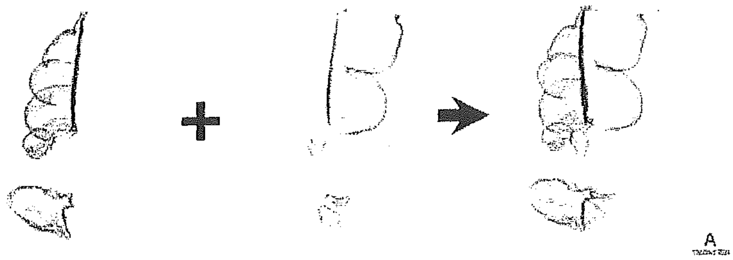

図4．Dual-contrast CT enema像
エア像と造影剤像の合成画像(図右)である。

medium bowel preparation (PEG-C法)を考案した[21]。PEG-C法は，体位変換の必要がなく，通常内視鏡と前処置を共有することが可能であり，病変描出能の点においても良好な成績を得ている(特許出願・公開中)[22]。前処置の方法は，PEG(ニフレック®)全量を水2Lに溶解し，このうちの1,620mLを内服後，残りをamidotrizoic acid，diatrizoic acid 76%，20mLを含むPEG-C溶液400mLとして最後に内服とする。3D-CT撮影後，エア像と造影剤像を構築し，その両方の画像データを合成することでDual-contrast CT enema画像が構築される(図4)。

おわりに

大腸癌診断における3D-CT検査は，検査上の注意や制限はあるものの，現状でも有用である。特にCT enema像は，患者負担の軽減や検査日程の短縮につながり，大腸癌術前検査の1つと数えることが可能である。

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腹腔鏡下大腸手術手技の標準化：当科における具体的手術手技

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総　説

腹腔鏡下大腸手術手技の標準化：当科における具体的手術手技

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要約：当科では1993年から腹腔鏡下大腸切除術を導入し，当初は良性疾患および早期癌に適応を限定していたが手技・成績の安定に伴い適応をSiのない進行癌へと徐々に拡大してきた。腹腔鏡下手術の割合も増加しており，2002年は40%，2003年は28%が腹腔鏡下手術であった。手術は血管処理を先行させる内側アプローチを原則としている。目的部位を十分に剥離授動した後，全例臍部トロッカー刺入部を小切開し腸管を体外へ挙上している。創縁の保護にはプロトラクター® を主に用いている。再建は主に自動縫合器を用いたfunctional end to end anastomosisまたは自動吻合器で行っている。

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KEYWORDS：colorectal cancer, laparoscopic surgery, functional end to end anastomosis

当科では1993年より腹腔鏡下大腸切除術を導入している。導入当初は適応を良性疾患，早期癌および進行癌でも多発性遠隔転移など根治的手術のできないものに限り開始した。早期癌で開腹術と比較して良好な術後経過とその予後に差がないことを確認し[1)]，1999年からは適応を深達度mpまで，2002年からは長径5 cm以下の深達度ss, N（－）まで，現在はSi以外の5 cm以下の大腸癌と徐々にその適応を拡大してきた。適応拡大に伴い年間手術症例数に占める腹腔鏡下手術の割合も全大腸癌手術症例の約30%に増加している。本稿では，大腸腫瘍に対する当科での腹腔鏡下手術の現状について述べる。

当科における腹腔鏡下大腸切除術の術式

郭清範囲は良性疾患およびmおよびsm1癌ではD1+α郭清，sm2, sm3まではD2郭清，MP, SS, SEではD3郭清，Siでは開腹術としている。病変部位は盲腸から直腸Raまでとしており，横行結腸は手術手技が困難であるためD2郭清まで，腹膜反転部近くはMPまでの症例に適応を限っている。

占拠部位別の手術術式

全例臍部よりOptiview trocar（Ethicon endosurgery, Johnson & Johnson）を用いてカメラを挿入・気腹している。肝転移，腹膜播種，腹水の貯留の有無，癒着の程度を確認する。

当科ではアプローチは①視野がよい，② non-touch isolationを施行する点から原則として内側アプローチとしている[2)]。血管や腸管膜の処理には超音波凝固切開装置は是非必要な器具であるが，当科ではソノサージ®（オリンパス）を主に使用している。同装置に付属の超音波トロッカーを用いることで力を必要とせず，出血することなく容易にトロッカーの挿入が可能である。また電気メスの機能を併せ持っているため，鉗子の入れ替えなく電気メスを使用することができる点も有用である。

1. 右側結腸（盲腸および上行結腸）

トロッカー挿入後，頭低位・右側高位に手術台をローテートし，小腸を排除し腫瘍部を確認する。十二指腸水平脚を確認し，この下側をメルクマールとして腸間膜を剥離すると回結腸動脈の分岐部が確認される。D3郭清を行う場合は203番のリンパ節の郭清を行った後，根部にて回結腸動脈を二重にクリッピングし切離する。同様に回結腸静脈をクリッピング後切離する。日本人では右結腸動脈は欠損している場合が多いが，確認された場合は回結腸動脈と同様に処理する。腸間膜の剥離を外側に向かって進め，尿管を確実に確認し後腹膜側へ落とす層で剥離を進めていく。外側まで剥離を進めたところで，ガーゼ（ラパーゼ®）を剥

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Table 1 The Number of LAC Cases (1993-2003)

	ALL	LAC(%)	Region								Pathological depth						
			C	A	T	D	S	Rs	Ra	Rb	m	sm	mp	ss	se	si	benign
1993	44	2(4.5)	0	1	0	0	1	0	0	0	0	1	0	0	0	0	1
1994	83	15(18.7)	1	2	3	1	6	2	0	0	7	3	1	0	2	0	2
1995	73	9(12.3)	1	2	0	1	5	0	0	0	3	3	0	0	0	0	3
1996	92	15(16.3)	1	2	1	0	11	0	0	0	5	9	0	0	0	0	1
1997	83	11(13.3)	3	0	2	0	5	1	0	0	0	6	2	0	0	0	3
1998	83	11(13.3)	2	1	0	0	6	1	0	1	1	8	0	0	0	0	2
1999	89	18(20.2)	1	1	1	3	8	3	1	0	3	9	5	1	0	0	0
2000	85	9(10.6)	3	2	0	0	3	1	0	0	2	2	1	1	0	0	3
2001	86	19(22.1)	1	4	2	2	7	1	2	0	1	10	4	2	0	0	2
2002	82	32(39.0)	3	5	4	1	13	1	5	0	5	12	3	9	1	1	1
2003	112	32(28.6)	3	8	3	0	16	1	1	0	6	8	6	8	2	1	1
Total	912	173(19.0)	19	28	16	8	81	11	9	1	33	71	22	21	5	2	19

LAC : laparoscopic-assisted colectomy

離した腸間膜下に留置する。ついで回腸末から盲腸，上行結腸を肝曲部に向かって後腹膜より剥離受動していく。この時，先に留置したガーゼが透見されるのでこれをメルクマールとし，内側のアプローチ層と連続させる。肝曲部まで剥離を進めた後，頭高位とし横行結腸から大網の剥離に移る。助手に大網を挙上してもらい，横行結腸中程から大網を肝曲に向かって剥離していく。肝曲まで剥離を進め，上行結腸を受動した部位まで連続させる。腫瘍近傍を把持し挙上して，十分に病変部位がフリーとなっていることを確認する。臍部トロッカー刺入部を 3.5 cm（腫瘍が大きい時には大きさに準じて）に小切開した後，創縁をプロトラクター® またはラップディスク® にて保護し腫瘍部の腸管を体外へ挙上する。口側・肛門側切離線を定め辺縁動静脈を処理する。吻合は functional end to end anastomosis を採用している。吻合後腸管を腹腔内へ還納し，小切開創を閉鎖し再度気腹する。腸管の捻じれや出血のないことを確認しトロッカー抜去する。トロッカー刺入部を縫合し手術を終了する。右側では基本的にドレーンは挿入しない。

2. 横行結腸

前述のようにD3 郭清は開腹にて試行している。MP までの D2 は肝曲または脾曲の受動と大網切除後に臍上部を小切開後中結腸動静脈へアプローチし，222 番リンパ節の郭清を行っている。

3. 下行結腸・S 状結腸

右側大腸と同様に臍部からトロッカーを挿入し腹腔内を観察する。頭低位，左側高位に手術台をローテートさせ，SD 部付近の腸管膜を把持挙上すると，下腸間膜動静脈が腸管膜の突っ張りとして確認される。総腸骨動脈分岐部より腹部大動脈に沿って頭側に剥離していくと，下腸間膜動脈の根部が確認される。D3 郭清を行う場合は根部にて切離し 253 番のリンパ節の郭清を行う。下腸間膜静脈も同レベルにて切離する。右側大腸癌と同様に腸間膜を外側に向かって剥離していく。左側でも尿管を確認し，後腹膜側に落とす層で剥離を進めていく。内側より充分剥離した後ガーゼを腸間膜下に留置し，ついで SD 部より下行結腸の受動を脾曲に向かって進めていく。下行結腸の受動後視野を尾側へ向け，S 状結腸下部から直腸にかけての受動を行う。腸管の右側から剥離を行い直腸後面，左側の順に剥離していくと操作しやすい。腫瘍部が充分剥離されフリーとなったところで臍部を小切開し腸管を挙上する。体外にて右側結腸と同様の手技で腸管の切離・再建を行う。基本的にドレーンは挿入しない。

4. 直　腸

血管処理はＳ状結腸と同様である。低位前方切除術の場合は腹膜反転部を全周に剥離していくが，右側から背側，左側，最後に前面の剥離を行うと操作しやすい。直腸では臍部の小切開層から腸管を挙上できないため，肛門側を自動縫合器で切離し，断端を小切開創から挙上する。切離にはエンドカッター等を用いてできる限り 1 発で切離することが望ましい。体外で口側の切離を行い断端にアンビルヘッドを挿入する。腹腔内へ還納し自動吻合器を用いて再建を行う。アンビルヘッドを自動吻合器に合体させた後に，カメラを臍部より恥骨上に変えて吻合部を直上より観察し，吻合部に過剰な脂肪織や介在物が挟まらないように注意する。吻合前に再度カメラの位置を臍部に戻し，腸管の捻じれがないことを確認する。また再建前には肛門よりイソジン加生食にて腸管内の洗浄を行い，管腔内転移・局所再発の抑制に努めている。最近では左側大腸癌症例では腸管の切除前に腹腔内用の腸管把持鉗子（エースクラップ®）を用いており，吻合前後の腸管内洗浄に有用である。腸管を吻合した後エアーを用いてリークテストを行い確実に縫合されたことを確認する。恥骨上トロッカー刺入部より 8

mm のマルチドレーンをダグラス窩に留置し，トロッカーを抜去し手術を終了する（Table 1）。

おわりに

大腸癌の治療において腹腔鏡下大腸切除術はその手技と器具の発達により開腹術と同等以上の成績を上げるようになってきている。しかし腹腔鏡下手術は技術的に難易度が高く，安全かつ確実に手術が行われるためには適切な術者のトレーニング，慎重な手術の適応の決定が必要であると考える[3)]。

