a smooth fashion. On the contrary, the graph of the beginner endoscopist shows quick changes in torque. All torque graphs can be looked up in appendix section 3.

Upper body motion

In table 5.2, the result of the most expressed body segments from all segments, of the reference expert, during the intubation phase and their expression rates are showed. The expression rate is presented for each plane in which the body segment moved. Subsequently the total for each segment is added.

Table 5.2: Body segment expression

Body segment	Plane	Expression rate per plane	Expression rate per body segment
Right Upper Arm	X	27%	27%
Right Forearm	X	60%	187%
	Y	83%	
	Z	44%	
Right Hand	X	64%	218%
	Y	100%	
	Z	55%	
Left Upper Arm	X	16%	16%
Left Forearm	X	25%	25%
Left Hand	Y	22%	49%
	Z	27%	

The most moved segments are both arms and hands, most of all the right forearm and hand. Both are moved in all three degrees of freedom.

Discussion

In this chapter, an elementary characterization of the components influencing the scope position and movement is proposed. These are just the elements controllable by the endoscopist, since factors like the anatomical environment also influence scope manipulation. Despite this, this study is focused on the elements that are trainable, since the next goal of the project is to train psychomotor skills.

The highest variation of the endoscope's position is seen during phase 2 (retroflexion and inspection) and 3 (duodenal intubation) of an EGD procedure, with emphasis on phase 3. These are the phases where multiple manners of scope manoeuvring are possible. This might indicate the difficulty of the phase and shows the need for clear instructions.

The calculation of the derived torque rotation at the insertion point is dependent on the shape of the curve, fitted with a cubic Bezier curve. In case certain sensors, between the tip and insertion point, are not detected (during short instances), the shape estimation is not accurate. As a consequence, the torque rotation will be less accurate and its course over time shows incorrect quick changes. Another consequence of the torque rotation is its relativeness. For each experiment, the Aurora probe is inserted in the instrument channel of the endoscope, and therefore will have a different position and orientation to start off with. The torque analysis for this study is only performed on data extracted from one experiment session, subsequently comparisons are possible. However, if it is desired, in a later stage of the Everest project, to compare between different experiments, the different offsets need to be taken into account.

An increasing curve, representing the scope translation during the intubation phase, seems logical, since the scope needs to reach the duodenum. A decrease or increase in torque indicates a gradual rotation when combining translation and torque results in a spiral movement towards the pylorus. A spiral path of the endoscope might be one the tricks for the pylorus intubation, identified by the motion analysis of this study.

Figure 5.6 illustrates the possibility of comparing the optimal movement of the expert with the novice, with the DTW synchronization. This could enable the measurement of the novice’s performance based on motion parameters and provide specific feedback to the novice. It would be especially beneficial when if the feedback is given directly, while practising on the simulator. This option requires more research into the possibility of synchronizing the expert's motion data to the captured movements of the students in real time. Preliminary results of online DTW comparison are presented by *Sielhorst et al.* [46].

Although it is proved to be possible to detect the wheel angles, based on a colour-coded configuration, the algorithm encounters problems when a big part of the wheel is occluded. When more than two colours on one scan line are occluded, the detected colour pattern is not unique anymore. This issue is dependent on the position of the endoscopist's hand and cannot be prevented. Manual compensation, by selecting the missing colours, is able to solve this problem. The software can give a signal on which images have too few colours detected. If this is the case, these images can be handled manually.

Conclusion

The endoscopic tracking setup, proved feasible to acquire data and perform measurements that enable the element-wise analysis proposed in this chapter. The element-wise analysis reveals relevant information about the different manoeuvres influencing the scope manipulation. In the future, online DTW synchronization, might enable expert and student comparison and provide direct feedback.

Chapter 6: General conclusion and recommendations

General conclusion

Chapter 1 and 5 have shown that the technical setup, built for recording endoscopic motion data, proves feasible for acquiring a motion library that includes all manoeuvres influencing scope manipulation. Yet, certain limitations, such as the wheel occlusion and high dependence of reliable endoscope data, need to be investigated further, as well as the possibility to record without the need of a fix patient table.

The DTW synchronization and similarity metrics defined in this thesis, not only give the possibility to compare the recorded experts, could additionally serve as a method to compare the captured movements of the student with the expert, online. Subsequently, a student can receive feedback while trying to replicate the movement.

The proposed methods to determine the optimal endoscopic movements; creating an average sequence or determining the reference procedure, prove to be feasible and able to represent the original recorded data. This is confirmed when considering the 3D position and the motion parameters; sequence time, path length and motion smoothness. However, the replay images of the average show that adjustments are needed, in order to take into account the physical constrains of the endoscopist's body as well as the endoscope when creating the average motion.

Additional results have shown that, with the recorded datasets, only a significant difference in path length is detected when comparing experts and beginner endoscopists. The scope torque results, do visually show difference in motion smoothness.

This study paved the way to determine and represent the optimal endoscopic movements for when the Everest project will move to the next phase and record patient data. The acquired motion library can be used to develop a serious game that focuses on the psychomotor skills determined by the proposed methodologies in this thesis. This game could educate and assess novices based on their tracked movements, so that they can gradually learn the individual manoeuvres, before completing their learning curve in a patient setting.

Recommendations

One of the limitations of the technical setup, especially when moving it to a patient setting, is the fixed position of the patient bed, in order to perform registration. The position needs to be fixed, relative to the external Kinect camera system. The setup would be more flexible and practical if either the movement of the table can be tracked, or if data acquisition is done without registration. It is expected that acquisition without registration will not be a problem for the Aurora system that tracks the 3D motion of the endoscope. However, for the Xsens system it might be more complex when using inertial motion capturing technology because the measurement is strongly influenced by drift. This causes problems when sequences need to be compared, unless the drift can be quantified. Another way is to minimize the drift as much as possible [47].

