Intro duction to the Mobile Robotics Lab
(OTA Lab)
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Research Topics (OTA Lab)

We have been studying multiple mobile robot systems since 1989. We consider intelligent systems as consisting of three factors: (a) multiple robots or intelligent machines (multiple agents), (b) human-beings who operate or cooperate with multiple agents, and (c) working environments. Now we deal with "design of robotics system", "design of large-scale production/transport systems", and "human analysis, service, and hyper-adaptability science" based on motion planning methodology, evolutionary computation, control theory, and so on. Our final target is to establish design methodology of multi-agent systems including artificial agents, humans and working environments through clarifying the underlying structure and function in the intelligence and mobility (mobiligence) of these agents.

Robot system design

- Learning difficult robot motion from human demonstration collected via a single RGB camera
- Automatic action recognition algorithm for industrial manual workers with human skeleton and object information
- Measurement Pose Optimization for Joint Offset Calibration with a Hand-Eye Camera
- Robot System Arrangement Using Experience-based Hierarchical Optimization Methods

Design and management of large-scale production, transport systems, and plants

- Off-line task assignment and motion planning algorithm considering agent's dynamics
- Development of Virtual Reality System for Identification of Specific Expert Skills in Refinery Inspection Task with Explainable AI
- A Framework to Support Failure Cause Iden6fica6on in Manufacturing Systems through Generalization of Past FMEAs

Human analysis, service, and the science of hyper-adaptation

- Development of a Nursing Skill Training System Based on Manipulator Variable Admittance Control
- Analysis of the relationship between DAT-SPECT and motor symptoms using machine learning
- Modeling of human gait and gait initiation
- Evaluation of changes over time in stance postural control mechanisms in stroke patients
- Modeling of standing postural control in Parkinson's disease patients

Learning difficult robot motion from human demonstration collected via a single RGB camera

Demonstration-based learning has achieved great success in the area of robot motion planning. In this process, a human demonstrator shows ideal motions in the target task using some demonstration techniques, such as kinesthetic teaching, in which human operators directly contact and move the robot end-effector [1], or teleoperation, in which human operators indirectly move the robot through the controller and some other devices [2].

In this study, we propose a new demonstration-based motion planning method that can facilitate difficult motion planning problems in cluttered environments by using only human motion data collected via a single RGB camera as demonstration data [3]. Since existing methodologies in this research area require expertise in robot systems or robot motion planning, using such a simple measurement system (a single RGB camera) to facilitate robot motion planning is worthwhile from the viewpoint of the application.

Figure 1 shows an overview of the proposed method. As shown in Figure 1, the human demonstrator first shows the ideal motion in the target task in front of the RGB camera, and the motion is recorded as image data (Figure 1(a)). Then, the three-dimensional human skeleton information is extracted from the recorded image using skeleton recognition software, which serves as the demonstration data for robot motion planning. The extracted skeleton data is converted to the robot motion through the optimization process and saved as the motion template (Figure 1(b)), and then used as the demonstration data for solving difficult motion planning problems as shown in Figure 1(c). The point of this approach is that the extracted human skeleton data includes a large amount of noise, which decreases the reliability of the demonstration data. Hence, it cannot be directly used as the "strict solution" of the robot motion planning problem. To address this issue, we specifically introduce the path modification and adaptation process to fit the primitive robot motion generated from unreliable human demonstration data to the new environment [4].

The results of simulation experiments showed that our proposed method can solve difficult motion planning problems faster and with a higher success rate than the state-of-the-art motion planner. Based on the results of the simulation experiment, we will add further improvements to our proposed method and enable its use in more practical situations.

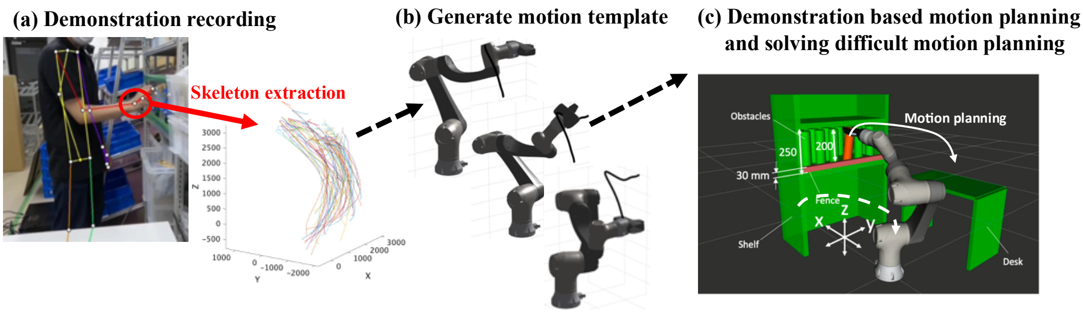

Figure 1. Overview of the proposed method. (a) Recording human motions and skeleton extraction, (b) Generate robot motion template based on the recorded human motion data, (c) Demonstration-based motion planning and solving difficult motion planning problem in the cluttered environment.