欧米と比較して日本における腹腔鏡下大腸切除術の普及度は高く，その技術も高い。しかし今後進行癌に対しても，腹腔鏡下手術がスタンダードになるためには多施設でのランダム化比較試験（RCT）が不可欠である。欧米では数件の RCT が進行中であるが，当科でも JCOG（日本臨床腫瘍研究グループ）での RCT の準備に参加しており本年中には開始予定である。

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Digestive Endoscopy (2005) **17**, 50–53

ORIGINAL ARTICLE

DAI-KENCHU-TO, A HERBAL MEDICINE, IMPROVES PRECOLONOSCOPY BOWEL PREPARATION WITH POLYETHYLENE GLYCOL ELECTROLYTE LAVAGE: RESULTS OF A PROSPECTIVE RANDOMIZED CONTROLLED TRIAL

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Background: This prospective randomized controlled trial examines the effect of combination of Dai-kenchu-to (DKT), a traditional Japanese herbal medicine, and polyethylene glycol electrolyte (PEG) lavage in precolonoscopic preparation.
Methods: Two hundred and eight-five colonoscopy patients from January to December 2001 were divided into two groups randomly; 144 patients into group A (with DKT) and 141 into group B (without DKT).
Results: Abdominal pain and nausea were observed in 17% and 24% of group A, and 15% and 21% of group B, respectively. Preparation scores were 0.28 ± 0.52 in group A and 0.81 ± 0.77 in group B. Times for reaching the cecum were 6.4 ± 3.6 min in group A and 7.3 ± 4.0 min in group B. Group A demonstrated significantly better preparation ($P < 0.001$) and shorter times ($P = 0.04$) than group B.
Conclusion: The present study indicates that DKT in combination with PEG is a safe and gentle method, improving precolonoscopic bowel preparation without increasing abdominal pain and nausea.

Key words: colonoscopy, colonoscopy preparation, Dai-kenchu-to, herbal medicine, polyethylene glycol.

INTRODUCTION

Colonoscopy is a safe, effective, and accepted means of evaluating the large bowel. The advantage of colonoscopy over barium enema lies mainly in the simultaneous diagnostic and therapeutic maneuvers that can be performed (such as obtaining biopsy specimens and polypectomy or endoscopic mucosal resection), in addition to direct visualization of the colonic mucosa.[1,2] Polyethylene glycol electrolyte lavage (PEG) has been the standard cleansing regimen for precolonoscopy bowel preparation since 1980.[3,4] The need to consume large fluid volumes and the bad taste of PEG are factors that limit patient compliance. In Western countries, patients may be expected to take more than 3 L of the solution. This is difficult to achieve in the Japanese patient population and the intake of 2 L of PEG solution is a widely accepted alternative. However, some studies have indicated that the quality of bowel preparation following a 2-L PEG intake is unsatisfactory.[5,6]

The use of cisapride as a treatment agent in combination with PEG has been trailed but has not been shown to be superior to preparation with PEG alone.[7–10] The present prospective randomized controlled trial examines the effect of combination treatment with Dai-kenchu-to (DKT) and PEG in colonic preparation for colonoscopy. DKT is a traditional Japanese Kampo medicine. It is known to increase gastrointestinal motility and reduce bowel obstruction.[11,12] The primary aim of the present study was to determine whether DKT improves the effectiveness and/or patient acceptability of bowel preparation when used with PEG.

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PATIENTS AND METHODS

The present study was a single blind, randomized controlled trial. All patients scheduled for elective ambulatory colonoscopy from January 2001 to December 2001 were considered for recruitment. Patients under 18 years of age, pregnant women, and patients deemed unable to follow the treatment regimen were excluded. All participating patients provided written informed consent. The principal investigator assessed the patients, obtained informed consent, and provided the DKT (Tsumura and Co., Tokyo, Japan) for patients randomly assigned to the DKT plus PEG treatment group. The patients, the nursing staff supervising the lavage, and the physician performing the colonoscopy were blinded to treatment assignment. The investigators had no financial relationship to the manufacturers regarding any of the products used in this study.

Colonic cleansing procedure

All patients were advised to eat a low-fiber diet on the day before colonoscopy. On the day of colonoscopy only clear liquids were allowed. At the time of study enrollment, patients were asked to fill out a baseline questionnaire about constipation using a three-point scale (0 = absent, 1 = mild, 2 = severe). Patients were then prospectively randomized in double-blinded fashion using sealed envelopes to receive either PEG (Ajinomoto Pharma Co., Ltd, Tokyo, Japan) only, or PEG plus DKT. DKT (2.5 g powder) was taken at 12.00 h and 21.00 h on the day before colonoscopy and at 7.00 h on the day of the colonoscopy. The effect on the osmotic pressure of DKT in combination with PEG has not been proven, so we gave DKT and PEG to the patient separately. Two litres of the PEG lavage solution were ingested within 2 h, starting 6 h before the colonoscopy. Before any sedation was given, all patients answered a questionnaire regarding their symptoms (including nausea and abdominal pain) during lavage using a three-point scale (0 = absent, 1 = mild, 2 = severe). Vomiting was scored as 2 in the question relating to nausea. All patients also provided the amont of time required to take the solution, the amont of time spent in defecation, and the frequency of bowel movements. All colonoscopies were performed between 13.00 h and 16.00 h by the same experienced endoscopist who was blinded to the type of bowel preparation used. The quality of the colon preparation was assessed immediately after colonoscopy by the endoscopist according to the following scale: 0 = excellent, no fecal material present; small amount of liquid material present; less than 5% of the colonic wall obscured; 1 = good, liquid material present; less than 25% of the colonic wall obscured; 2 = moderate, liquid material present; less than 50% of the colonic wall obscured; 3 = poor, solid material present; more than 50% of the colonic wall obscured; 4 = impossible, insertion to the cecum not possible due to a great amount of solid or liquid material.

Insertion time to reach the cecum was also recorded.

Statistical analysis

Numerical data were expressed as mean and standard deviation (SD). Non-parametric scores were compared using the Wilcoxon test. Qualitative data were evaluated using the chi-squared test, and parametric data were compared with the Student's *t*-test.

RESULTS

A total of 285 patients were enrolled: 144 patients in group A and 141 in group B (Table 1). In all cases, colonoscopy successfully reached the cecum. The mean ± SD patient age for the two groups was 60 ± 11 and 61 ± 10 years, respectively. The ratio between men and women was 92 : 52 and 79 : 62, respectively (not significant [NS]). The frequency of bowel movements showed no significant difference between the two groups: 7.9 ± 3.1 times and 7.7 ± 3.6 times, respectively (Table 2). The time spent in defecation also showed no significant difference between the groups: 3.3 ± 1.6 h and 3.0 ± 1.5 h, respectively. The presence of abdominal pain was reported in 17% of patients in group A and 15% of patients in group B, with abdominal pain scores of 0.17 ± 0.38 and 0.15 ± 0.35 for group A and group B, respectively (NS) (Table 3). Nausea was reported in 24% of group A and 21% of group B. The nausea scores were 0.28 ± 0.55 in group A and 0.21 ± 0.43 in group B (NS). The preparation scores were 0.28 ± 0.52) in group A and 0.81 ± 0.77 in group B. Group A demonstrated significantly better preparation ($P < 0.001$) (Table 4). The times for reaching the cecum were 6.4 ± 3.6 min in group A and 7.3 ± 4.0 min in group B, with group A demonstrating significantly shorter times ($P = 0.04$).

Table 1. Patient characteristics

	A group	B group	*P* value
	144 cases	141 cases	
Male : female	92 : 52	79 : 62	
Age (mean ± SD)	60 ± 11	61 ± 10	NS

DISCUSSION

A variety of regimens have been studied as adjuncts to standard PEG lavage. Rhodes *et al.* evaluated the use of metoclopramide in conjunction with PEG, randomly assigning 40 patients to receive either metoclopramide 10 mg or placebo 30 min before receiving PEG.[13] Patients receiving metoclopramide experienced significantly less nausea and bloating, but there was no significant difference seen with respect to colon cleansing.

Sharma *et al.* reported that magnesium citrate or bisacodyl before PEG lavage improved colonoscopy preparation and that these stimulant laxatives did not affect hemodynamics or serum electrolytes.[14] Brady *et al.* also evaluated the laxative bisacodyl in combination with PEG lavage, concluding that bisacodyl did not significantly influence adequacy of

Table 2. Defecation results

	A group	B group	*P* value
Frequency of defecation	7.9 ± 3.1	7.7 ± 3.6	NS
Time in bathroom (hours)	3.3 ± 1.6	3.0 ± 1.5	NS

All values are mean ± SD.

Table 3. Abdominal pain and nausea

	A group	B group	*P* value
Presence of abdominal pain	25 (17%)	21 (15%)	
Degree of abdominal pain	0.17 ± 0.38	0.15 ± 0.35	NS
Presence of nausea	34 (24%)	29 (21%)	
Degree of nausea	0.28 ± 0.52	0.21 ± 0.43	NS

All values are mean ± SD.

Table 4. Condition of preparation and time required for colonoscope to reach cecum

	A group	B group	*P* value
Preparation score	0.28 ± 0.52	0.81 ± 0.77	$P < 0.001$
Time to reach cecum (min)	6.4 ± 3.6	7.3 ± 4.0	$P = 0.04$

All values are mean ± SD.

colon cleansing, the amount of PEG required, or patient satisfaction.[15] Fifteen Japanese studies have shown good results with the use of sodium picosulfate in combination with PEG.[16,17] Investigators have reported that the sodium picosulfate combination not only achieved good bowel preparation but also suggested that the amount of PEG could be decreased from over 2000 mL to 1500 mL or 1000 mL. Clinically, however, the use of stimulant laxatives tends to increase patient discomfort, particularly abdominal discomfort and nausea, especially in patients without constipation.[18]

The gastrointestinal stimulant cisapride was introduced in 1993 and has been used in many experimental and clinical studies worldwide.[7–10,19] Ueda *et al.* reported that when cisapride was used in addition to magnesium citrate lavage, it decreased the time required for bowel cleansing and increased the quality of bowel preparation in patients older than 60 years.[7] Other studies have failed to demonstrate similar results and the efficacy of cisapride as an adjuvant to standard PEG lavage remains uncertain.