During the experiments, described in the first chapter, the endoscopic procedures were annotated with key time points that translate into different phases. The labelled phases made it possible to set up quantifiable similarity metrics to compare the similarity of 3D motions between sequences. Still, in a setting where students use the endoscopic simulator, the phases are unknown. Therefore, it is interesting to invest in a system that is trained with an annotated dataset. A supervised learning model could be trained to recognize the phases in similar, not annotated, sequences.

The created warping paths, after synchronizing either two sequences or constructing an average sequence, will eventually allow for visualization of two or more recordings over the same timeline. This enables navigation through multiple recordings and enables the ability to replay the phases synchronously, which allows for visual comparison of the similar endoscopic manoeuvres.

Sielhorst et al. describes the possibility to perform online DTW synchronization [46]. This would allow to compare and synchronize the captured 3D movements of the student, in real time, with the pre-defined expert motion. This can provide the student not only with an initial estimate for performance, but possibly also a measure to compare the similarity of motion. However, an online synchronization might not be as reliable as offline, therefore testing and more research is needed.

Each endoscopic procedure exists out of difficult and less difficult tasks. Comparing expert recordings might reveal common parts between experts, which indicate trivial procedure parts. Yet, this might not happen due to different education backgrounds of experts. Another option, is to let an expert label the average sequence and the different elements manipulating the scope, for crucial parts. This way a student can focus their efforts on training the most difficult parts of the endoscopic procedure.

Bibliography

[1] T. McCashland, R. Brand, E. Lyden, and P. de Garmo, “The time and financial impact of training fellows in endoscopy,” *Am. J. Gastroenterol.*, vol. 95, no. 11, pp. 3129–3132, 2000.

[2] K. K. Wang, B. Ott, A. Geller, and J. Densmore, “Endoscopic enducation: What is the cost of training?,” *Gastrointest. Endosc.*, vol. 41, no. 4, p. 1995, 1995.

[3] G. Subhas, A. Gupta, and V. K. Mittal, “Necessity for improvement in endoscopy training during surgical residency,” *Am. J. Surg.*, vol. 199, pp. 331–335, 2010.

[4] L. Soler, S. Nicolau, A. Hostettler, J. Fasquel, and V. Agnus, “VIRTUAL REALITY AND AUGMENTED REALITY APPLIED TO ENDOSCOPIC AND NOTES PROCEDURES,” pp. 362–365, 2009.

[5] A. V Haycock, P. Youd, P. Bassett, and B. P. Saunders, “Simulator training improves practical skills in therapeutic GI endoscopy : results from a randomized , blinded , controlled study,” *Gastrointest. Endosc.*, vol. 70, no. 5, p. 835–845.e2, 2009.

[6] G. Dafnis, A. Ekbom, L. Pahlman, and P. Blomqvist, “Complications of diagnostic and therapeutic colonoscopy within a defined population in Sweden,” *Gastrointest. Endosc.*, vol. 54, no. 3, 2001.

[7] R. E. Sedlack, “Mentoring, Education and Training Corner Towards our Gaols - An overview,” *E-learning*, vol. 73, no. 10, p. 28, 2007.

[8] L. Harpham-lockyer, F. Laskaratos, P. Berlingieri, O. Epstein, L. Harpham-lockyer, and F. Laskaratos, “Role of virtual reality simulation in endoscopy training,” *World J. Gastrointest. Endosc.*, vol. 7, no. 18, pp. 1287–1294, 2015.

[9] W. Qiao, Y. Bai, R. Lv, W. Zhang, Y. Chen, S. Lei, and F. Zhi, “The Effect of Virtual Endoscopy Simulator Training on Novices: A Systematic Review,” *PLOS ONE open access*, vol. 9, no. 2, 2014.

[10] S. R. Dawe, J. A. Windsor, J. A. J. L. Broeders, and P. C. et al. Cregan, “A Systematic Review of Surgical Skills Transfer After Simulation-Based Training,” *Ann. Surg.*, vol. 259, no. 2, 2014.

[11] J. Park, H. MacRae, L. J. Musselman, and P. et al. Rossos, “Randomized controlled trial of virtual reality simulator training : transfer to live patients,” *Am. J. Surg.*, vol. 194, pp. 205–211, 2007.

[12] N. King, A. Kunac, E. Johnsen, G. Gallina, and A. M. Merchant, “Design and validation of a cost-effective physical endoscopic simulator for fundamentals of endoscopic surgery training,” *Surg. Endosc.*, vol. 30, no. 11, pp. 4871–4879, 2016.

[13] A. Haycock, A. D. Koch, P. Familiari, and F. Van Delft, “Training and transfer of colonoscopy skills: a multinational, randomized, blinded, controlled trial of simulator versus bedside training,” *Gastrointest. Endosc.*, vol. 71, no. 2, pp. 298–307, 2010.

[14] E. Boyle, A. Kennedy, O. Traynor, and A. D. K. Hill, “Training Surgical Skills Using Nonsurgical Tasks — Can Nintendo Wii TM Improve Surgical Performance?,” *JSURG*, vol. 68, no. 2, pp. 148–154, 2011.

[15] A. Ali, Y. Subhi, and C. Ringsted, “Gender differences in the acquisition of surgical skills : a systematic review,” *Surg. Endosc.*, pp. 3065–3073, 2015.

[16] T. Susi, M. Johannesson, and P. Backlund, “Serious Games – An Overview,” 2007.

[17] M. Graafland, J. M. Schraagen, and M. P. Schijven, “Systematic review of serious games for medical education and surgical skills training,” *Br. J. Surg.*, vol. 99, no. 10, pp. 1322–1330, 2012.