Keywords: Lerning from Demonstration (LfD), Motion Planning, Skeleton Recognition

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Automatic action recognition algorithm for industrial manual workers with human skeleton and object information

Time and motion studies, which involve dividing a worker's actions into several micro-actions, are a fundamental analytical technique in industrial engineering (IE). Through this analysis, we can identify redundant parts of the worker's actions and make improvements based on it [1]. However, the problem with this approach is that it takes a large amount of time since it is usually performed by human analysts by hand. Therefore, to address this problem, we developed an automatic action recognition algorithm for industrial manual workers.

Although there are a huge number of studies that have tried to develop human action recognition algorithms [2], there are a relatively small number of studies that have dealt with human action in industrial situations. This is because, in the context of industrial manual workers, object and human-object interaction information must also be considered to recognize the worker's action. For example, although the action of reaching for an object and transporting an object are similar in terms of human kinematics, we can clearly discriminate between them in terms of the interaction of the objects. Therefore, to address these issues, we developed a specific algorithm which can deal with the human object interaction information.

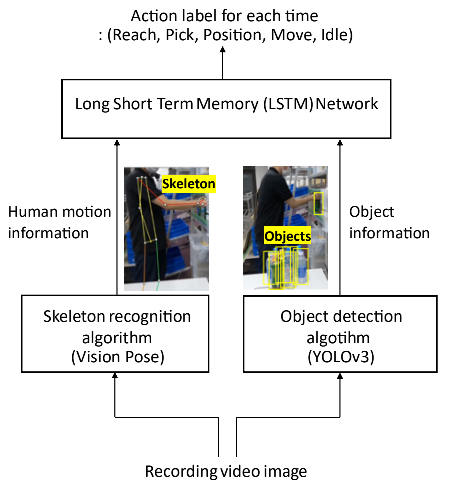

Figure 1. Overview of the proposed algorithm.

Figure 1 shows the overview of the proposed algorithm's architecture. The input of the network is the image data of the human motion in the target task. This data is sent to both the skeleton recognition algorithm and object detection algorithm, and we get both human skeleton and object position (bounding box) information. Then, each data is input to the LSTM network, a type of machine learning technique for processing time series data, and the algorithm finally obtains an action label for each time sequence. Hence, by processing human motion information and object information, we can consider the interaction between the human and the objects.

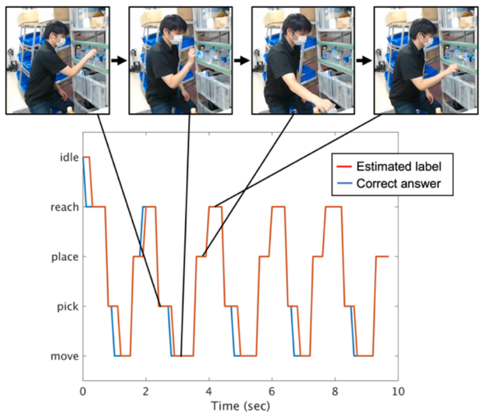

Figure 2. Results of the experiment.

To verify the effectiveness of the proposed algorithm, we conducted an experiment. In the experiment, a participant performed a picking and placing task by moving target objects from a shelf to a desk, or vice versa. The motions of the participant were recorded by a RGB video camera. Figure 2 shows the results of the experiment. As shown in Figure 2, we can describe the participant's action well at each time sequence and it bring us some insights to improve the process. From Figure 2, we can identify motions that can be performed relatively quickly (good action) and those that take relatively longer (redundant action). The mean accuracy of recognition for this experimental task is around 90%. Since we only verified the performance of the proposed recognition algorithm in an experimental environment, we plan to verify it in more practical situations in the future.

Keywords: Action Recognition, Object Detection, Industrial Engineering, Time and Motion Study.

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Measurement Pose Optimization for Joint Offset Calibration with a Hand-Eye Camera

Accuracy of the robot motion manipulation is critical aspects for industrial manufacturing, since industrial robot arm owes various delicate works, such as assembling and welding. Hence, calibration of the robotic arm is very important processes for the practical industrial situations. In this regard, robotic manipulators' motion accuracy can be affected by several factors, such as manufacturing tolerance, set-up errors, and wear and tear. While online teaching can ensure that manipulators coincide with the desired and actual motions, it can be a lengthy and resource-intensive procedure. Offline teaching with robot calibration can reduce the cost of online teaching, but joint offset calibration is essential for accurate motion. Several methods for calibration have been proposed, including using specialized equipment to constrain the end-effector or tracking a laser pointer. However, joint angle offsets can account for up to 90% of the RMS value of the error, and joint offsets often change with daily use, making calibration an ongoing challenge.

