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研究課題名（和文）Understand human tool-use in motion and contact for robotic tooling

研究課題名（英文）Understand human tool-use in motion and contact for robotic tooling

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研究成果の概要（和文）：この数年でディープラーニングや強化学習により優れたロボットが開発されているが、未だに道具を扱う素早い運動では人より数倍遅い。我々は人が道具の使い方を学ぶ時の運動学習を計測し、新たなインタラクションロボットの開発に挑んだ。作業中の腕の剛性時系列データを計測新たに生み出し、運動学習中の剛性の変化に着目した。

研究成果の学術的意義や社会的意義
With the population rapidly declining in Japan, there is a need to automate the workforce. Our study revealed the key planning process enabling humans to rapidly complete interaction tasks, thereby pushing us one step closer to realizing interaction robots capable of rapidly assembling components.

研究成果の概要（英文）：Even the most advanced robots are nowhere close to achieving the speed or robustness of human workers, especially when contact with the environment is necessary to the task like fitting an object into a hole. We analyzed human strategies when inserting a tool or peg into a hole, and attempted to replicate the strategy to develop a new robot for contact tasks.

研究分野：計算論的脳科学

キーワード：interaction robot　motor control　motor adaptation

１．研究開始当初の背景

While deep learning and reinforcement learning have led to advanced robots capable of generalizing their learning to many tasks, even the most advanced robots of today cannot match the speed and robustness of human workers at interaction tasks, such as inserting a rod into a tight hole. The most common strategy taken by robots is to separate interaction into the two domains of free movement and contact control. In free movement, the robot employs position control to align itself the object to insert with the entrance of the hole. Once contact is established, force control is used where the measurement of the interaction force is used to guide the object into the hole. While this separation of the two control domains makes the robot more robust, it comes at the cost of speed. Furthermore, studies of human movements has revealed that the brain control both the force and the arm’s stiffness during interaction, the latter playing an important role in stabilization. However, specifically how the force and the arm’s stiffness are regulated during interaction remains unknown during handheld tooling and other interaction tasks. By studying and learning from humans completing interaction tasks, this may inspire a biomimetic control law that mimics the robustness and speed of human force control.

２．研究の目的

A goal of this study was to understand how humans control their arm during dynamic interactions with the environment. Specifically, we were interested in the control law that regulates both the force and the arm’s stiffness during interaction. By measuring these two variables during handheld tooling, and analyzing how their time-series changes with practice, we aimed to understand the brain’s interaction control mechanism to yield a fast and robust interaction controller for robots.

３．研究の方法

A dedicated robotic interface was used to measure the hand’s position, speed and force during real and virtual tooling tasks. The robotic interface provides force feedback of the interaction, which can be rendered in a virtual environment to change the size of the object or the width of the hole, enabling us to precisely control several parameters and to observe adaptations in the strategy used to insert the object after practice. We also developed a new method to estimate the stiffness of the arm in real time to assess its change along the trajectory and across trials.

４．研究成果

The project started by estimating the human control law when regulating the force to control a cursor to track a randomly moving target (Figure 1, taken from Takagi et al, IEEE Transactions in Neural Systems and Rehabilitation Engineering, 2018). Participants exerted a force against a fixed robotic handle to control a cursor’s movement to make it follow a randomly moving target. A linear control law commonly used in the literature was employed to estimate each participant’s feedback gain. While the force could be inferred using the estimated feedback gain, the presence of correctional forces (known as submovements) interfered with the estimation, and did not yield a stable control law that can be used in a robot. This study revealed that human force control cannot be described as a linear feedback control law, highlighting the need for more sophisticated control algorithms to reproduce the robustness of human force control.

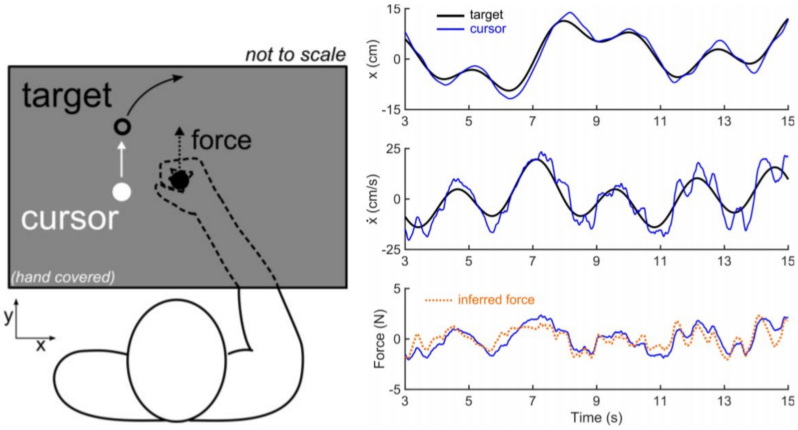

Figure 1. A linear control law could not explain the correctional forces observed during a force tracking task.