[18] M. El-Beheiry, G. McCreery, and C. M. Schlachta, “A serious game skills competition increases voluntary usage and proficiency of a virtual reality laparoscopic simulator during first-year surgical residents’ simulation curriculum,” *Surg. Endosc. Other Interv. Tech.*, pp. 1–8, 2016.

[19] F. Attal, S. Mohammed, M. Dedabrishvili, F. Chamroukhi, L. Oukhellou, and Y. Amirat, “Physical Human Activity Recognition Using Wearable Sensors.,” *Sensors (Basel).*, vol. 15, no. 12, pp. 31314–38, 2015.

[20] J. Ansell, J. Mason, N. Warren, P. Donnelly, N. Hawkes, S. Dolwani, P. Donnelly, and N.

Hawkes, “Systematic review of validity testing in colonoscopy simulation,” *Surg. Endosc.*, 2012.
[21] S. H. Arnold, M. B. Svendsen, L. Konge, L. B. Svendsen, L. Preisler, M. B. Section, and S. H. Arnold, “Three-dimensional motion tracking correlates with skill level in upper gastrointestinal endoscopy,” 2015.
[22] M. B. Svendsen, L. Preisler, J. G. Hillingsoe, L. B. Svendsen, L. Konge, M. B. Svendsen, L. Konge, C. C. Educa-, L. Preisler, J. G. Hillingsoe, and L. B. Svendsen, “Using motion capture to assess colonoscopy experience level,” *World J. Gastrointest. Endosc.*, vol. 6, no. 5, pp. 193–199, 2014.
[23] P. B. Cotton and C. B. Williams, *Practical gastrointestinal endoscopy*. 1990.
[24] J. A. Martin, G. Regehr, R. Reznick, H. Macrae, J. Murnaghan, C. Hutchison, and M. Brown, “Objective structured assessment of technical skill (OSATS) for surgical residents,” *Br. J. Surg.*, vol. 84, no. 2, pp. 273–278, 1997.
[25] “Formative DOPS : Diagnostic upper gastrointestinal endoscopy (OGD),” *R. Coll. Physicians*, pp. 1–5, 2016.
[26] Xsens Technologies B.V., “MVN User Manual - User Guide MVN, MVN BIOMECH, MVN Link, MVN Awinda,” 2015.
[27] D. Roetenberg, H. Luinge, and P. Slycke, “Xsens MVN : Full 6DOF Human Motion Tracking Using Miniature Inertial Sensors,” *Tech. Rep.*, pp. 1–7, 2013.
[28] A. M. Franz, W. Birkfellner, K. Cleary, T. M. Peters, and L. Maier-hein, “Electromagnetic Tracking in Medicine – a Review of Technology , Validation and Applications,” *IEEE Trans. Med. Imaging*, vol. 33, no. 8, 2014.
[29] N. Medical, “Aurora Technology.” [Online]. Available: http://www.ndigital.com/medical/products/aurora/#technology. [Accessed: 13-Feb-2017].
[30] A. Darzi, S. Smith, and N. Taffinder, “Assessing Operative Skills,” *BMJ Br. Med. J.*, vol. 318, pp. 887–888, 1999.
[31] M. Lineberry and E. Matthew Ritter, “Psychometric properties of the Fundamentals of Endoscopic Surgery (FES) skills examination,” *Surg. Endosc. Other Interv. Tech.*, pp. 1–9, 2017.
[32] A. D. Koch, S. N. Buzink, J. Heemskerk, S. M. B. I. Botden, R. Veenendaal, J. J. Jakimowicz, and E. J. Schoon, “Expert and construct validity of the Simbionix GI Mentor II endoscopy simulator for colonoscopy,” *Surg. Endosc. Other Interv. Tech.*, vol. 22, no. 1, pp. 158–162, 2008.
[33] W. G. Park, N. J. Shaheen, J. Cohen, I. M. Pike, D. G. Adler, J. M. Inadomi, L. A. Laine, J. G. Lieb, M. K. Rizk, M. S. Sawhney, and S. Wani, “Quality indicators for EGD,” *Gastrointest. Endosc.*, vol. 81, no. 1, pp. 17–30, 2015.
[34] R. H. Herrera and M. van der Baan, “Automated seismic-to-well ties?,” pp. 1–36.
[35] H. Chen, Y. Li, and Z. Wu, “Dynamic time warping distance method for similarity test of multipoint ground motion field,” *Math. Probl. Eng.*, vol. 2010, p. 12, 2010.
[36] G. a Ten Holt, M. J. T. Reinders, and E. a Hendriks, “Multi-Dimensional Dynamic Time Warping for Gesture Recognition,” 2007.
[37] N. Padoy, T. Blum, S. Ahmadi, H. Feussner, M. Berger, and N. Navab, “Statistical modeling and recognition of surgical workflow,” *Med. Image Anal.*, vol. 16, no. 3, pp. 632–641, 2012.
[38] M. Müller, “Dynamic Time Warping,” in *Information Retrieval for Music and Motion*, 2007, p. 318.
[39] L. Rabiner, B. Labs, M. Hill, and B.-H. Juang, *Fundamentals of Speech Recognition*. Englewood Cliffs, New York, 1993.
[40] F. Petitjean, A. Ketterlin, and P. Gançarski, “A global averaging method for dynamic time warping, with applications to clustering,” *Pattern Recognit.*, vol. 44, no. 3, pp. 678–693, 2011.
[41] B. Yao and S. C. Zhu, “Learning deformable action templates from cluttered videos,” Lotus Hill Research Institute, Los Angeles, 2009.
[42] K. Wang and T. Gasser, “Alignment of curves by dynamic time warping,” *Ann. Stat.*, vol. 25, no. 3, pp. 1251–1276, 1997.
[43] C. D. Smith, T. M. Farrell, S. S. McNatt, and R. E. Metreveli, “Assessing laparoscopic