Use of a concentrated senna extract in combination with PEG has also been evaluated. Ziegenhagen *et al.* randomly assigned 120 patients to receive the senna preparation or placebo a day prior to ingestion of PEG.[20] Satisfactory cleansing of the colon was observed in 90% of patients receiving senna, compared with 57% of patients in the placebo group. A study conducted by these authors, however, failed to demonstrate any advantage of senna use with PEG for precolonoscopic preparation.[18] In addition, the elderly patients in the study tended to experience greater abdominal pain with senna use.

In the present study, we examined the effect of DKT and PEG as a cleansing regimen prior to colonoscopy. DKT is a traditional herbal medicine, which is a mixture of zanthoxylum fruit, ginseng root, dried ginger root, and malt sugar. It has been shown to increase gastrointestinal motility and reduce bowel obstruction.[11,12] Good clinical results with DKT as a treatment for paralytic ileus have been reported.[21]

This study showed that DKT in combination with PEG improved bowel preparation for colonoscopy without increasing abdominal pain, nausea or early defecation. Although no difference in the frequency of bowel movement and the time required for defecation was seen, the bowel preparation score or remaining stool volume was significantly lower in the group who received DKT. This suggests that DKT enhanced gastrointestinal motility, resulting in increased stool evacuation. An experimental study using resected guinea-pig ileum suggests DKT increases gastrointestinal motility through its effect on acetylcholine (ACh) and tachykinin in the enteric nervous system, and the subsequent interaction of ACh with the 5-HT4 receptor.[22,23] This mode of action was also supported by results from an *in vivo* study using a canine model which evaluated phasic contraction of the vestibule of the stomach, the duodenum and the jejunum, induced by intragastric dosage of DKT.[24] It has been reported that motilin, the gastrointestinal hormone in blood plasma, increases in humans after a single dosage of DKT.[25] With regard to gastrointestinal contraction, zanthoxylum is considered the active DKT ingredient, in particular hydroxy β-sanschool, the chief component of zanthoxylum.[23] Studies suggest that giving DKT has other effects including increased rectal temperatures following an anesthesia-induced decline (in a leporid model);[26] intensifying gastrointestinal blood flow (murid model);[27] and significantly increasing vasoactive intestinal polypeptide in human blood plasma.[28]

CONCLUSION

This study indicates that DKT in combination with PEG improved bowel preparation for colonoscopy without increasing patient discomfort in terms of abdominal pain, nausea or earlier defecation. DKT and PEG appears a safe and gentle combination regimen for colonoscopy preparation. Routine administration of DKT in combination with PEG thus appears appropriate in this clinical setting.

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FAce MOUSe: A Novel Human–Machine Interface for Controlling the Position of a Laparoscope

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Abstract—**Robotic laparoscope positioners are now expected as assisting devices for solo surgery among endoscopic surgeons. In such robotic systems, the human–machine (surgeon–robot) interface is of paramount importance because it is the means by which the surgeon communicates with and controls the robotic camera assistant. We have designed a novel human–machine interface, called "FAce MOUSe," for controlling the position of a laparoscope. The proposed human interface is an image-based system which tracks the surgeon's facial motions robustly in real time and does not require the use of any body-contact devices, such as head-mounted sensing devices. The surgeon can easily and precisely control the motion of the laparoscope by simply making the appropriate face gesture, without hand or foot switches or voice input. Based on the FAce MOUSe interface, we have developed a new robotic laparoscope positioning system for solo surgery. Our system allows nonintrusive, nonverbal, hands off and feet off laparoscope operations, which seem more convenient for the surgeon. To evaluate the performance of the proposed system and its applicability in clinical use, we set up an *in vivo* experiment, in which the surgeon used the system to perform a laparoscopic cholecystectomy on a pig.**

Index Terms—**Face gesture, human–machine interface, laparoscopic surgery, robotic camera assistant, solo surgery.**

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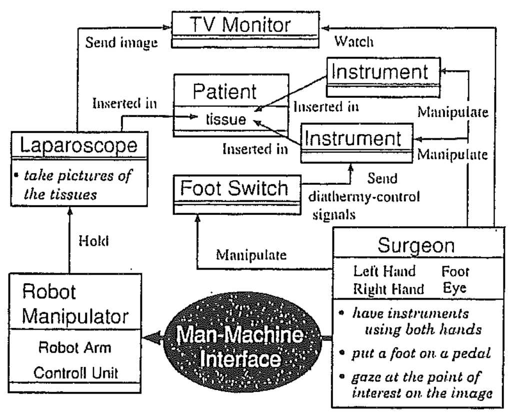


Fig. 1. Diagram of action flow in endoscopic solo surgery.

I. Introduction

In current laparoscopic surgery, the vision of the operating surgeon usually depends on the camera assistant responsible for guiding the laparoscope. The assistant holds the laparoscope for the surgeon and positions the scope according to the surgeon's instructions. This method of operation is frustrating and inefficient for the surgeon, because commands are often interpreted and executed erroneously by the assistant. Also, the views may be suboptimal and unstable because the scope is sometimes aimed incorrectly and vibrates due to the assistant's hand tremors. The introduction of robotic technologies, specifically, the development of robotic laparoscope positioning systems to replace the human assistant, is a major step toward the solution of this problem. Laparoscope positioning systems will enable endoscopic solo surgery, in which the surgeon carries out all surgical work alone, without the support of the human camera assistant.

Fig. 1 illustrates the action flow in an endoscopic solo surgery. As shown in this figure, the operating surgeon manipulates a variety of surgical instruments using both hands and one foot, while watching the TV monitor screen displaying the image of the patient's body from the laparoscope. A robotic manipulator, instead of a camera assistant, holds the laparoscope. The surgeon is relying on a human–machine interface to carry out the positioning of the laparoscope manipulator. Thus, a user-friendly (i.e., surgeon-friendly) design of the human–machine interface that controls the laparoscope positioner plays an important role in the realization of solo surgery.

Several robotic laparoscope positioning systems have been devised in the last ten years. The first product, named AESOP, was released to the marketplace in 1994 [1] by Computer

Motion, Inc., Goleta, CA, USA. The human–machine interface of most laparoscope positioners proposed in the early years included a joystick (a teleoperation type [2] or instrument-mounted type [3]) or foot pedal [4], and each required the use of the surgeon's hand and/or foot. These types of interfaces, however, seem generally difficult to use because surgeons already use their hands and/or feet to control a variety of surgical tools. To solve this problem, several researchers have introduced a voice-activated system based on the verbal aspect of human speech [4]–[8]. In these systems, the surgeon's voice is at first turned into words or sentences using a voice-recognition engine, and the appropriate actions (as manipulator control commands) are then generated from the recognized texts. Initially, the voice-activated system seemed to be an effective approach because verbal instructions are natural for humans and neither hands nor feet are required to control the laparoscope. However, this system does have some inherent limitations, such as reduced accuracy in positioning, long reaction times, and erratic movements in a noisy environment. We believe that a motion-based laparoscope controller, using the movement of the surgeon's head, is the best solution because nonverbal instructions such as face gestures are more intuitive and faster than verbal instructions. Also, because these gestures have the potential ability to represent not only the direction of scope motion but also the degree of motion, such as velocity, laparoscope positioning accuracy may be improved. Several laparoscope manipulators with a head navigation interface have previously been developed [9]–[13]. Such systems, however, failed to fully utilize the nonverbal features of facial motion. These systems were limited to detecting dominant head gestures, which only served as discrete (verbal) commands, and required not only head movements but also simultaneous control of an additional footswitch. Furthermore, the surgeon had to wear head-mounted sensing devices, such as a headband and gyro sensor, which were stressful for the surgeon.

To make the most of the advantages of nonverbal and noncontact instructions, we have designed a novel human–machine interface, called "FAce MOUSe," for controlling the laparoscope positioner. This proposed human interface is an image-based system which tracks the surgeon's facial motion robustly in real time and does not require the use of body-contact sensing devices. Using the FAce MOUSe interface, we have developed a new robotic laparoscope positioning system for solo surgery. Our system, which seems to be the most convenient for the surgeon, allows nonverbal, hands off and feet off laparoscope operations.

In Section II, we will explain the concept of FAce MOUSe in greater detail.

II. Concept of FAce MOUSe

First of all, we will summarize the degrees of freedom (DOFs) of the laparoscope and the surgeon's face. Then, we will discuss the correlation between laparoscopic and facial motions, and describe the FAce MOUSe concept.

A. Laparoscope DOFs

Due to the constraints imposed by operating through the trocar point, laparoscope movements are kinematically re-

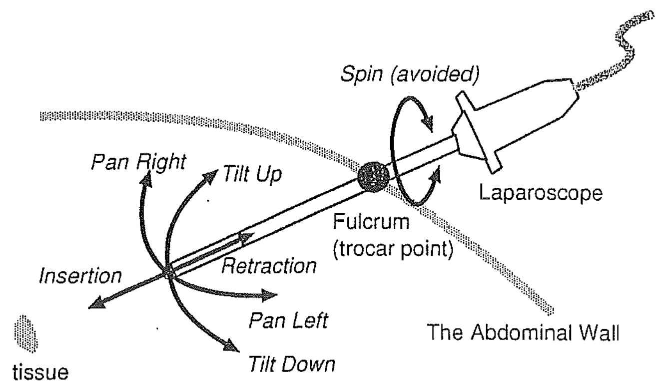


Fig. 2. Laparoscope DOFs.

stricted to four DOFs: the first and second DOFs for pivoting about the trocar insertion point, i.e., pan and tilt motions, which produce a translation of the patient's body image on the monitor screen; a third DOF for insertion and retraction along the longitudinal axis, which produces a magnification or reduction of the visualized laparoscopic field; and another DOF for spinning about the insertion axis, which produces a rotation of the visualized image around the image center. The surgeon, however, usually needs to avoid the rotation of the visualized image on the monitor screen during the operation because this demands additional mental effort [14] that is not needed. The camera-holding robot thus requires only three DOFs-two rotation angles (*pan* and *tilt*) and a translation along the camera optical axis (*insertion* and *retraction*), as shown in Fig. 2.

B. DOFs for the Surgeon's Face

In standard laparoscopic surgery, such as a laparoscopic cholecystectomy, the surgeon usually stands in front of the TV monitor displaying the scope image, and observes the surgical point of interest on the screen. Therefore, we can assume *fronto-parallel* and *distance-constant* interaction, i.e., the surgeon's face remains almost parallel to the TV monitor screen and the distance between the surgeon and the screen is almost constant during the entire interaction time. Notice that during this kind of interaction, the DOFs for the surgeon's face are reduced from six to three, namely, a translation two-dimensional (2-D) vector (x, y) and a rotation θ in the face plane [see Fig. 3(a) and (b)]. When the motion of the face is small, the translation vector can be approximately replaced with pitch and yaw motions [Fig. 3(c)], while the scalar θ corresponds to the roll motion angle.