To address this challenge, researchers have proposed using a single camera and a marker on the ground for calibration. However, the accuracy of pose estimation using this method is lower than laser tracking because of physical constraints. Therefore, in this study, we propose a new method for determining optimal measurement poses using a hand-eye camera and a marker. Based on the previous observability index O1[1], we proposed a new index Ov1 to evaluate the effect of the error in the pose estimation based on the camera images on the offset calibration. The offset calibration with the marker measurement at the poses, which obtained the optimization to maximize the proposed index, realized higher accuracy than other approaches. Figure 1 and 2 shows the comparison of the optimized pose for calibration by the hand-eye camera. As shown in these figures, the calculated poses from our proposed method are different from the one calculated from the method of previous study. Based on the results of this study, we will add further improvement into the proposed method to achieve higher precision which can be applicable in the practical situations.

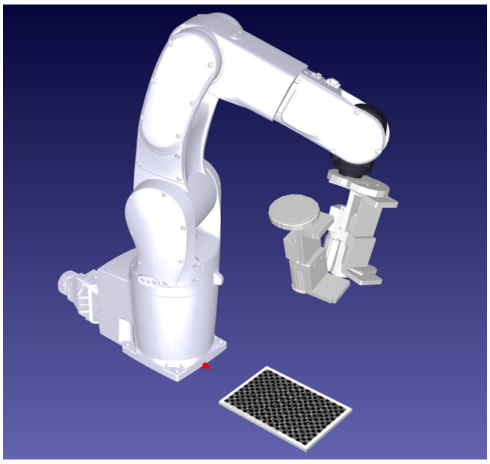

Figure 1. Optimized poses by the method of previous study [1].

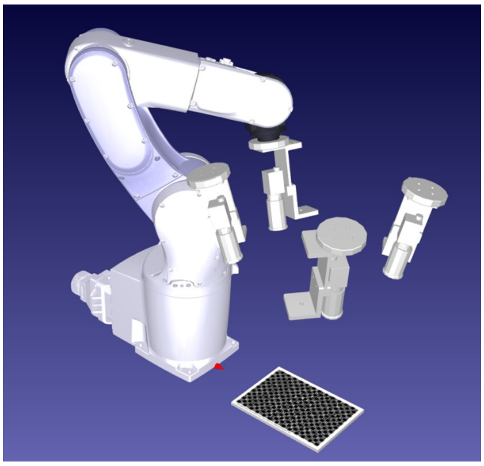

Figure 2. Optimized poses by our proposed method.

Keywords: Calibration, Measurement pose optimization, Hand-eye camera

References

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Robot System Arrangement Using Experience-based Hierarchical Optimization Methods

Industrial robots perform various tasks such as welding, assembling, spraying, and transportation in practical industrial environment. Although the motion planning or motion planning of the industrial robots are mostly focused on to improve the working efficiency, it is also highly influenced by the arrangement of the robot environment components, such as the base, conveyors, sensors, objects, and robots, during the execution of these tasks. Moreover, if the environment of a robotic system changes, the robot's motion must also change, even if it performs the same task, leading to significant changes in its tact time or energy efficiency. Therefore, the location and arrangement of the robotic environment significantly impact industry efficiency, and to enhance the productivity of a robotic system, it is crucial to have a proper setup of the robot system environment, along with planning effective robot movements.

However, most of conventional studies focused on the motion planning or path planning among those two aspects, hence, there is few studies which developed the algorithm to identify both optimal motion and environment arrangements. Therefore, this study proposed the new optimization methods for industrial robotic system which can facilitate both robot motion and environment arrangements' optimization. Specifically, to address the difficulty of combined optimization problem of motion planning and environment arrangement, we used hierarchical algorithm [1] and experience-based method [2-3]. The former is to decompose the complicated problem into more simple ones to reduce the calculation cost, and the latter is to reuse the past solutions in similar optimization problem to find optimal solution faster, and we introduced two experience-based method for both motion planning and environment arrangement part.

To verify the effectiveness of the proposed method, we conducted the simulation experiment with a pick and place robotic system (Figure 1). In the experiment, the optimal robot motion from pick position to the place position, and positions of conveyors are calculated and compared with conventional techniques. Figure 2 shows the results of the experiment. As shown in Figure 2, we can solve combined optimization problem faster than conventional methods though our proposed method (left plot in Figure 2). Based on the results of this study, we will add further improvements on the proposed method.