manipulative skills," *Am J Surg*, vol. 181, pp. 547–550, 2001.
[44] M. K. Chmarra, "TrEndo Tracking System: Motion Analysis in Minimally Invasive Surgery," 2009.
[45] X. Li, B. Li, S. Song, C. Hu, and M. Q. Meng, "Endoscopes Shape Reconstruction Based on Electromagnetic Localization and Curve Fitting," *Int. Conf. Robot. Biomimetics*, pp. 819–824, 2012.
[46] T. Sielhorst, T. Blum, and N. Navab, "Synchronizing 3D movements for quantitative comparison and simultaneous visualization of actions," *Proc. - Fourth IEEE ACM Int. Symp. Symp. Mix. Augment. Reality, ISMAR*, pp. 38–47, 2005.
[47] R. G. J. Damgrave and D. Lutters, "The Drift of the Xsens Moven Motion Capturing Suit during Common Movements in a Working Environment," *Proc. 19th CIRP Des. Conf.*, pp. 338–342, 2009.

Appendix

1: BEST innovation course activities

Business Engineering and Surgical Technologies (B.E.S.T.) Innovation course

From participant to organizer and team coach

FROM PARTICIPANT TO…

TEAM COACH

TEACHER

AND FACULTY

B.E.S.T.
Business Engineering
and Surgical Technologies

Introduction

The BEST adventure started in August 2016, at the end of a 10 week internship at IHU, when I participated in this med-tech innovation course.

The BEST innovation course consists of an online and on-site course and combines minimal invasive surgery with engineering and entrepreneurship. The online lectures and tests serve as preparation for the on-site course. The 5 day boot camp is an intense program where participants practice minimal invasive surgery skills, write business plans, develop prototypes and learn from well-known experts from different backgrounds. The course does not follow conventional education methods, instead it inspires students by exposing them to the latest innovations and lets them learn together in multidisciplinary teams while solving an emerging medical problem. It is expected from the students to directly implement their learning from the interactive entrepreneurial lectures they receive during the course.

As a participant in 2016, I greatly enjoyed the inspiring and international course about med-tech innovation. From a young age I have been interested in education. I have been tutoring, teaching, facilitating and coaching since I was able to. So I was eager to get involved in the course from the organizational side. I expressed my interest to Silvana and later when I started my graduation internship in January 2017 at IHU, the BEST team gave me the opportunity to get involved. This started with promotion activities like lecture talks and managing social media. As the deadline for the Taiwan course came closer, I took on more tasks. To my happy surprise, I was even asked to come to Taiwan as part of the organization team. After a successful BEST course in Taiwan, the course in Strasbourg was quickly approaching and my responsibilities expanded.

Main role and responsibilities

Promotion

My tasks for BEST started by taking care of promoting BEST via social media and by giving two lecture talks at the University at Twente that I had arranged. Together with another former participant, I started gathering testimonials from former BEST participants in order to use them for marketing posts on Facebook and Instagram. Eventually they were also featured on the BEST website.

Communication and selection

When students started applying for the course, I became responsible for handling communication with them by managing the BEST email account. I sent information to the students as well as answered their questions. Finally, I took care of subscriptions for the course and I helped with the student selection process.

Figure 1: Testimonial example on BEST website

Team coaching

Both in Taiwan and Strasbourg I was a team coach of one of the project teams. Being a team coach meant I had the responsibility of guiding a team of 5 or 6 students in their quest of creating a technical solution for the medical need presented to them. The goal of the challenge is to propose, by the end of the week, an innovative product and an associated business plan. It should appear as a complete and self-consistent med-tech device start-up project. A coach's role is to facilitate the team's process, and sometimes individual guidance of students, to help them meet the given challenge by working with their team and applying newly learned knowledge. The goal is to empower them to reach their full potential and get as much as possible out of the intense week.

Engineering challenges

Both in Taiwan and Strasbourg, I was responsible for the engineering challenges that existed out of two practical exercises. The exercises are meant to challenge the students into thinking for an engineering solution or improvement of current medical techniques. The first challenge was about discovering the different imaging modalities of minimal invasive surgery, their possibilities and limitations. The second challenge is about the interface of flexible endoscopy and its limitations when it comes to surgical interventions and how to possibly solve this. The exercises were already designed, however for Taiwan and Strasbourg I needed to adapt them to better fit this year's program. To make one of the challenges more interesting a newly created bleeding model was added.

Dry lab

One of my ideas for an extra hands on exercises for the students was endoscopic painting. This is a simple and fun way to train laparoscopic skills without the need for specific equipment or models. It is a skill box students could potentially build at home with a webcam, pencils and a box. Most students were enthusiastic to try this entertaining exercise while at the same time training their laparoscopic skills.