C. Correspondence Between Laparoscope Motions and Face Motions in Previous Work

Kobayashi *et al.* [9] related the face-roll, face-pitch, and face-yaw motions to scope-zoom, scope-tilt, and scope-pan motions, respectively. Furthermore, they developed another command method [10], in which the determination of the scope-pan and scope-tilt angles is based on the time of the face-roll motion while the scope-zoom is controlled by the face-pitch motions (in this method, the face-yaw motion is not used for positioning the scope). In their system, the surgeon can drive the laparoscope manipulator by moving his/her head in

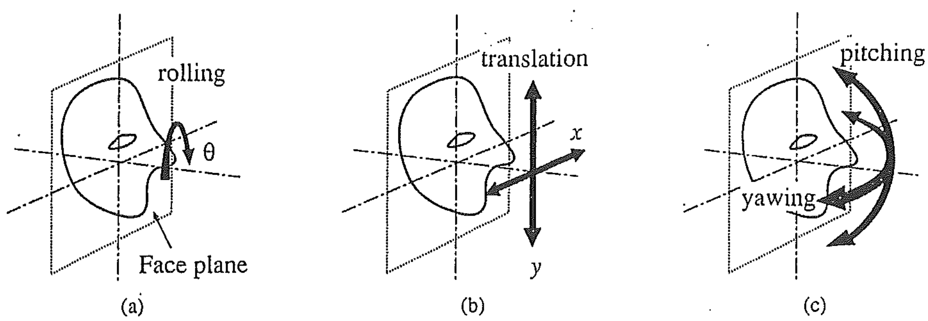


Fig. 3. Face DOFs. (a) A rotation in the face plane (rolling). (b) A translation in the face plane. (c) Pitching and yawing motions.

the appropriate direction, followed by turning on an additional knee switch to confirm the motion request.

In the endoscope-holding robot, EndoSista [11], commercially available from Armstrong Healthcare Ltd., High Wycombe, U.K., a face-rolling motion is used as a toggle switch to change the significance of the pitch motion [12]. At first, a nod motion (face pitching) indicates the camera tilt and a side-to-side head motion (face yawing) indicates the camera pan. After the surgeon makes a roll motion, a nod up indicates the camera retraction (image reduction) and a nod down indicates the camera insertion (image magnification). The surgeon can control the motion of the laparoscope by making such head gestures, in conjunction with a foot switch to avoid the execution of inappropriate input. In the latest version of EndoAssist [13], the foot switch is also used as a trigger instead of rolling the face, which changes the significance of the face-pitch motion.

D. Discussion

Face gestures are nonverbal and seem suitable for the precise control of scope motion. Furthermore, face gestures do not require the use of the hands or feet, and so they are convenient for the operating surgeon. The previous face motion-based laparoscope positioners, however, did not fully utilize the advantages of face gestures.

- They did not allow hands-free and feet-free laparoscopic operations. The surgeon was required not only to make the face gesture but also to control an additional foot or knee switch, which could confuse the surgeon.
- Although face gestures are nonverbal, typical head gestures were related only to several discrete commands (verbal texts) such as "zoom/tilt/pan the scope," which are inherently the same as voice-activated systems. While this approach is reasonable for discrete, high-level tasks, it is inappropriate for continuous low-level controls, such as the fine adjustment of laparoscopic positions.

To make the most of the merits of face gestures, we worked out a new laparoscope control scheme: FAce MOUSe.

E. FAce MOUSe

Fig. 4 illustrates the FAce MOUSe control scheme. As shown in Fig. 4(a), the state of the robotic laparoscope positioning system can be broken down into the following three states [17].

1) *SHIFT state: guiding the laparoscope for maintaining the surgical point of interest in the center of the video frame.* This state corresponds to pan and tilt camera functions.
2) *ZOOM state: guiding the laparoscope for providing the required target magnification.* This state corresponds to insertion and retraction camera functions.
3) *STILL state: keeping the laparoscope still.* This state means the surgical view is to be fixed.

All surgery work time can be classified into any of these states from the viewpoint of laparoscope operation.

Let us consider how to control not only the laparoscope motion itself but also the transition between these states by making face gestures only. We refer to the face motion for the transition state as the *Trigger Action*, and that for guiding the laparoscope as the *Guiding Action* [see Fig. 4(a)]. The method for positioning the laparoscope through face motions is summarized as follows.

Step 1) Make a Trigger Action to Change the STILL State to the SHIFT/ZOOM State: The thick solid lines in Fig. 4(a) correspond to this step. To complete the transition, the following three consecutive face motions are required [also see Fig. 4(b) and (c)]: 1) put the position and pose of the face in the standard position and pose; 2) roll the face counterclockwise (for *SHIFT*) or clockwise (for *ZOOM*); and 3) return the face "precisely" to the standard position and pose. Note that the surgeon cannot make this action unconsciously.

Step 2) Make a Guiding Action in the SHIFT/ZOOM State: The thick broken lines in Fig. 4(a) correspond to this step. Once the system comes into the *SHIFT* or *ZOOM* state, the face translation is represented as a vector from the standard position, and the direction and magnitude of the vector are, respectively, transformed into the direction and velocity of the laparoscope motion. As shown in Fig. 4(b), the face intuitively shifts parallel to the scope image plane, corresponding to the identical pan and tilt movements of the laparoscope when the state is *SHIFT*. On the other hand, when the state is *ZOOM*, the up and down movements of the face correspond to the zoom-out and zoom-in movements, respectively, of the laparoscope [see Fig. 4(c)].

Step 3) Make a Trigger Action to Change the SHIFT/ZOOM State to the STILL State: The thin solid lines in Fig. 4(a) correspond to this step. All the surgeon has to do is roll the face [see Fig. 4(b) and (c)]. As soon as the rolling motion is detected, the laparoscope motion stops and the state returns to *STILL*. Note that this action is very easy to do.

This control scheme is analogous to that of a computer mouse device (with two buttons), as shown in Fig. 5. Accordingly, this is why we called our scheme FAce MOUSe. *Guiding Action*, in which the 2-D translation in the face plane is dominant, corresponds to the mouse body movement on the mouse pad plane.

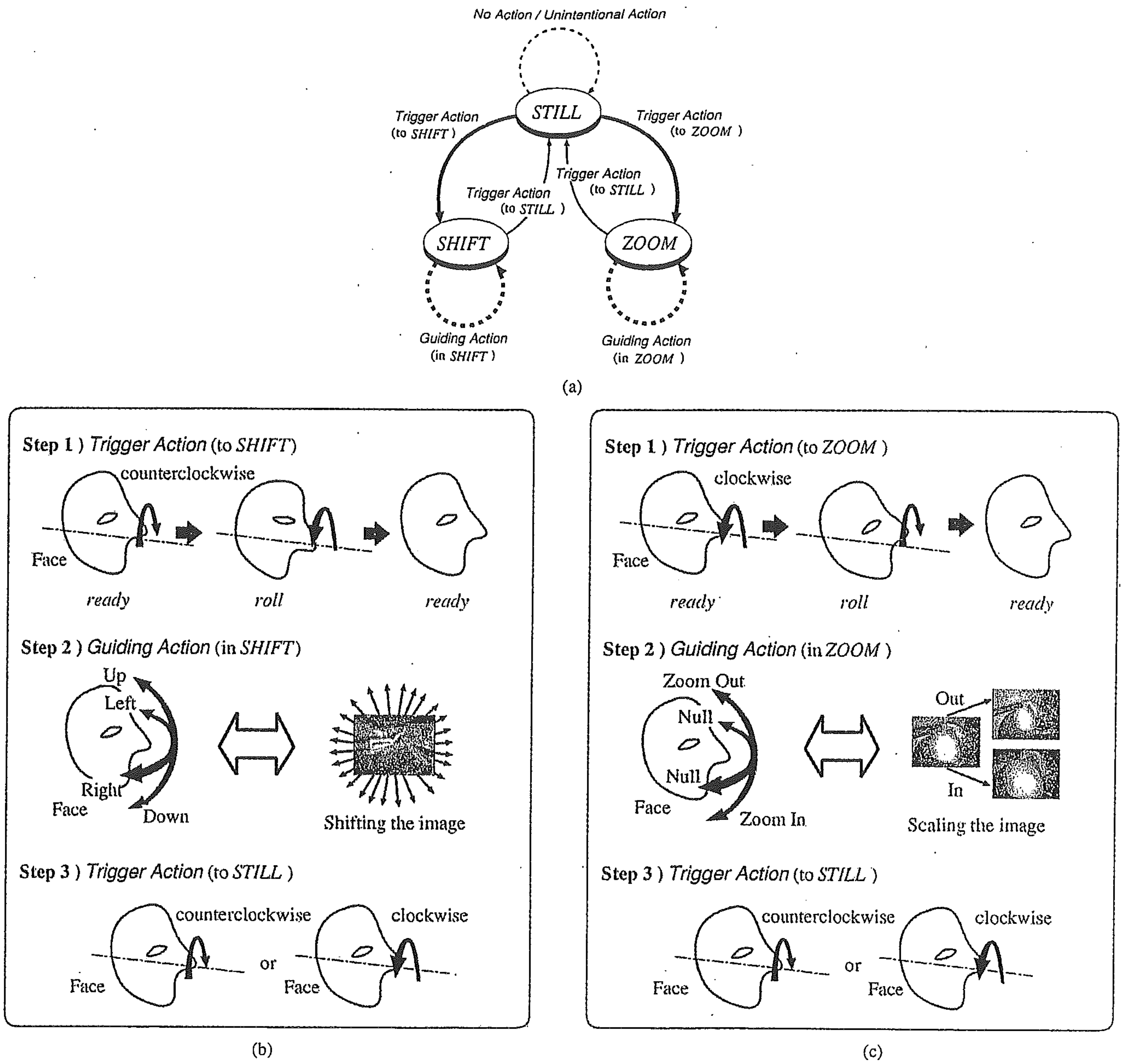


Fig. 4. FAce MOUSe control scheme. (a) State transition diagram. (b) Face motions for pan/tilt camera functions. (c) Face motions for scope insertion/retraction.

Trigger Action, in which the 1-D rotation in the face plane is dominant, corresponds to mouse button operations such as click (i.e., press and release the button). The correspondence between the *Guiding* and *Trigger Actions* and mouse device operation is summarized in Table I.