The next task was to measure the force and the arm's stiffness during a handheld tooling task, but to do so, we had to develop a new methodology to estimate the arm's stiffness in real-time as the existing method of electromyography requires a lengthy calibration process, and the stiffness estimate is highly sensitive to the speed and the force of the movement, making it difficult to obtain accurate measurements during rapid tooling. We proposed a new method of estimating the arm's stiffness by measuring the power grasp force (Figure 2), which showed an insensitivity to the speed and the force of the movement, and we successfully reproduced observations of the arm's stiffness reported in other studies (Takagi et al, eNeuro, 2019). Furthermore, we showed that the power grasp force is linearly related to the magnitude of the arm's stiffness during postural control (Takagi et al, Scientific Reports, 2020).

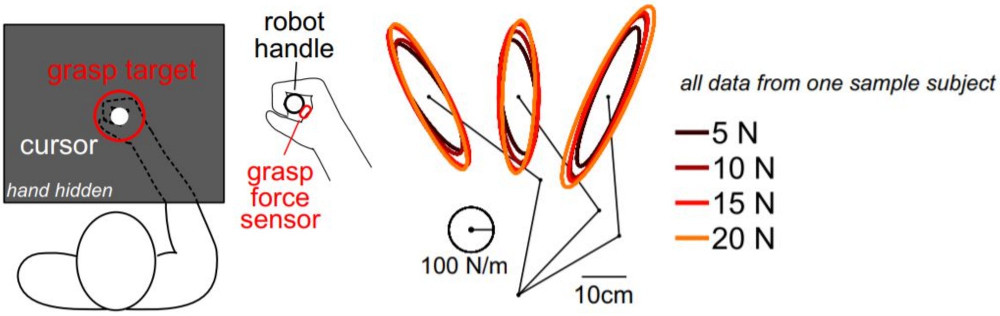

Figure 2. The newly proposed grasp force measure was shown to be linearly related to the arm's stiffness ellipse size. The grasp force provides high temporal resolution estimates of the stiffness without requiring calibration.

Using the newly developed grasp force measure of the arm's stiffness, we measured how the arm's force, stiffness and trajectory time-series changed over trials during a real and virtual handheld tooling task (Takagi & De Magistris et al, Scientific Reports, 2020). While in standard reaching movement (without requiring an insertion), the stiffness remained constant throughout the movement (Figure 3c, dotted blue line), during insertion the stiffness increased along the movement, peaking during the interaction with the fixture. Our analysis of the trajectory showed that participants used two strategies during insertion (Figure 4). In the slow down strategy, the tool was brought nearly to a stop prior to its insertion into the fixture. In the ballistic strategy, the tool's peak movement speed was observed during insertion, enabling participants to complete the tooling task faster. While the ballistic strategy resulted in some failed attempts requiring a heavy adjustment of the movement, the overall time needed to insert the tool into the fixture 130 times was shorter with the ballistic strategy. Thus, this ballistic strategy is the ideal one that our robotic algorithm should aim for.

Early computational modelling suggests that the ballistic strategy requires a contiguous motion plan that activates the muscles in the arm based on planning in both the free movement (moving the tool up to the fixture) and the contact phases. In the near future, the data from the ballistic strategy will be used to yield a robotic controller based on nonlinear optimal control to control the force and the arm's stiffness simultaneously.