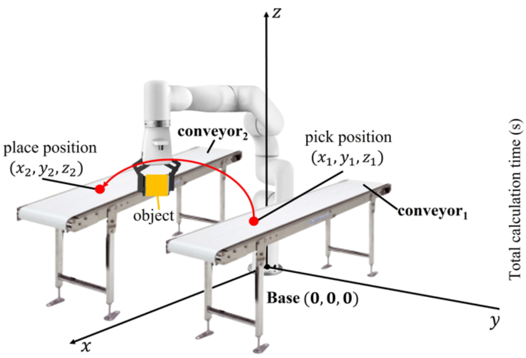

Figure 1. Schematic image of the typical pick and place robotic system.

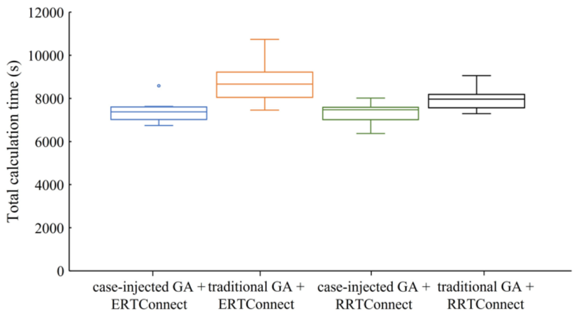

Figure 2. Boxplot of path length of four combinations of method.

Keywords: Robot motion planning, Environment arrangement, Experience-based optimization

References

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Off-line task assignment and motion planning algorithm considering agent's dynamics

With the advancement of automation in logistics warehouses and the flexibility of manufacturing lines, the demand for Automated Guided Vehicles (AGV) has been increasing. When operating a system composed of multiple AGVs, two problems need to be addressed: 1) task assignment, which determines where each AGV receives and delivers target products, and 2) motion planning, which generates path from initial to target positions with avoiding the collisions with other AGVs while completing tasks as quickly as possible. In order to find the optimal solution for these two problems, it is important to consider the dynamic characteristics of AGVs, which represents the specific acceleration/deceleration pattern of AGVs as shown in Figure 1. However, the algorithm which can perform both task assignment and path planning considering the dynamics of AGVs has not been proposed in previous studies.

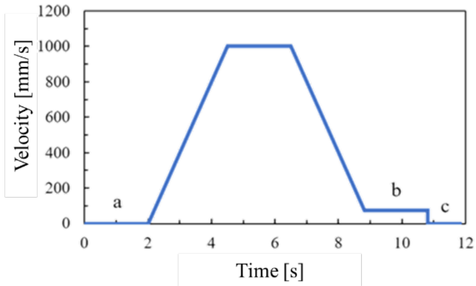

Figure 1. The dynamics (velocity curve) of the AGV used in this study. The AGV accelerates and decelerates following this curve.

Therefore, in this study, we developed an algorithm that performs task assignment and motion planning while considering the dynamic characteristics of AGVs and minimizing the time required to complete tasks including motion planning and movements of AGVs. Specifically, we used Conflict-Based Search with optimal Task Assignment (CBS-TA) [1], a representative solution algorithm for task allocation and motion planning problems, as a base and developed an algorithm that minimizes the time required to complete tasks by considering the dynamic characteristics of AGVs [2]. In our proposed algorithm, we introduced a heuristic function that reflects the dynamic characteristics of AGVs, assuming a speed curve as shown in Figure 1, and performed task allocation and motion planning using multiple search trees based on the CBS-TA framework. Furthermore, by continuously performing motion planning for both picking up and transporting the target products, we made it possible to achieve consistent optimization from task allocation to the completion of transportations.

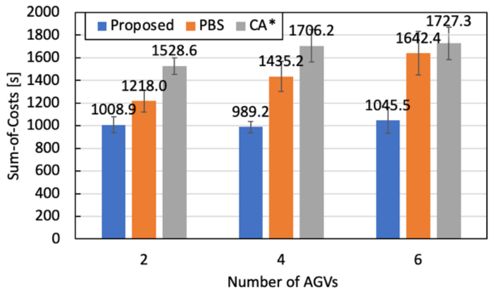

Figure 2. The result of the simulation experiment. The horizontal axis indicates the number of AGVs, and the vertical axis indicates the sum of the computation time of the motion plan and the total travel time of AGVs.

After implementing the proposed method on a computer, we conducted simulation experiments to verify its effectiveness. In the experiments, we randomly generated environments and solved the combinate problem of task allocation and motion planning for multiple AGVs while varying the number of AGVs, and compared the proposed method with the method of previous studies from the perspective of motion planning and the time required for task completion. As a result, as shown in Figure 2, it was demonstrated that the proposed method can perform both task allocation and motion planning for multiple AGVs within a shorter time compared to other methods. Based on the results of this study, in the future, we plan to further improve the proposed method while increasing the number of AGVs and setting up more complex environments.