Our FAce MOUSe control scheme is based on the nonverbal aspect of human gestures and provides the surgeon with a means of total hands-off and feet-off laparoscope operations, while also achieving rapid reaction and high positioning accuracy. To maintain high levels of "safety" during surgery, however, we must note the following two points.

- Without exception, unintentional movements, which could be misunderstood as *Trigger Action* (to *SHIFT*) or *Trigger Action* (to *ZOOM*) in the *STILL* state, should be avoided.
- *Trigger Action* (to *STILL*) should be definitely and immediately recognized in the *SHIFT/ZOOM* state.

We performed a successful FAce MOUSe implementation by paying great attention to these points.

III. Implementation

A. FAce MOUSe System Overview

We designed a novel human–machine interface for controlling the laparoscope with the above method. The system configuration and overview are shown in Fig. 6. Our laparoscope positioning system, the FAce MOUSe system, consists primarily of a charge-coupled device (CCD) camera placed just over the TV monitor, an all-purpose PC (CPU: Intel Pentium III, 600MHz, OS: Vine Linux 2.0) with a video-capturing device, a robot manipulator that holds the laparoscope, a scan converter for superimposing graphics on the scope image, and a foot switch [see Fig. 6(a) and (b)]. For face tracking, we used a commercially available zoom camera, Sony EVI-D30, whose

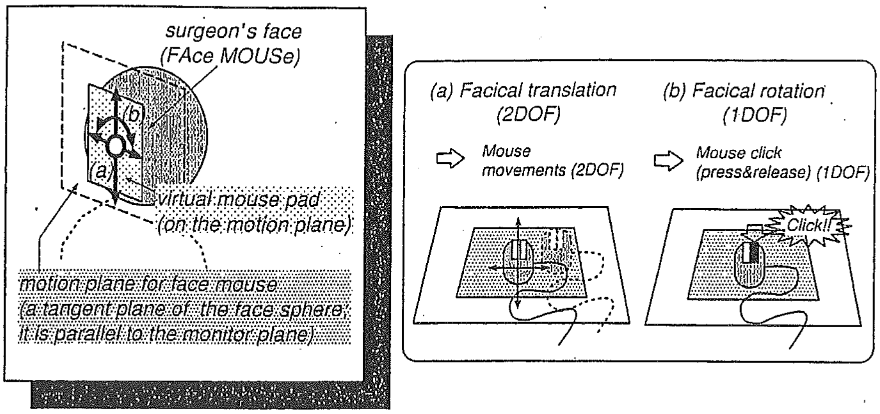
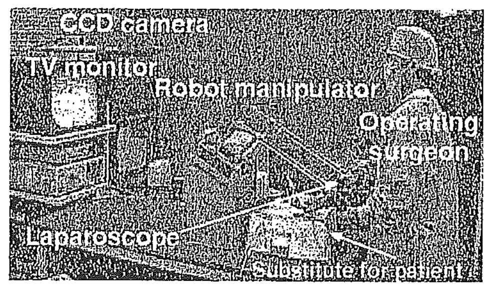


Fig. 5. Analogy between facial motion and mouse operation.

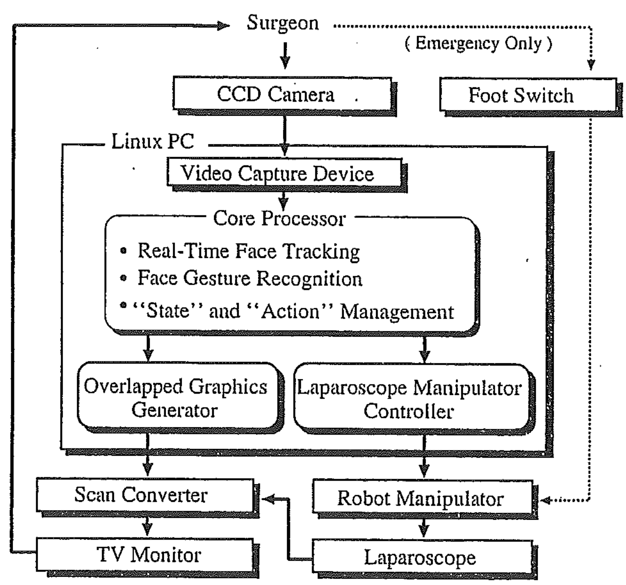
TABLE I
CORRESPONDENCE BETWEEN GUIDING/TRIGGER ACTIONS AND MOUSE DEVICE OPERATIONS

FAce MOUSe	Computer mouse device
Trigger Action (to *SHIFT*)	Click the left button
Trigger Action (to *ZOOM*)	Click the right button
Trigger Action (to *STILL*)	Press the left/right button
Guiding Action	Slide the mouse body on the pad

pan/tilt/zoom can be controlled manually using an infrared (IR) remote commander. A systematic calibration process is not necessary; all one needs to do before using the FAce MOUSe interface during surgery is to use the remote commander to roughly adjust the camera parameters so that the surgeon's face is near the center of the video image and the projection size is appropriate. Once the camera is set in the appropriate position and pose, the core system in the PC can detect and track the surgeon's facial features in real time (30 Hz) from a sequence of video images captured through the CCD camera. Assuming that the surgeon's face is moving on a virtual plane parallel to the TV monitor screen (that is, the surgeon's face has only three DOFs), the system estimates the position and pose of the surgeon's face in real time from the image-processing result and then recognizes the surgeon's facial gestures (i.e., the *Trigger* and *Guiding Actions*). According to the state of the system and the gestural action recognition result, the control command is sent to the laparoscope manipulator. The kinematic mechanism of this manipulator was inspired by and is similar to that used in the LARS surgical robot designed by Taylor *et al.* [3]. As shown in Fig. 7, our manipulator has a planar double-parallelogram mechanism (two DOFs) and a ball-screw mechanism (one DOF). The planar double-parallelogram mechanism allows movements only around an arc whose center is the point of trocar insertion, which corresponds to the pan and tilt scope motions and produces a translation of the patient's body image on the monitor screen, with respect to the surgeon's reference work frame. The ball-screw mechanism enables translation along the longitudinal axis of the laparoscope, which corresponds to the zoom-in and zoom-out motions and produces a magnification or reduction of the visualized laparoscopic field. The system state and image-processing results are also superimposed graphically on the laparoscope image using a scan converter (as feedback information for the surgeon), and



(a)



(b)

Fig. 6. FAce MOUSe system configuration. (a) System overview. (b) Hardware components.

the resulting image is displayed on the TV monitor. In the current version, an emergency foot switch for stopping a scope movement is also provided, but there has been no need to use it.

B. *Software Components Overview*

Fig. 8 shows the overview of the FAce MOUSe software system. The following three processes run on the main computer: FAce MOUSe core process (CORE), overlapped graphics generator (OGG), and laparoscope manipulator controller (LMC).

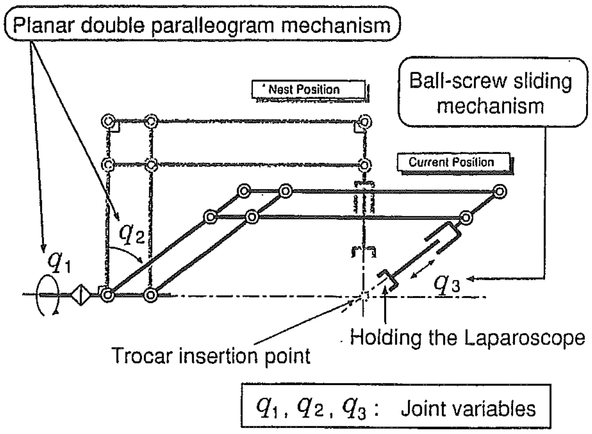


Fig. 7. Mechanism of laparoscope manipulator.

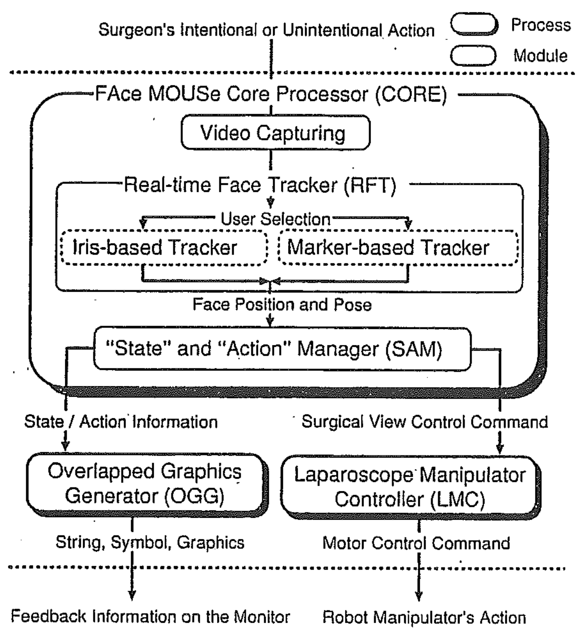


Fig. 8. FAce MOUSe software components.

The CORE process mainly consists of the following two software modules: real-time face tracker (RFT) and state and action manager (SAM). The RFT module detects and tracks the surgeon's facial features in real time from the image sequence captured through the surgeon-surveillance CCD camera. The SAM module manages the state of the laparoscope manipulator and the surgeon's facial actions, based on the time sequence of the position and pose coming from the RFT module. As a result, the CORE process generates the surgical view control command and outputs it to the LMC process while sending the state and action information to the OGG process.

The OGG process outputs feedback information for the surgeon graphically on the PC display, and the resulting image (graphics) is synthesized with the laparoscopic image signals using the scan converter.

The LMC process converts the surgical view control commands to motor control commands and then drives the robot manipulator.

In Sections III-C–E, we will explain each software component in more detail.

C. *FAce MOUSe Core Process (CORE)*

1) Real-Time Face Tracker (RFT): During surgery, the laparoscopic surgeon usually wears a gown, cap, and mask, so that almost all facial features, such as the mouth, nose, and hair do not appear in the surveillance image. Taking this into account, we developed two robust, RFTs: an iris-based tracker and a marker-based tracker. The iris-based tracker extracts, at most, two black circular shapes, which are the surgeon's irises, from the surveillance image using simple thresholding and the Hough transformation technique. The marker-based tracker uses simple thresholding and a conventional labeling algorithm to detect and track a black rectangular marker attached to the surgical cap in advance. Although the iris-based method requires careful selection of the thresholding and Hough transformation parameters according to illumination conditions or individual variations of the visible size of the irises (the irises are partially occluded by the eyelid), there is no difference in the tracking performance between the two face trackers. Both trackers can work at a frequency of 30 Hz. The details of these face-tracking methods can be found in [18]. Assuming *distance-constant and fronto-parallel interaction* (described in Section II-B), the system estimates the position and pose of the surgeon's face in real time from the image-processing result. When using the iris-based tracker, the midpoint of the line segment joining the centroids of the left and right irises is known as the position of FAce MOUSe, and the angle between this line segment and the horizontal axis of the image (i.e., the x axis) is known as the pose of FAce MOUSe [see Fig. 9(a)]. When using the marker-based tracker, the centroid of the marker and the angle between the principal axis of inertia of the marker region and the image x axis are regarded as the position and pose of FAce MOUSe, respectively [see Fig. 9(b)]. As shown in Fig. 8, the surgeon can select either tracker in advance as the FAce MOUSe tracker (in the current version, we cannot use both trackers simultaneously).