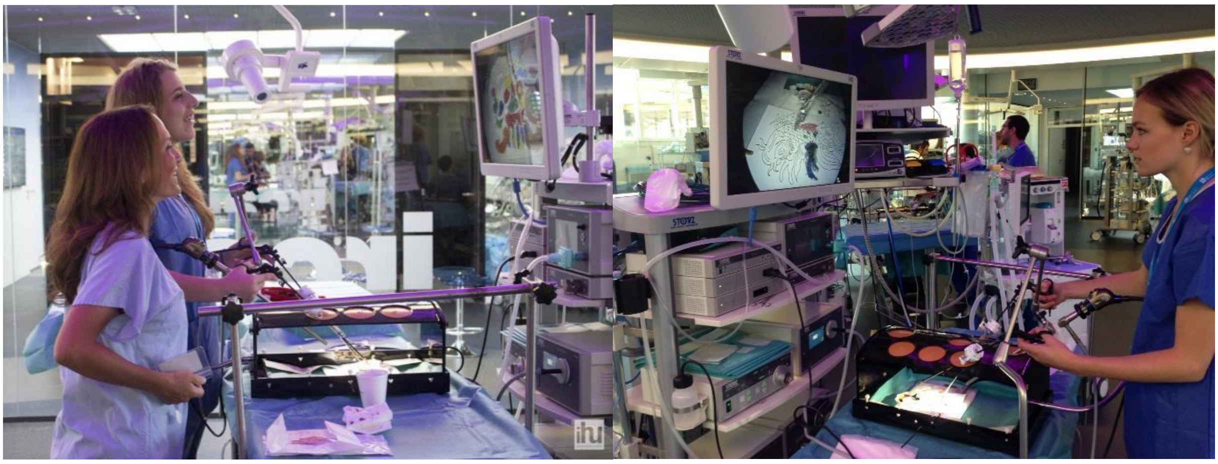


Figure 2: Endoscopic painting during the best course in Strasbourg

Another dry lab responsibility was the Laparoscopic Training and Testing model (LASTT) where the laparoscopic skills of students were assessed based on the time it took to fulfil certain tasks. For this I organized the lab rotations in order to coordinate the students and give instructions during the sessions.

Professional and personal development

Coaching

Being a team coach gave me a lot of valuable experience and made me realize (again) that I gain a lot of energy from the process of empowering others to unlock their full potential. I greatly appreciate the role of observing a team closely and to discover the best way to guide them, either as a group or as individuals. I feel honoured to be in this position, I appreciate the trust the team puts in me. I therefore see it as my duty to coach them as best as possible. I learned that coaching is not about telling people what to do, it is about helping them to learn rather than teaching them. It is about giving them a chance to examine what they are doing in the light of their intentions. Like Socrates once said: "I cannot teach anybody anything. I can only make them think"

My experience as a coach has taught me that it is not always best to be overly involved as a coach. It is important for the team to know you are there for them, they need to feel your support.

However, sometimes this means that you must put your trust in them to be able to figure things out on their own. They need to fully own the process they are going through. When you take too much responsibility as a coach, they will not learn to reflect on themselves and maybe rethink their actions. Especially in Taiwan I was challenged with a difficult team process because of some strong personalities. This caused clashes within the team and didn't help them to work well together. In the beginning, they mainly complained a lot (their expectations regarding the course were not met, in their opinion), which influenced the atmosphere in the team negatively. Next to this, two of the most dominant guys started competing against each other (instead of against other teams), since they both wanted to take the lead. I could feel the potential of the group being limited by the negative emotions. It was not safe for people to speak up or be creative. One of the dominant guys, attempted in using his alliance with me (same nationality) to gain power. It was a difficult position to handle as a coach. Happily, with the help of our experience faculty, I learned how to deal with these personalities. We tried giving them the incentive to rethink their behaviour and what they had done to their team spirit. We let them contemplate the effects of their attitude. I could not teach them the team spirit I thought they needed. I could only try to help them to figure this out by themselves so they could understand the importance of a team spirit and let them examine what they were doing in the light of their intentions. It was important for them to realize that they could only get as much out of the course as they put into it. That it is not about what is happening to you, but about how you react to it.

Having this experience in Taiwan made me handle team dynamics differently from the start in Strasbourg. I positioned myself less present to take the lead and more observant, since I noticed that closely observing my team brought me good insights in Taiwan. Each team is different, for example, my team in Strasbourg had more experience and knowledge due to their backgrounds. So the kind of guidance they needed was different. This was the moment where I remembered what a supervisor had done during one of my internships; He applied 'bottom up' management. This means that as manager you trust in the responsibility and expertise of your people and ask them what they need from you, instead of the other way around. Opposed to a more traditional approach, you don't tell them what to do better or what they are doing wrong, but instead you facilitate their improving and learning curve. I already started applying this approach by observing the team and individual team members to see where and how I could help the team best (providing structure, encouragement, guiding discussions, providing information, sharing experience). I decided to take this a bit further and also stimulate my team to think about what they needed. They mainly indicated to need to help to structure the steps they needed to take. Next to that I noticed that despite the high level of knowledge and experience they were a bit insecure, so I focussed my coaching mainly on encouraging them and providing structure. The 'bottom up' approach can be fruitful very fast and stimulates responsibility of the team. Although it does require some level of self-reflection, next to that it is a bit ambitious to expect from people to know what they need within a week time.

Dealing with stress

Working towards a deadline, for a quality course like BEST, and performing during the intense week can be stressful. Especially when the first time you help out as an organizer, is the first time BEST is held in Taiwan. Which means many first experiences, new responsibilities and new impressions. Together with two other colleagues we flew earlier to Taiwan to prepare the start of the course, working with the Taiwan team. After the first days I was not sure how I could continue for a full week, dealing with all the new responsibilities and impressions. However, I managed to stay calm and trust that it would work out.

When I look back I can understand that I was able to stay calm and trust it would work out, because I learned from the people around me. I looked at how the faculty around me handled the high time pressure. I could see the trust and confidence they had in things working out, like they always do. There is always a solution. They trusted in the team to be able to get it together in the end. This team feeling helped me to calm down and trust as well. Next to that, stress decreases the creative capability of your brain, so when you learn to stay calm solutions will arise sooner. This is definitely something I learned from my own experience as well. In the end, the physical symptoms of stress completely vanished, I was able to trust in the team and the process of figuring out solutions. What helped with this, is the fact that working for the BEST course, also gives me back a lot of energy.

This experience taught me that having stress is not necessarily a bad thing, it is all about how you deal with it. Your perspective on what is stressful is just depending on your experience, it does not necessary mean something really goes wrong. This helped me staying calm and think clear. Due to this, in Strasbourg my stress maintained on a lower level.

