学　位　論　文　内　容　の　要　旨

博士の専攻分野の名称　　博士（情報科学）　　氏名　海老名　光希

学　位　論　文　題　名

Development of machine learning-based skill assessment system for laparoscopic surgery using motion-capture

（モーションキャプチャを用いた腹腔鏡手術のための機械学習による技量評価システムの開発）

Laparoscopic surgery has become widespread due to its minimal invasiveness to the patient. However, the difficulty of surgery, such as limited visual information and inconsistent hand-eye coordination, makes it difficult to aqquire the technique quickly. Moreover, the recent restriction of working hours and shortage of surgeons have resulted in insufficient training time, and the establishment of efficient training methods and objective surgical skill analysis is becoming urgent. Therefore, this study developed the motion capture (MoCap) based surgical instrument measurement system and established the automatic skill assessment system.

By attaching individual pattern marker sets, this system can measure the movement of multiple surgical instruments simultaneously, and the grasping force/position on the grasper was also measured with the instrument movement. The validation experiment confirmed that this system can measure surgical training with sufficient accuracy for skill analysis (within 1 mm positional error). Through measurement experiments in wet-lab training, 144 cases of the lymphadenectomy and the renal parenchyma suturing were recorded. This study also developed the measurement system for practical surgical training, where there are many obstacles. The validation experiment confirmed that the developed system has sufficient measurement accuracy (approximately 2 to 4 mm error depending on the instrument). Using the developed system, measurement experiments were conducted on 43 cases of laparoscopic radical nephrectomy in cadaveric surgical training, and it was confirmed that the system could measure with a high measurement success rate of more than 90%. To improve the measurement stability, the hybrid measurement system consisting of MoCap system, inertial measurement unit (IMU) and distance sensor was also developed and its accuracy was investigated.

Based on the measurement data of wet-lab training, the skill analysis was conducted. Some kinematic indices representing the motion characteristics were calculated, and principal component analysis was performed. The automatic feature calculator, tsfresh, was also used in the analysis. The analysis result showed that in addition to the operational efficiency and velocity-related factors, vibration, complexity of operation, and irregular motion were also involved in the skill differences. The skill analysis on the grasping force measurement also indicated that the stability of the grasping force and the overexert at the beginning of the task contributed to the skill difference.

The machine learning-based surgical skill assessment system was developed. The classification model and the regression model based on the total score of global operative assessment of laparoscopic skills (GOALS), which is one of the surgical skill assessment metrics, were constructed. Model validation showed that this system can assess surgeon skill with a median accuracy of 75.0% (classifica-

tion) and MAE_{median} = 2.36 (regression) for the lymphadenectomy task, and 85.5% (classification) and MAE_{median} = 1.13 (regression) for the suturing task. By combining the evaluation models with SHAP, one of the explainable artificial intelligence (AI) methods, an automatic surgical skill feedback system was developed. The system can provide the surgeon with a GOALS score, a three-level evaluation, and automatically generated comments on the basis of the evaluation. Explainable AI was also applied to skill analysis, which revealed the factors that most contributed to skill differences among the indices generated by the automatic feature calculator. The result of the analysis showed that operation stability and efficiency mainly contributed to the lymphadenectomy task, and the path length of both hands and the vibration of the left hand were especially important in the suturing task.

This study verbalized the surgical skills of expert surgeons, and developed the skill assessment system which provides quantitative and concrete feedback immediately after surgical training.