Keywords: Automated Guided Vehicle, Path Planning, Task Assignment, Agent’s Dynamics

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evelopment of Virtual Reality System for Identification of Specific Expert Skills in Refinery Inspection Task with Explainable AI

Refinery inspection is the fundamental meintenace task that expert inspectors move around the vast reifinery area and try to find any defects or sign of it. Since even the slight defects will cause serious accidents in later, it owes a critical role for safety management of the refinery. Therefore, to achive the more stable and safety refinery operation, it is important to investigate how expert inspectors can find such a small defects in a vast refinery area, and how different their inspection behavior from novice's one [1], namely, identification of the expert inspection skill is a critical aspects for refinery safety management.

From above background, in a previous work, a Virtual Realiry (VR) system is used to collect data of both experts and novices inspectors, and clarify the differences between them [2]. As a results, they revealed that expert inspectors tend to set their head in more effective position for finding the defects (e.g., lowerer position for leakage inspection). However, the problem of these previous studies in the lack of temporal and spatial specificity of the expert's skill. Namely, since most of existing studies compared the mean value of the entire inspection process by appling statistical analysis methods, i.e., it is unclear "when" and "where" the expert skill was observed in the entire working processes, and this makes difficult to teach the specific skills for novices.

Therefore, to solve the above issue, in this study, we proposed new analytical framework of the refinery inspection skill which based on the Explainable-AI (XAI) technique. XAI is a kind of analytical technique in the mechine learning filed which tries to visualize and explain the reason for generating the specific out such as prediction or classification. Since it can identify the most important part among wntire time series input data, we adopt this framework for solving lack of specificity problem.

In our proposed method, Covolutional Neural Network (CNN) with Class Activation Map (CAM)[3] are used for classification of the data of inspection behavior into two labels (experts vs novices), and visualize the reason for it. Figure 1 shows the example of obtained results from our analysis. The graph shows the head positions of the participants, and the colors indicate their contribution to the prediction results. As shown in this figure, through the visualization of the CAM architecture, we can identify the specific expert skills such as "the expert inspector tend to gaze from lower angle than novices in this equipment". Hence, by comparing one's own actions with those of skilled operators while inspecting similar objects, we believe that the system can encourage novice workers to make specific improvement plans. In the future, we will develop the educational training system based on this results.

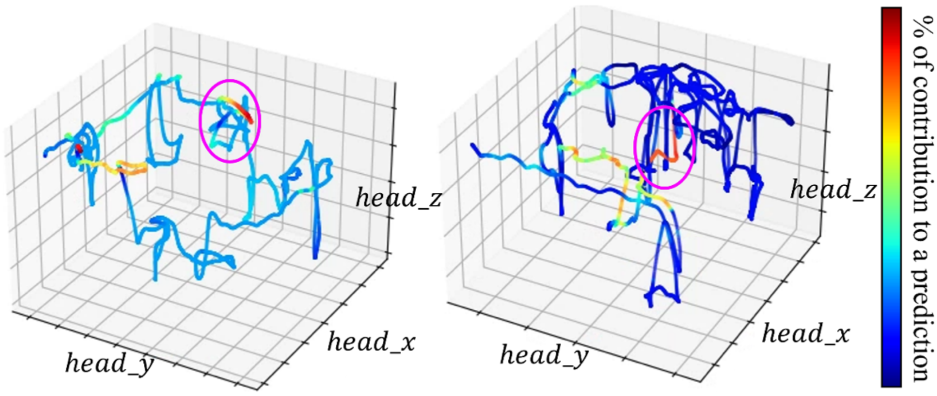

Fig 1. Examples of visualization of the basis for skill discrimination by CAM.

Keywords: Expert Skills, VR, Machine Learning, XAI, CAM

References

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A Framework to Support Failure Cause Identification in Manufacturing Systems through Generalization of Past FMEAs

Inspection and maintenance of manufacturing systems require experts who are familiar with the system's structure and potential defects that may occur. It is a concern in the Japanese manufacturing industry that the shortage of experts makes identifying the defect causes and maintenance activities difficult in the future. A practical approach to compensate for the lack of engineering skill is to refer to the past failure analysis that experts have conducted to identify the causes of failures and repair them.

In this study, we proposed a framework for reasoning possible causes of failures in manufacturing systems based on the past FMEAs (Failure Mode and Effect Analyses) analyzed for various manufacturing systems. The framework generalizes past FMEA descriptions using a combination of classes and properties in the domain ontology of manufacturing systems. The framework searches the possible causes of given failure from the generalized FMEA descriptions through the narrowing down process to consider the possible cause that satisfies the process in the target manufacturing system represented by the partial-order model generated from SysML diagrams. The comparison between the causes inferred by the proposed framework and by skilled experts for three typical failures in the manufacturing system and the interview with them about the plausibility of the inference results showed that more than 73 % of outputs were valid failure causes.