Business knowledge

The BEST course fits my study background, Technical Medicine, very well. Both programs are designed to learn how to look for medical needs, rather than trying to find a medical application for a new technology (some call it techno pushing). Next to this, both programs are focused on solving these medical needs with innovative medical technologies. Of course, Technical Medicine is a six year program, with much more depth and specialization compared to the BEST course. But compared to BEST, my Technical Medicine study program does not touch the business side of bringing new technologies to the market. This is not an objective of the study program. This is why being involved in this course, adds great value to my business knowledge and therefore widens my perspective on med-tech innovation.

Because of BEST, I now have an understanding of how patentability or freedom to operate works. I have helped set up business plans and have an idea how to start funding for a new product. Personally it gives me the knowledge base upon which I could decide whether the world of med-tech innovations is something for me.

Take away insights

Hard skills and soft skills

One of the things I realised because of the BEST course is, that hard skills are important, but worth less without good soft skills. Soft skills usually get little respect and attention, but they are essential for getting any idea into practise. I think that one of the reasons that soft skills get less attention, is because they are less measurable and therefore more subjective. In a course like BEST, where teams are competing against each other in order to find the most innovative solution, it is clear to see how important teamwork, leadership, time management and communication skills are in order to meet the challenge. For example, you can imagine that working in an international and multidisciplinary team calls for good communication skills and requires enough empathy to understand each other in order to work well together.

I believe in the future, being able to work with people from different backgrounds becomes more and more important. Jobs become more dynamic, global and flexible. This is backed up by the increasing amount of interdisciplinary studies, like Technical Medicine. With Technical Medicine for example we aim to bridge the gap between medicine and technology, therefore it is important we acquire the soft skills needed to be able to work with people from both areas of expertise.

Personally the BEST course in Taiwan taught me a lot about working with people from different backgrounds. More specifically, about working with people from an Asian background. Since people from an Asian background tend to be less direct in their communication and are used to work less on a team. To figure out their thoughts or opinion requires more patience and good observation, especially as a western person. I remember encouraging the western members of my team to have more patience with their Asian team members and really try to understand their motives.

Most impactful for me were the things I learned about leadership. First of all because of the inspiring examples from some of the entrepreneurial experts I met during the course. Some of them are a great example for me. Getting to know them and the other experts taught me more about the kind of leader I want to become and the leadership skills I find important. And second of all, I learned new leadership skills through my own experience as a team coach, about which I wrote in the previous section. Both coaching experience taught me that if you want to be a good leader in general, not just for specific people, you need to be able to be a humble chameleon. Each team and each individual has different needs in order to reach a common goal, and it is up to you to do your best to fulfil these needs. In this quest it is less important who you are or what your background is. In Taiwan I struggled with letting go of my involvement and feeling of responsibility and in Strasbourg I had to deal with my insecurity due to having less professional experience than some of my team members. However, I overcame my personal struggles, in order to coach my team as I could.

Career perspectives

One of the main reasons I am very engaged with the BEST course is because education interests me a lot and I think the BEST course is a very well-designed course that applies a big range of educational facets. Being involved in this course and especially being a team coach showed me again how much personal energy get out of doing this type of work. Working in the BEST organization team and with the faculty members that consists of experts in med-tech innovation from all over the world, showed me some possible directions for my future career as well. Through my study program I have built a great skillset and applied this during my internship in the research for the medical-technical domain. Through my extra curriculum activities, I improved upon my soft skills and explored positions like team leader, tutor, team coach, team manager and organizer. I have noticed that I thrive when I am in a position where I can empower others, coach them, and guide them towards new insights. Therefore, I am now sure that I will continue on this path and focus more in the field of education and leadership, while staying in the field of med-tech innovation.

Finally I am extremely grateful to have gotten the opportunity to be involved in the BEST course and to have been able to experience many aspects of organizing this course. It has been an intense, inspiring and eye opening experience.

2: Other average sequence results

With dataset 1 average sequences are computed of the endoscopist positions. These are visualized per phase and for visualization purposes, only the first 2 minutes of each phases are visualized.

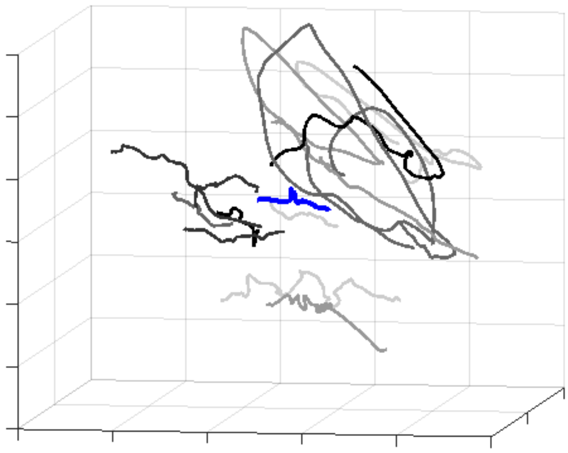


Figure: Average (blue) of the position of the endoscopist right hand during phase 1 (insertion).

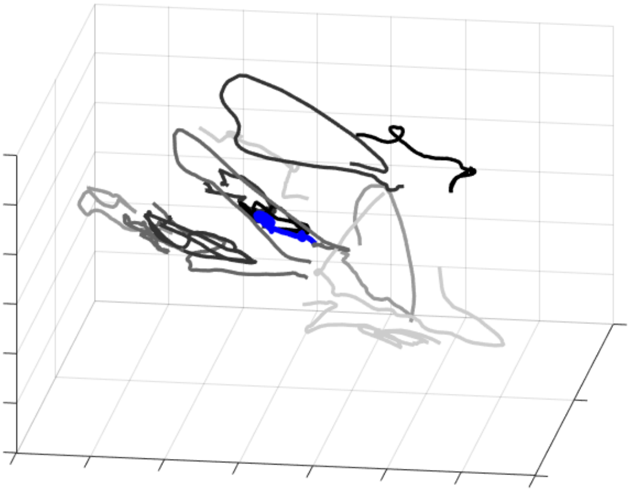


Figure: Average (blue) of the position of the endoscopist right hand during phase 2 (retroflexion and inspection).