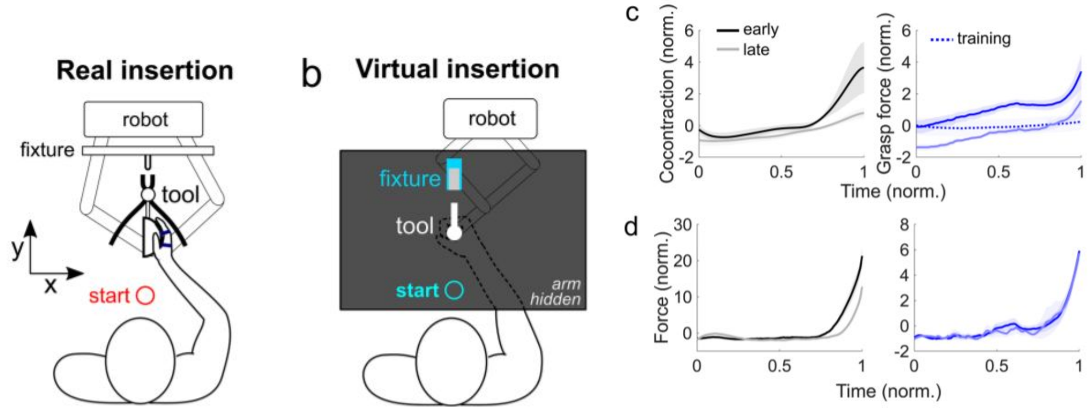

Figure 3. Real and virtual insertion of a tool into a fixture was examined. The arm's stiffness increased slowly along the movement while the tool approached the fixture, reaching its climax at the time of insertion.

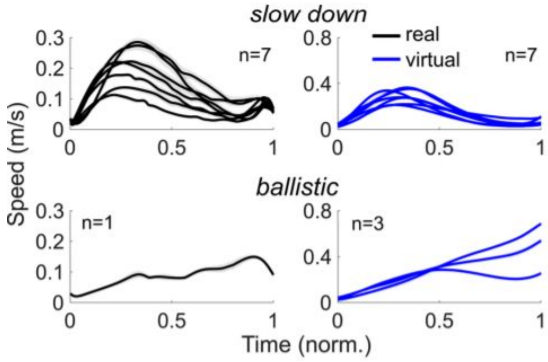

Figure 4. Two control strategies emerged during insertion. In the slow down strategy, the tool was brought nearly to a stop prior to its insertion into the fixture. In the ballistic strategy, the tool's peak movement speed was observed during insertion, enabling participants to complete the tooling task faster.

５．主な発表論文等

〔雑誌論文〕　計4件（うち査読付論文　3件／うち国際共著　1件／うちオープンアクセス　3件）

１．著者名 Takagi A.、Kambara H.、Koike Y.	４．巻 6
２．論文標題 Increase in Grasp Force Reflects a Desire to Improve Movement Precision	５．発行年 2019年
３．雑誌名 eneuro	６．最初と最後の頁 NA
掲載論文のDOI（デジタルオブジェクト識別子） 10.1523/ENEURO.0095-19.2019	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 －

１．著者名 Takagi A.、Xiong G.、Kambara H.、Koike Y.	４．巻 10
２．論文標題 Endpoint stiffness magnitude increases linearly with a stronger power grasp	５．発行年 2020年
３．雑誌名 Scientific Reports	６．最初と最後の頁 NA
掲載論文のDOI（デジタルオブジェクト識別子） 10.1038/s41598-019-57267-0	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 －

１．著者名 Takagi Atsushi、Kambara Hiroyuki、Koike Yasuharu	４．巻 26
２．論文標題 Reduced Effort Does Not Imply Slacking: Responsiveness to Error Increases With Robotic Assistance	５．発行年 2018年
３．雑誌名 IEEE Transactions on Neural Systems and Rehabilitation Engineering	６．最初と最後の頁 1363～1370
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/TNSRE.2018.2836341	査読の有無 有
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１．著者名 Takagi Atsushi、De Magistris Giovanni、Xiong Geyun、Micaelli Alain、Kambara Hiroyuki、Koike Yasuharu、Savin Jonathan、Marsot Jacques、Burdet Etienne	４．巻 10
２．論文標題 Analogous adaptations in speed, impulse and endpoint stiffness when learning a real and virtual insertion task with haptic feedback	５．発行年 2020年
３．雑誌名 Scientific Reports	６．最初と最後の頁 22342
掲載論文のDOI（デジタルオブジェクト識別子） 10.1038/s41598-020-79433-5	査読の有無 無
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 －

〔学会発表〕　計0件

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関