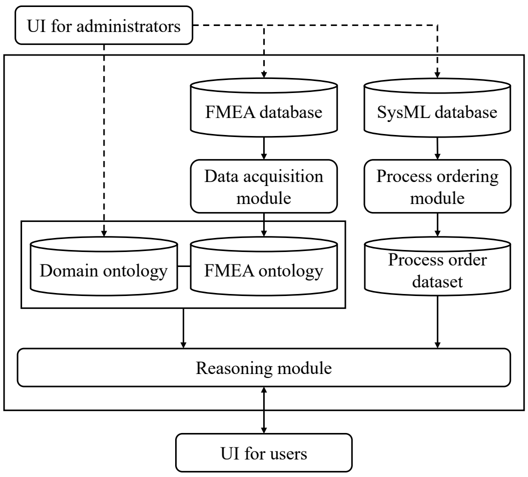

Fig. 1 Overview of the proposed framework

Keywords: Fault Cause Identification, FMEA, Ontology

Reference:

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Development of a Nursing Skill Training System Based on Manipulator Variable Admittance Control

Due to the recent aging society and shortage of nursing experts, the use of robot-based skill training systems is an emerging topic in nursing education, as many innovative robotic systems have been developed to simulate real patients, offering a safe and self-directed platform for nursing students to learn and practice their skills. Among these training systems, several human patient simulators (HPS) [1-3] have been proposed to simulate the patient's performance during patient transfer; however, without an entire motion model and control strategy, most HPS show limited effectiveness in simulating actual patient behavior.

Herein, this work presents a novel patient transfer training system that has the potential of improving the practical skills of nursing students. The reason we set the patient transfer skill as the target of our system is that it is one of the highest risk motions which causes both patient and nurse's injury among many nursing skills, hence improving the novice's skill of patient transfer contributes to reduce the injury in the practical situation. The procedure of development our training system is as follows. First, we propose a simplified force model for patient transfer motion to estimate the contact force in the absence of wearable sensors (Figure 1). We then reveal the correlation between the nurse's force and patient's motion during the transfer through the utilization of the variable admittance model. Finally, we demonstrate the feasibility of the proposed patient transfer training system by performing several experiments on a UR10e robot. To the best of our knowledge, this system is the first patient transfer skills training system that simulates force interaction between nurse and patient using a collaborative robot.

Figure 2 shows the example of the training of the patient transfer motion with proposed training system. As shown in Figure 2, the patient can train and learn the transfer motion through the system. We anticipate that our proposed system will be an effective aid for student nurses to learn patient transfer skills. We believe that this innovative approach can make a contribution to the field of nursing education, addressing the current challenges of inadequate resources for nursing education.

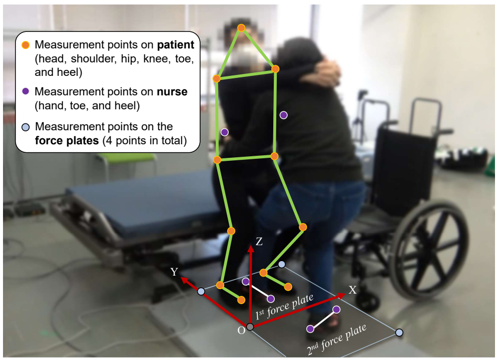

Figure 1. Modeling interaction between the patient and nurse.

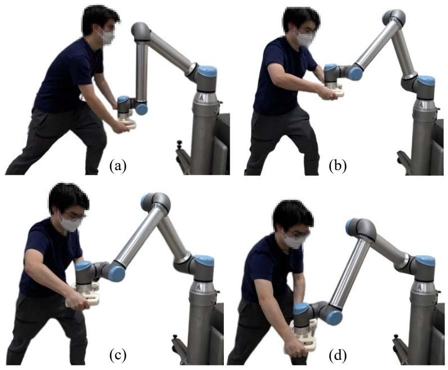

Figure 2. Example of the training with proposed system.

Keywords: Robot patient, Modeling of human motion, Nursing education

References

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Analysis of the relationship between DAT-SPECT and motor symptoms using machine learning

Parkinson's disease is a neurodegenerative disorder that causes various motor and non-motor symptoms. Patients with Parkinson's disease show degeneration and loss of dopamine neurons in the substantia nigra of the brain. DAT-SPECT is often used to obtain information on the amount of dopamine in the brain; it indirectly measures dopamine levels by capturing DAT, which regulates dopamine uptake. The evaluation using DAT-SPECT is mainly done visually or by SBR, which is a scalar evaluation value. However, in this case, the influence of the evaluator's subjectivity and the loss of three-dimensional information are inevitable.

Therefore, we are developing a system to investigate the relationship between DAT-SPECT and motor symptoms by capturing 3D DAT-SPECT features of Parkinson's disease patients. The system uses 3D DAT-SPECT images as input and outputs several scores calculated from UPDRS, an index to evaluate motor function. Convolutional neural networks were used for regression analysis. To understand how the system learned, Grad-CAM was used to visualize the areas that significantly affected the results.