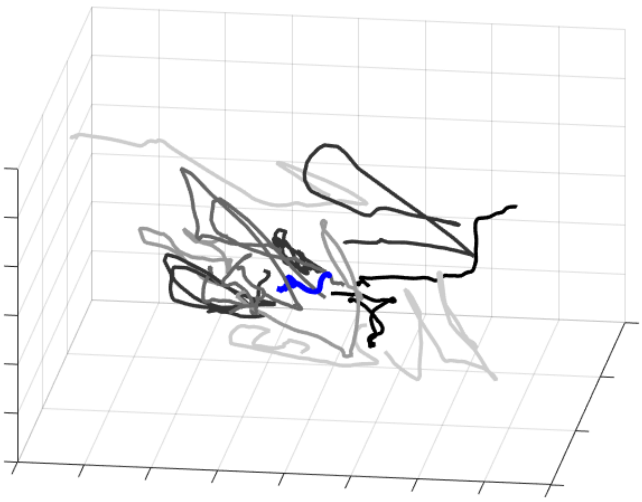


Figure: Average (blue) of the position of the endoscopist right hand during phase 3 (duodenal intubation).

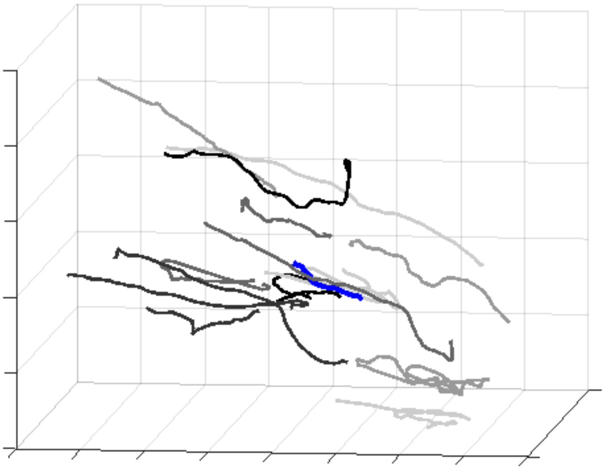


Figure: Average (blue) of the position of the endoscopist right hand during phase 4 (retraction).

3: Other torque graphs during duodenal intubation

In chapter six the torque information of a reference expert is analysed. Next to that a difference is show between an expert and beginner endoscopist. Here the other torque graphs are visualized, firstly of the expert and secondly of the beginners.