In actual practice, it could be difficult sometimes to set the TV monitor just in front of the operating surgeon due to the presence of other surgical equipment in the operating room. Furthermore, because we did not require a precise setting of the face-tracking camera, affine distortion of the face plane, the image plane and the TV monitor plane could result. Nevertheless, our system works well because we utilize the relative displacement (deviation) of FAce MOUSe, not the absolute coordinates, and the surgeon can always monitor the relative change of the detected face position and pose by checking the indicator superimposed on the TV monitor (even if distortion exists, the surgeon can flexibly adjust his/her face motion). For details, see Sections III-C.2 and D.

2) State and Action Manager (SAM): The software module SAM recognizes the surgeon's face gestures based on the time sequence of the position and pose of FAce MOUSe, and controls the state of the laparoscope manipulator. We will first define the three virtual mouse pads and two special states of FAce MOUSe.

Three virtual mouse pads (see Fig. 5): We denote the three rectangular regions, which correspond to *virtual* mouse pads superimposed on the face motion plane, as D_{ready}, D_{trigger}, and D_{guiding} ($D_{\mathrm{ready}} \subset D_{\mathrm{trigger}} \subset D_{\mathrm{guiding}}$). D_{ready} indicates the standard position of FAce MOUSe. D_{trigger} and D_{guiding} are

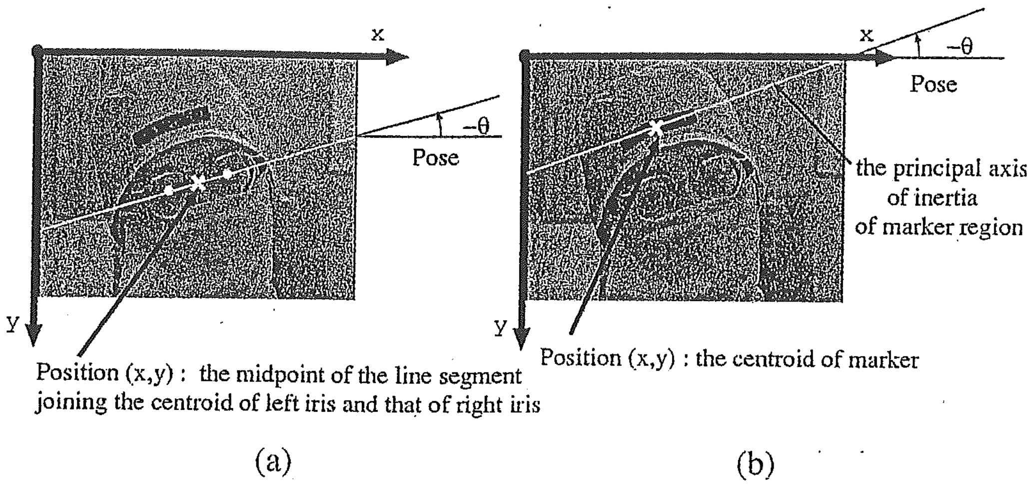


Fig. 9. Estimating the position and the pose of the surgeon's face. (a) Iris-based method. (b) Marker-based method.

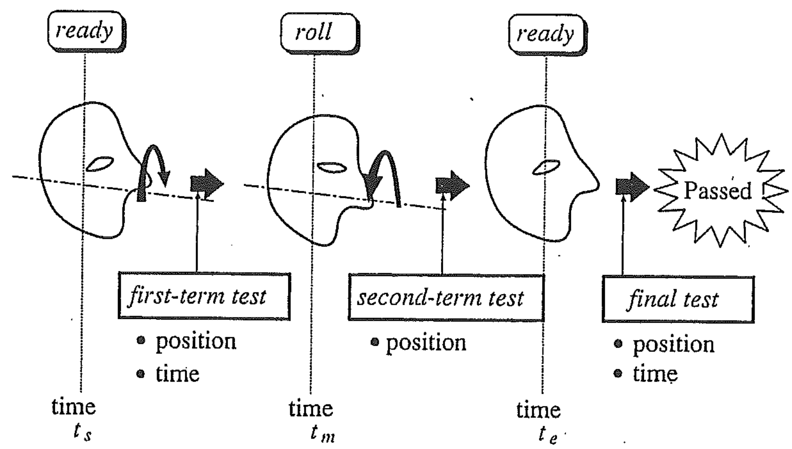


Fig. 10. Recognition process of *Trigger Action*.

the virtual mouse pads for *Trigger Action* and *Guiding Action*, respectively. As an example, the *Guiding Action* must be made within the region D_{guiding}.

Two special states of FAce MOUSe: Let $(x(t), y(t))$ and $\theta(t)$ be the position and pose, respectively, of FAce MOUSe coming from the RFT module at time t. For convenience, we define the following special states of FAce MOUSe.

- *ready* state:
  The state of FAce MOUSe is referred to as "*ready* at time t" if both $(x(t), y(t)) \in \mathcal{D}_{\text{ready}}$ and $|\theta(t)| < \theta_{\text{flat}}$.
- *roll* state:
  The state of FAce MOUSe is referred to as "*roll* at time t" if both $(x(t), y(t)) \in \mathcal{D}_{\text{trigger}}$ and $|\theta(t)| \geq \theta_{\text{roll}}$.

θ_{flat} and θ_{roll} indicate the thresholds for restricting the pose of FAce MOUSe and $0 \leq \theta_{\text{flat}} \leq \theta_{\text{roll}}$ (in practice, $\theta_{\text{flat}} = 2°$, $\theta_{\text{roll}} = 12°$).

The process in the SAM module varies with the state of the laparoscope manipulator, as follows.

a) *The case where the state of the laparoscope manipulator is STILL.*

The system regularly checks whether the state of FAce MOUSe changes to *ready*. The following special process is executed just after the *ready* event occurs (at most, this process occurs during the 5 s period T_{max}, which will be defined below). Let t_s be the time when the *ready* transition event has occurred. If the FAce MOUSe state changes to *roll* at time $t = t_m (> t_s)$ while passing the *first-term test*, and if it returns to *ready* at time $t = t_e (> t_m)$ while passing the *second-term test*, and if the *final test* is also passed, then the face action during time $[t_s, t_e]$ is regarded as a *Trigger Action* (see Fig. 10), and the state of the laparoscope manipulator is changed according to the rolling motion angle at time $t = t_m$: the state is changed from *STILL* to *SHIFT* if $\theta(t_m) > 0$, or *STILL* to *ZOOM* if $\theta(t_m) < 0$. The details of the above three-term tests are the following.

- The *first-term test* (from *ready* to *roll*)
  The following conditions must be satisfied simultaneously:

$$(x(t), y(t)) \in \mathcal{D}_{\text{trigger}} \text{ during } t = [t_s, t_m) \quad (1)$$

$$t_m - t_s < T_{\text{stay}}. \quad (2)$$

- The *second-term test* (from *roll* to the second *ready*)
  The following condition must be satisfied:

$$(x(t), y(t)) \in \mathcal{D}_{\text{trigger}} \text{ during } t = [t_m, t_e). \quad (3)$$

- The *final test.*

  The following conditions must be satisfied simultaneously:

$$|x(t_e) - x(t_s)| \le \varepsilon_x \quad (4)$$
$$|y(t_e) - y(t_s)| \le \varepsilon_y \quad (5)$$
$$t_e - t_s < T_{\max} \quad (6)$$

  where ε_x and ε_y indicate predetermined positive constants. T_{stay} and $T_{\max}$ are the thresholds for restricting the time for action, and $T_{\text{stay}} < T_{\max}$ (in practice, $T_{\text{stay}} = 2$ s, $T_{\max} = 5$ s).

b) *The case where the state of the laparoscope manipulator is SHIFT/ZOOM.*

If either the condition

$$(x(t), y(t)) \notin \mathcal{D}_{\text{guiding}} \quad (7)$$

or the condition

$$|\theta(t)| \ge \theta_{\text{roll}} \quad (8)$$

is satisfied, then the system considers the surgeon's face action as a *Trigger Action* and changes the state of the laparoscope manipulator to *STILL* while sending the 3-D vector $\mathbf{0} = (0, 0, 0)^T$ (indicating the stop of laparoscope motion) to the laparoscope manipulator controller (LMC). Otherwise, the system regards the surgeon's facial gestures as a *Guiding Action* and calculates the face deviation vector $\boldsymbol{x}(t)$ as

$$\boldsymbol{x}(t) = (x(t) - x_{\text{origin}}, y(t) - y_{\text{origin}})^T \quad (9)$$

where $(x_{\text{origin}}, y_{\text{origin}})$ indicates the position of FAce MOUSe just after the state of the laparoscope manipulator changes from *STILL* to *SHIFT/ZOOM*. Then, the system outputs the deviation vector $\boldsymbol{x}(t)$ to the overlapped graphics generator (OGG) as one portion of the feedback information for the surgeon, while sending the following 3-D vector to the LMC process as the surgical view control command:

$$\boldsymbol{v}(t) = \begin{cases} (\boldsymbol{x}(t)^T, 0)^T, & \text{if the state is } SHIFT \\ \left(0, 0, \boldsymbol{x}(t)^T \begin{pmatrix} 0 \\ 1 \end{pmatrix}\right)^T, & \text{if the state is } ZOOM. \end{cases} \quad (10)$$

The first and second elements of the command vector $\boldsymbol{v}(t)$ correspond to the horizontal and vertical components of the view shifting velocity, while the third element indicates the view scaling velocity along the optical axis.

3) Consideration of Safety: Our implementation takes surgery safety into account. Basically, *Trigger Action* (to *SHIFT/ZOOM*), representing a left/right click of the mouse, is made by changing the state of FAce MOUSe from *ready* to *roll* and by returning to *ready*, as shown in Fig. 10. Notice that the *ready* state is natural for the surgeon. Therefore, FAce MOUSe may often change to the *ready* state by the surgeon's unintentional movements. But, in such a case, it would be very rare to pass the *first-term test* because the *roll* state requires the surgeon to make unusual movements. On the other hand, when the surgeon feels fatigue or doubt, the angle of the head may indicate a slight leaning. In the current implementation, the system cannot recognize such fatigue or doubt signs. As a result, the system may regard this natural leaning of the surgeon's head as a *roll* gesture. Even in this case, it is very difficult to pass all three tests. Especially, such nonmanipulative gestures do not seem to satisfy the final conditions (4)–(6), which require the surgeon to make the fast and fine positioning of FAce MOUSe.