As a result, it was confirmed that the estimation accuracy was better when 3D DAT-SPECT images were used as input than when only SBR was used as input. The visualization results showed that the area around the striatum, especially around the putamen, significantly affected the estimation results. This is consistent with the finding that the putamen is related to motor function within the striatum.

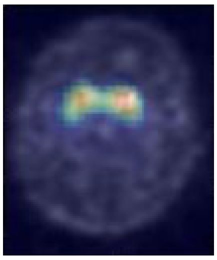

Figure 1. An example of using Grad-CAM to visualize the areas that significantly affected the results. The closer the color is to red, the greater the influence.

At present, there are predictions for improvement in estimation accuracy, so we are aiming for better estimation by taking into account the heterogeneity of data distribution and the amount of data. In addition, although this analysis was conducted only for motor symptoms, patients with Parkinson's disease often present non-motor symptoms from the early stage of the disease. In the future, we will conduct the same analysis for non-motor symptoms to clarify the relationship between motor and non-motor symptoms.

Keywords: DAT-SPECT, Parkinson’s disease, Machine learning

References

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Modeling of human gait and gait initiation

Gait and gait initiation are daily tasks for us. Therefore, when these are disturbed due to aging or disease, they can greatly impair our daily lives. In order to prevent the occurrence of such disorders and to perform rehabilitation effectively, it is important to understand the mechanism of human gait. Our approach is to create a controller model and control the musculoskeletal model on a computer.

Although various modeling studies have been conducted on gait control, no gait simulation that controls a body model capable of three-dimensional motion has been realized. One of the challenges is the difficulty in adjusting control parameters because the body model needs many joint degrees of freedom. We propose an approach in which the control parameters are adjusted by adding joint degrees of freedom step by step, starting from a condition with a small number of joint degrees of freedom. This approach has enabled a musculoskeletal model with 70 muscles and 15 joint degrees of freedom to walk.

The gait initiation, which is the transition from stance to gait, is an important movement that is often impaired and may lead to falls. During gait initiation, it is known that a characteristic phenomenon (anticipatory postural adjustment, APA) is observed, in which the center of pressure of the foot shifts backward once, but the necessity of this phenomenon has not been fully elucidated. We have developed and investigated a neural controller model for stance, gait, and gait initiation. We found that simply switching between stance and gait control is not sufficient to make the transition from stance to gait. In addition, APA was observed even though the control parameters were adjusted to achieve the transition to gait, suggesting the usefulness of APA in the gait initiation.

At present, some of the features of the model motion are different from those of actual human motion. In the future, we will investigate the causes of this difference, examine the limitations of the model, and analyze the effects of aging and disease on the model.

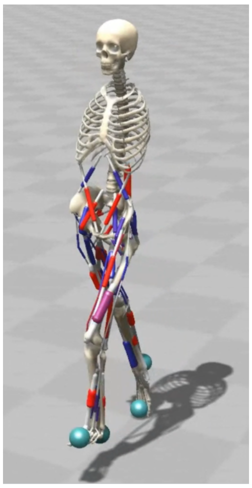

Figure 1. The musculoskeletal model used in gait simulation (70 muscles and 15 joint degrees of freedom).

Keywords: Gait, Gait initiation, Musculoskeletal model, Forward dynamics simulation

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Evaluation of changes over time in stance postural control mechanisms in stroke patients

Stroke is mainly caused by rupture or occlusion of an artery, which interrupts blood flow to the brain, resulting in a lack of oxygen. Stroke patients often have balance problems and are at increased risk of falling. Although there have been studies on the ability of stroke patients to balance while standing, there have been no studies on the control mechanism.

We investigated the characteristics of sway in the stance posture of stroke patients by using a neural controller model that we have developed. The musculoskeletal model that can represent the asymmetrical posture that stroke patients often show is controlled by the neural controller model. The control parameters were adjusted using optimization to reproduce the patient's sway features obtained from motion capture. The adjusted control parameters were subjected to dimensionality reduction by non-negative matrix factorization, and the differences in the control parameters among the groups were compared.

As a result, the dimensions of 45 control parameters were reduced to 6 dimensions. Comparing stroke patients and young healthy participants, significant differences were confirmed for two of the six components This indicates that the proposed method can capture differences in postural sway characteristics between different groups. These two components are related to the extension of each joint, and to the suppression of rapid extension of the lumbar region and ankle.

In the future, we will investigate how the control parameters change depending on the site of injury and the number of days since the onset of injury, and aim to identify the factors that are important for effective functional recovery. In order to prevent patients from falling, it is essential to examine not only the quiet stance posture, but also how the patient maintains the stance posture when subjected to external forces. We aim to analyze both conditions using a mathematical model in conjunction with our previous postural simulations under external disturbance.