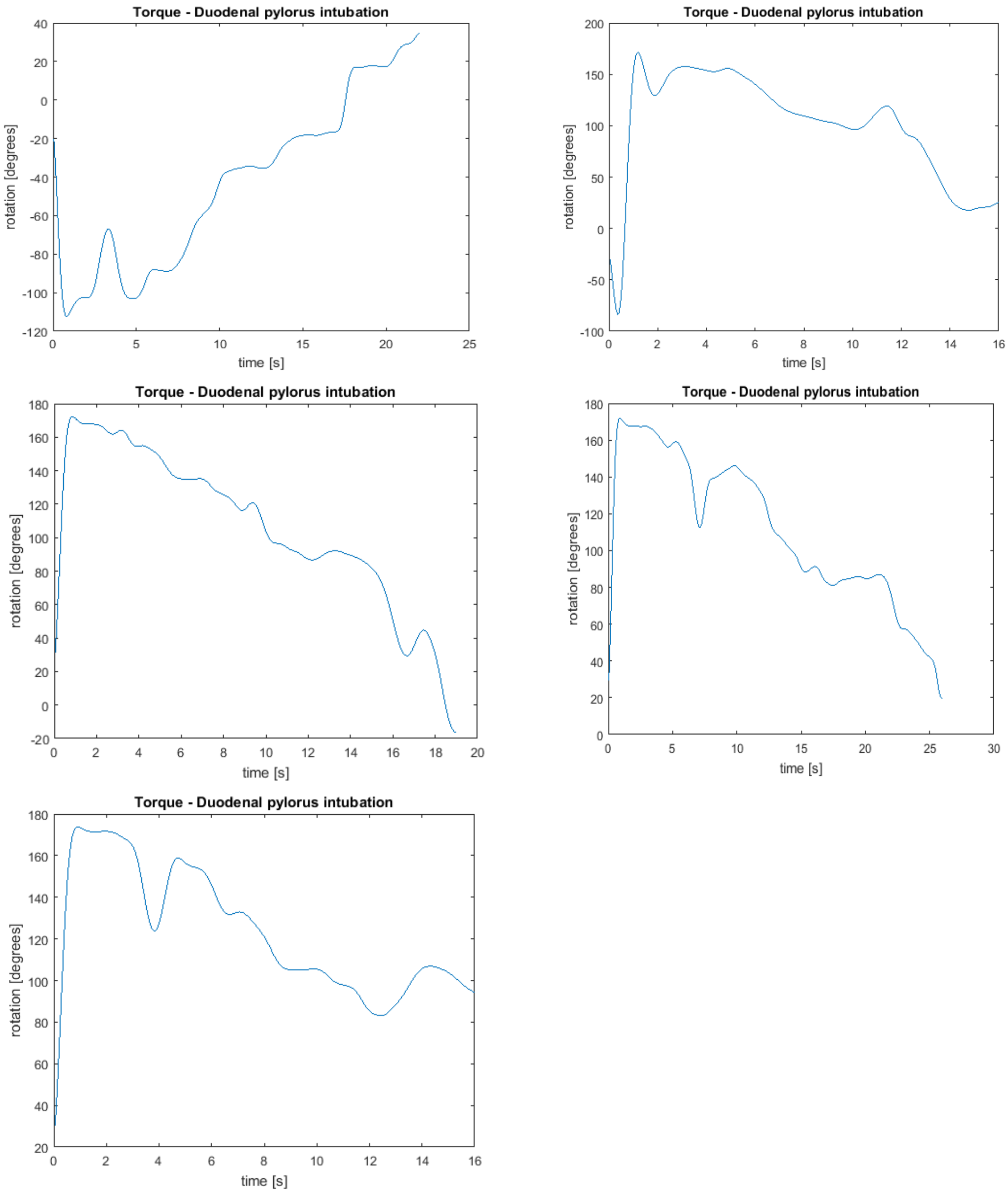
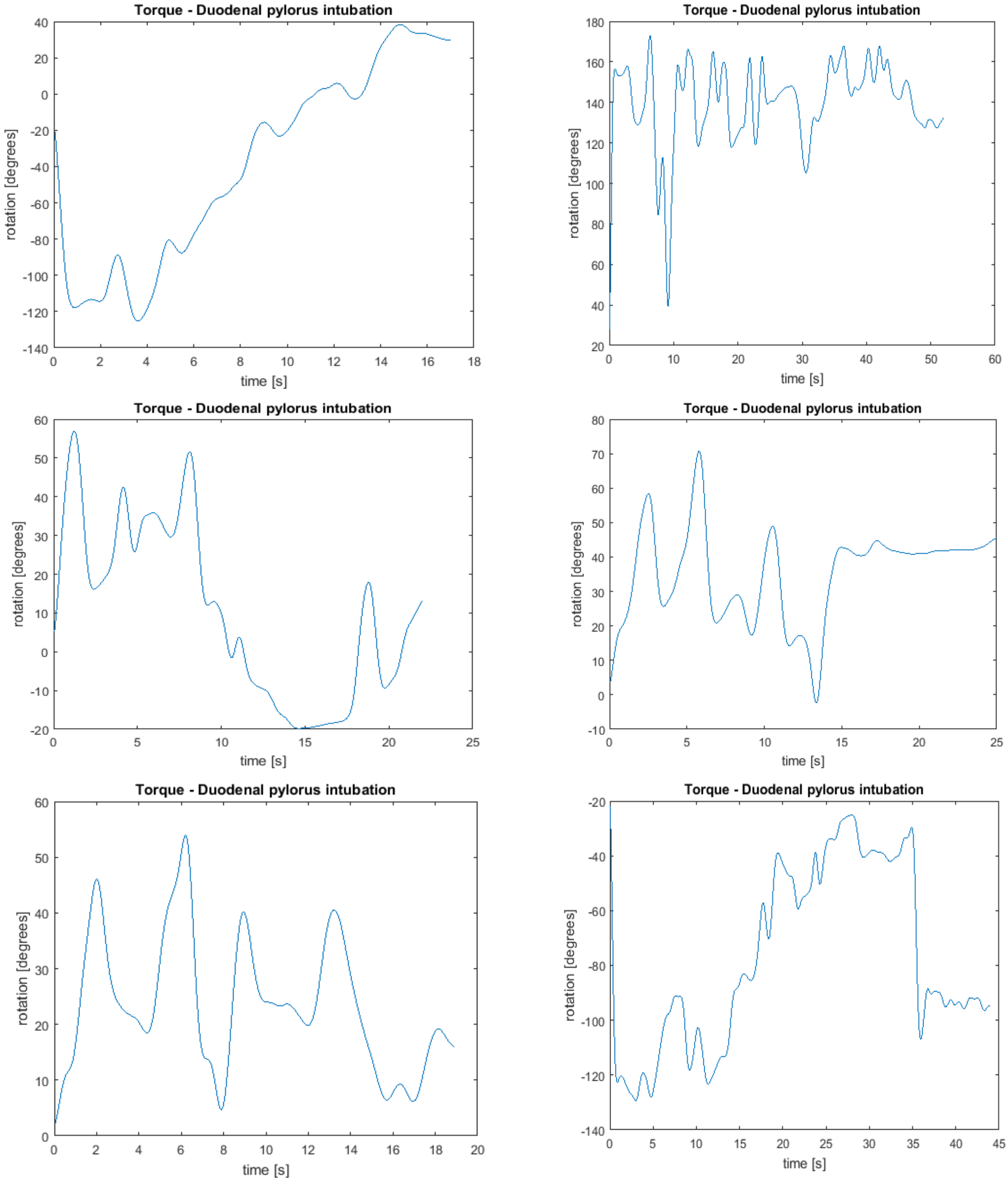
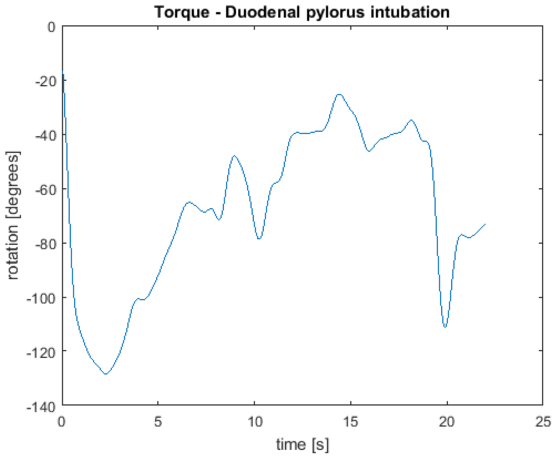


Figure: Expert torque graphs, during duodenal intubation





All expert graphs show a smooth increase or decrease of the torque curve. The beginner graphs are in general less smooth, show quick changes and variate in their course.

Figure: Beginner torque graphs, during duodenal intubation