Compared with *Trigger Action* (to *SHIFT/ZOOM*), it is much easier to make *Trigger Action* (to *STILL*) in the *SHIFT/ZOOM* state. All the surgeon has to do is satisfy (7) or (8). This provides the means for a rapid stop of laparoscope movements. Although unintentional movement may infrequently satisfy these conditions, a high level of safety can be maintained because this type of misunderstanding only results in stopping of the scope movement.

D. Overlapped Graphics Generator (OGG)

The OGG process assists the surgeon in making the appropriate face gesture by transforming the following information, which comes from the SAM module in the CORE process, into strings, or symbols, or graphics.

1) The state of the laparoscope manipulator as a string. According to the state of manipulator, one of three strings ("Still," "Shift," or "Zoom") is superimposed at the top center of the laparoscope image.
2) The state of FAce MOUSe as a string.

   In the current version, when the state of the laparoscope manipulator is *STILL* and the state of FAce MOUSe is *ready*, the string "Ready" is displayed at the top-center position, instead of the string "Still". Furthermore, the string "Stillhold" is output at the same position when the time constraint (2) or (6) is violated.
3) The position and pose of FAce MOUSe and the virtual mouse pad as graphics.

   The FAce MOUSe position (x, y) and pose θ and the virtual mouse pad (either $\mathcal{D}_{\text{ready}}$, $\mathcal{D}_{\text{trigger}}$, or $\mathcal{D}_{\text{guiding}}$), which are graphically represented in Fig. 11, are displayed at the top-left corner of the monitor screen. The kind of virtual mouse pad is automatically selected according to the state of the laparoscope manipulator.
4) The face deviation vector $\boldsymbol{x}(t)$ as a symbol.

   The face deviation vector $\boldsymbol{x}(t)$ is drawn as a vector at the center of the laparoscope image when the state of the laparoscope manipulator is *SHIFT* or *ZOOM*.

Examples of OGG outputs overlaid on the laparoscopic image are shown in Fig. 12.

E. Laparoscope Manipulator Controller (LMC)

The LMC process transforms the view control command vector $\boldsymbol{v}(t) = (v_1, v_2, v_3)^T$ (10) into the motor control command $\dot{\boldsymbol{q}}(t) = (\dot{q}_1, \dot{q}_2, \dot{q}_3)^T$ as follows:

$$\text{For } i = 1, 2, 3: \dot{q}_i = \begin{cases} K_i v_i, & \text{if } v_i > \epsilon_i \\ 0, & \text{if } v_i \le \epsilon_i \end{cases} \quad (11)$$

where $q_i (i = 1, 2, 3)$ indicates the joint variable of the 3-DOF laparoscope manipulator shown in Fig. 7. K_i indicates a proportional constant and ϵ_i is an infinitesimal value. By filtering using ϵ_i, the sway caused by unintentional body movements or

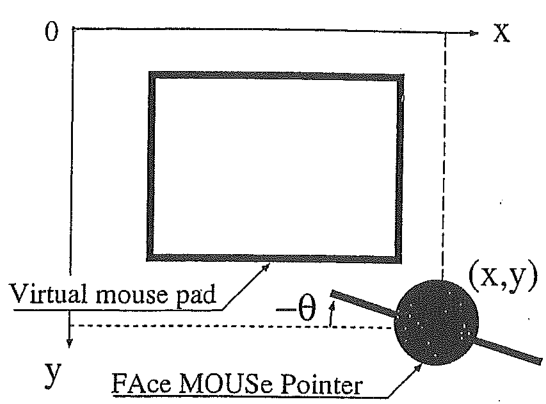
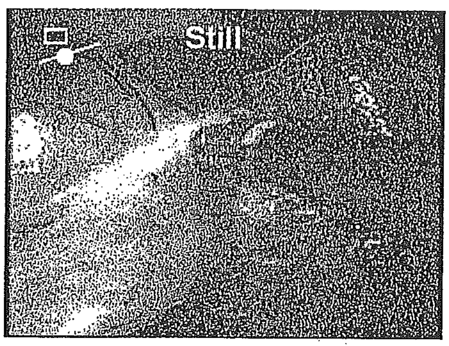
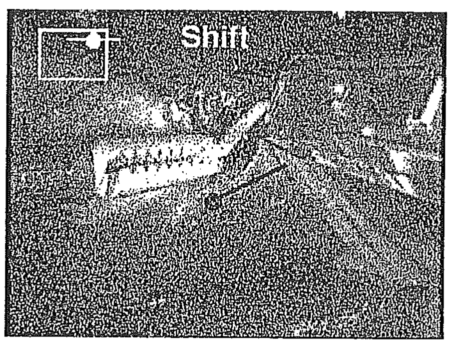


Fig. 11. Graphical representation of FAce MOUSe and virtual mouse pad.



(a)



(b)

Fig. 12. Examples of feedback information overlaid on the laparoscopic image.

image noise can be eliminated, and also the surgeon can easily stabilize the motion of the laparoscope.

Our FAce MOUSe system is applicable to other types of laparoscope manipulators or other medical robots by simply rewriting (11) according to the robotic kinematics. Please note that, in our case, this transformation equation is very simple due to the remote-center-of-motion mechanism in which the motions of all axes are kinematically decoupled at the insertion point.

IV. Experiment

To evaluate the performance of our system, an experiment was first conducted under laboratory conditions using a conventional laparoscopic surgical training box and standard laparoscopic equipment (all from Olympus Optical Co. Ltd, Tokyo, Japan). Next, an *in vivo* experiment was carried out, in which a surgeon used our system in a conventional laparoscopic operating room environment and a regular set of instruments (also all from Olympus Optical Co. Ltd) to perform a laparoscopic cholecystectomy on a pig.

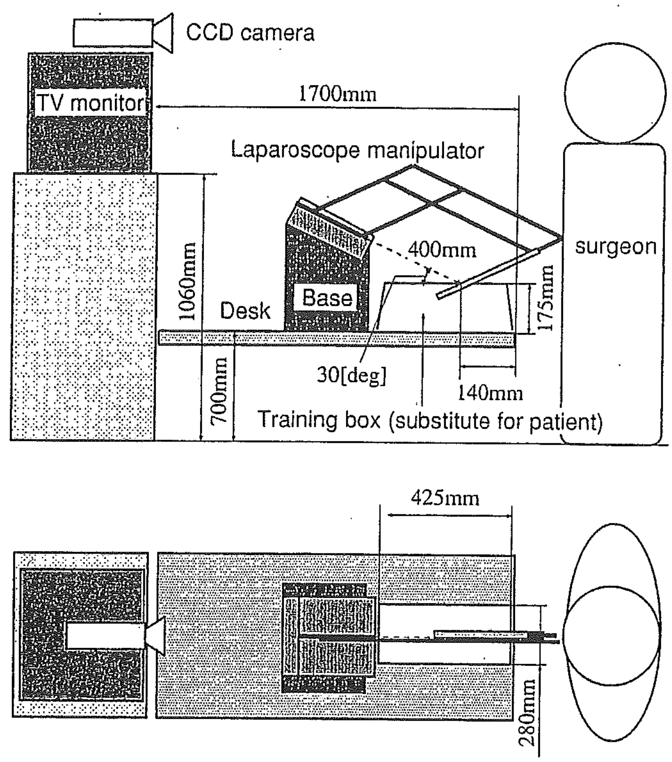


Fig. 13. Setup of laboratory experiment.

A. Laboratory Experiment

The following two tasks were used to evaluate the basic performance of our system: 1) directing the scope along a 25-cm rope (for evaluating scope movements in the *SHIFT* state) and 2) magnification of a 10-mm ball (for evaluating scope motion in the *ZOOM* state). Note that these tasks did not require a surgical operation or surgical instruments, such as forceps and scalpel. This experiment involved three subjects (named A, B, C). Subject A was familiar with the FAce MOUSe interface but the other two subjects had never used the system before. A schematic representation of the experimental setup is shown in Fig. 13 (see Fig. 6(a) also).

1) Task 1: The 25-cm rope was placed in the training box so that it formed a shape like a reversed "S" [see Fig. 14(a)]. The rope contained 10 knots at 20-mm intervals. The visual field of the camera was displayed on a 400 × 300-mm monitor, and a 40-mm circular mark was put on the screen. The three subjects were asked to direct the scope from one end of the rope to the other, such that the 10 knots passed through the circular mark in order and, at the end, the rope tip was at the center of the mark. A referee measured the time taken to complete the task with a stopwatch and recorded the distance between the center of the mark and the end point of the rope on the display screen, as a measure of positioning accuracy. This procedure was repeated for 10 consecutive trials per subject.

The times for task completion and the final positioning errors for each trial are plotted in Fig. 15(a) and (c), where the three

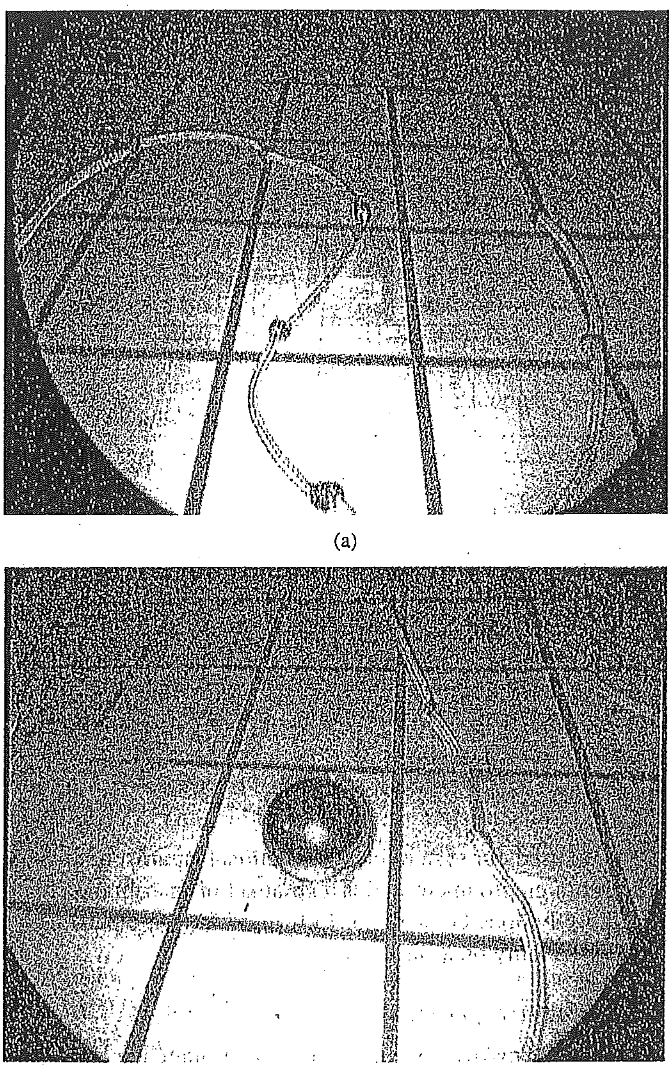


Fig. 14. Examples of laparoscopic images taken at the laboratory experiment. (a) A 25-cm rope with 10 knots. (b) A 10-mm metallic ball.

curves correspond to the three subjects A, B, and C. The overall mean time for task completion was 45 s. The improvement in speed due to learning between trial 1 and trial 10 was about 42% of the initial trial time (the mean time for trial 1 was 62 s; for trial 10, it was 36 s). The mean and maximum positioning errors were 4.8 mm and 12 mm, respectively, which corresponded to 0.97% and 2.4% of the diagonal length of the monitor screen.