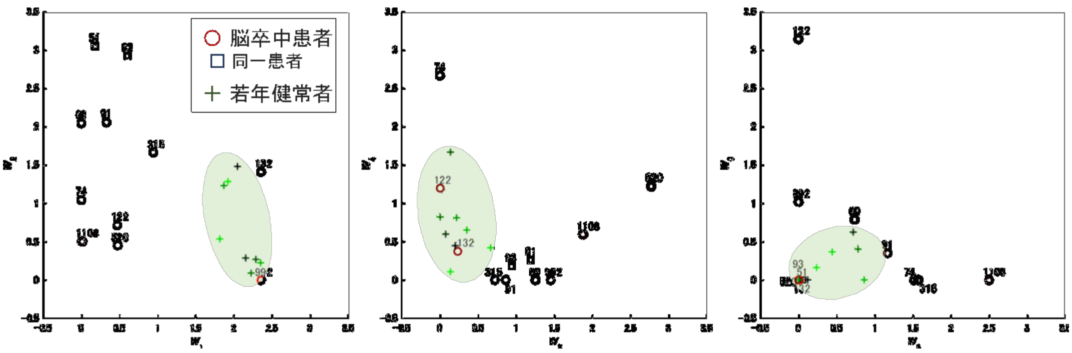

Figure 1. The control parameters fitted to the experimental data are dimensionally reduced to 6 dimensions. The green ellipse indicates the area where young healthy participants are distributed. Significant differences were observed between stroke patients and young healthy participants for components 1 and 3.

Keywords: Stroke, Musculoskeeltal model, Forward dynamics simulation

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Modeling of standing postural control in Parkinson's disease patients

Patients with Parkinson's disease (PD), a neurodegenerative disorder, exhibit abnormal posture, a characteristic standing posture, in addition to impaired postural control. Increased muscle tone, which is steady muscle activity, has been suggested as a cause of abnormal posture. However, it is difficult to measure muscle tone in the standing posture, and the relationship between muscle tone and postural abnormalities has not been clarified in detail. Abnormal posture causes dysphagia and back pain, and greatly affects quality of life. It is important to elucidate the mechanism of abnormal posture in order to establish a treatment for abnormal posture. Therefore, we aim to elucidate the mechanisms of abnormal posture and postural dysregulation in PD by performing forward dynamics simulations of postural control using a computer model.

In our previous study, we investigated the hypothesis: "In patients with PD, the abnormal posture is a static standing posture with small local center of gravity sway in response to increased muscle tone" using a computer model. Using the computer model and standing data from actual PD patients, we estimated muscle tones of various magnitudes (Fig. 1). The posture with the smallest center of gravity sway was calculated using an optimization method for the estimated muscle tones. The calculated posture and the center of gravity sway in the standing posture were compared with the posture and center of gravity sway of actual PD patients. The results showed that the difference between the posture and the center of gravity sway was the smallest at higher muscle tone than that of normal subjects (Fig. 2). This indicates that the posture with the smallest sway of center of gravity at higher muscle tone than that of the normal subjects is close to the actual standing data of PD patients, and their sway of center of gravity is also close to that of the normal subjects. These results are consistent with the hypothesis, and suggest that the posture in which the center of gravity sway is locally smaller in PD patients at increased muscle tone may be an abnormal posture [1].

Keywords: Parkinson's disease, Abnormal posture, Muscle tone

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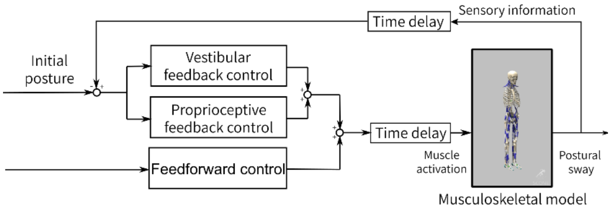

Figure 1. Computational model. The model consists of feedforward control representing muscle tones and feedback control using proprioceptive and vestibular information. In addition, time delays due to information transmission and muscle activity are considered.

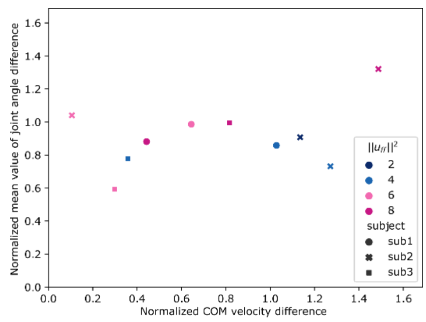

Figure 2. Normalized average values of the joint angle difference and normalized differences of the average COM velocity between simulation and experimental results for each subject. $||u_{ff}||^2$ represents the magnitude of whole-body muscle tone. The closer to the origin, the closer the posture and sway are to the experimental values.