2) Task 2: A 10-mm metallic ball was placed in the training box [see Fig. 14(b)] and initially the laparoscope was set so that the display size of the ball was 30 mm. Also, a 100-mm circular mark was put on the monitor. The three subjects were asked to magnify the ball so that its size was consistent with the size of the mark. A referee measured the task completion time and recorded the final display size of the ball as a measure of accuracy. This was repeated for 10 consecutive trials per subject.

The task completion times and the accuracy measures at each trial are plotted in Fig. 15(b) and (d). The learning curve for Task 2 is almost flat, while the Task 1 curve does not level off within ten trials. This happened because Task 2 was simpler than Task 1, in which the subject had to make a variety of face motions. The overall mean time for task completion was 18 s. The mean and maximum positioning (magnification) errors were 1.3 an 5 mm, respectively (i.e., 1.3% and 5% of the target size).

3) Summary of Results: In all of the tests, we did not fin any case in which our system was misguided. All subject performed both tasks correctly and nonstop for all trials. Thes experimental results demonstrate the effectiveness of FAc MOUSe, such as easy camera guidance and high positionin accuracy. Notice especially that it is very difficult to us the conventional head navigation systems or voice-activate systems to perform nonstop pan and tilt scope operation along a complex, curved path, as used in Task 1. Although on of the subjects was familiar with our system, there were n differences in task time and error among the three subjects.

B. In Vivo Experiment

In the above laboratory experiment, the use of surgical instruments was not included in the assessment tasks. In using ou system to perform a real operation, however, the surgeon woulc have to make face gestures while also precisely controlling surgical tools with his/her hands and/or foot. Fatigue caused b much longer operation times (than those for Task 1 and Task 2) may have a negative influence on face motions. Furthermore the surgeon may sometimes move his/her face in an extreme anc unintentional manner because of tool extraction or insertion, o conversation with another person in the operating room. Even in these cases, the system should maintain a high level of safety To evaluate the applicability of our system to clinical use, an *in vivo* laparoscopic cholecystectomy was performed on a pig.

1) Experimental Setup: A schematic representation and photograph of the *in vivo* experimental setup are shown in Fig. 16. Four insertion holes were made on the abdominal wall of the pig prior to the surgical operation. In the Fig. 16 schematic representation, L and R indicate the trocar points for instruments used by the surgeon, C indicates the insertion point for the laparoscope, and A indicates the insertion position of additional instruments. After trocar insertion, the laparoscope manipulator was mounted on a holder hanging over the surgical table, on which the pig was already in place. The laparoscope manipulator was positioned precisely so that its remote rotation center was consistent with trocar point C (see Fig. 7). The setup time for the manipulator was about 20 min. Instead of a human camera assistant, the system was used for the entire procedure until the removal of the gallbladder.

In addition to the operating surgeon and robotic camera assistant, another surgeon took part in the laparoscopic cholecystectomy experiment as an assistant. He undertook the responsibility of lifting up the liver, which was hanging over the gallbladder to be removed. He performed this task only by supporting the liver with an additional instrument inserted through trocar point A. Incidentally, this task could be performed without an assistant surgeon by introducing a passive instrument holder (see [15] for an example). Therefore, the operating surgeon was in a situation similar to solo surgery.

2) Results: The entire operative procedure was successfully and safely completed with our system. No one used the emergency footswitch for shutting down the system. The number of lens cleanings was also zero. The operating time inclusive from trocar insertion until the removal of the gallbladder was about

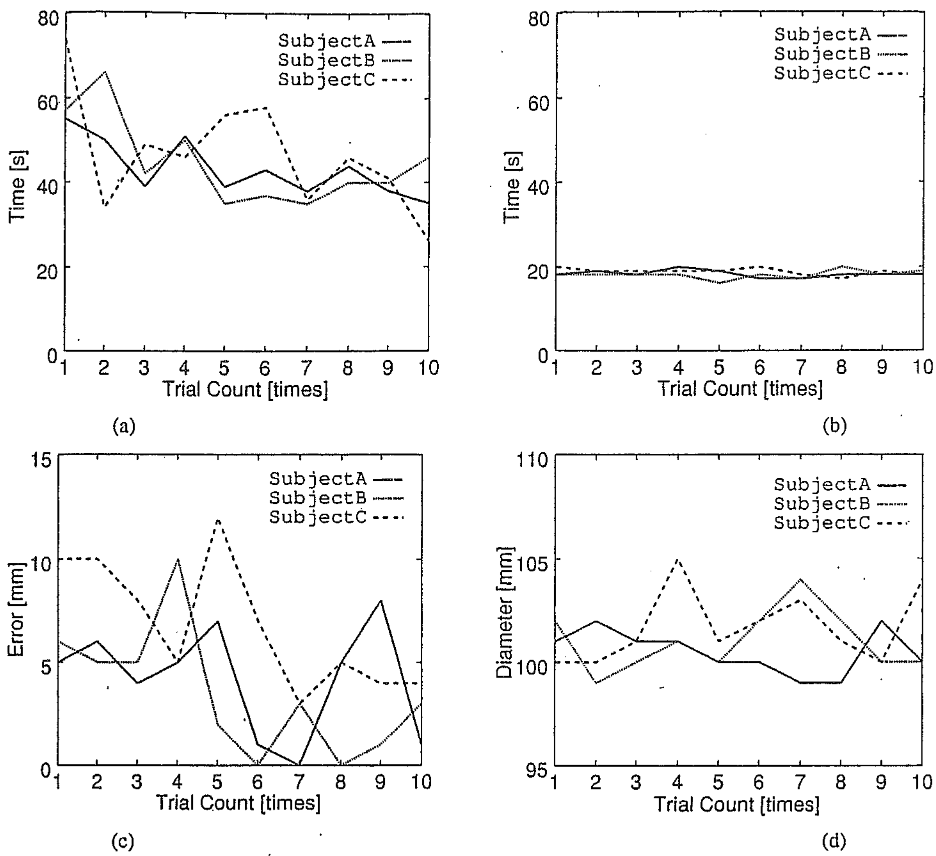


Fig. 15. Results of laboratory experiment. (a) Time to complete Task 1. (b) Time to complete Task 2. (c) Positioning accuracy in Task 1. (d) Positioning accuracy in Task 2.

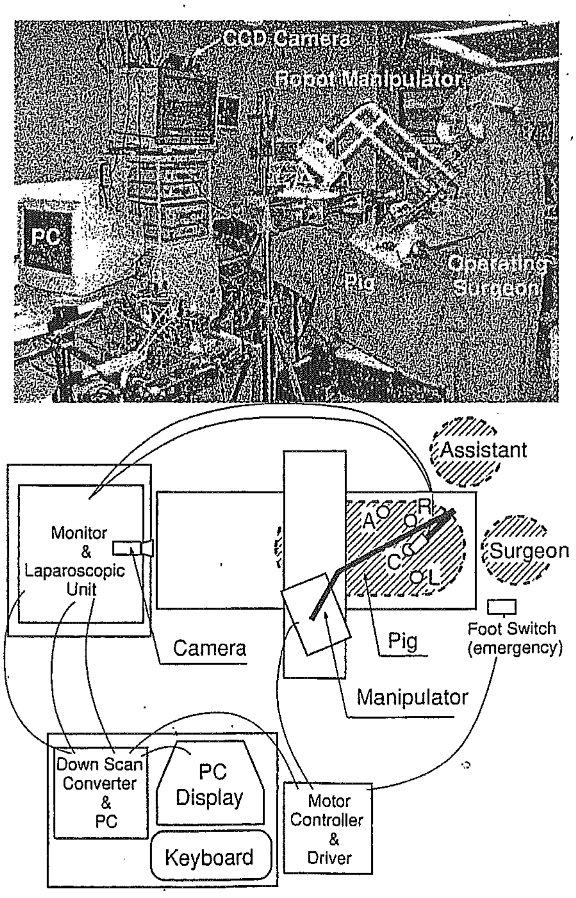


Fig. 16. Setup of *in vivo* experiment.

44 min (2642 s), which was broken down into 2113 s (80.0%) for the *STILL* state, 311 s (11.8%) for the *SHIFT* state, and 218 s (8.2%) for the *ZOOM* state. The number of state transitions for *STILL* → *SHIFT* and *STILL* → *ZOOM*, and vice versa, were 40 and 50, respectively. In this experiment, the robot never obstructed the surgeon's work, and worrisome incidents and technical problems did not occur. Fig. 17 shows scenes of the surgeon's facial motions in the experiment. The upper part of Fig. 17 consists of the scope images which the surgeon looked at; the lower part consists of the images of the surgeon's face from the surveillance camera. Each pair of images was taken at the same time.

The number of times during the operation that the surgeon made a *Trigger Action* to the system to drive the laparoscope manipulator (i.e., Step 1 of Fig. 4) was 97 times, which breaks down into 90 times for being recognized correctly by the system and seven times for not being recognized correctly. Although 252 *ready* transitions (including the intentional 97 transitions) were observed in the *STILL* state, the system never mistook any other motion of the operating surgeon or any other surgeon who was present during the experiment. (e.g., see the second, third, and fourth images of Fig. 17, which show a surgeon walking behind the operating surgeon.) This result demonstrates that our face-gesture recognition algorithm in the SAM worked well.

The number of times that the surgeon made face gestures to stop the laparoscope motion (i.e., Step 3 of Fig. 4) was 90 and these were all correctly recognized. We received many positive comments, such as fast reaction time, high positioning accuracy,