3版

様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

科研費 KAKENHI

科学研究費助成事業　　研究成果報告書

平成 ３０ 年　 ６ 月 ２０ 日現在

機関番号：８２６２６

研究種目：挑戦的萌芽研究

研究期間：2015～2017

課題番号：１５Ｋ１２６２３

研究課題名（和文）人工手指を自分の手指のように動かす：ヒト脳活動を用いた人工手指の自然な学習

研究課題名（英文）Sixth finger project: Natural learning of an additional limb by the human brain

研究代表者

ＧＯＷＲＩＳＨＡＮＫ　ＡＲ．Ｇ（Gowrishankar, Ganesh）

国立研究開発法人産業技術総合研究所・情報・人間工学領域・国際客員研究員

研究者番号：１０５７０２４４

交付決定額（研究期間全体）：（直接経費）　　2,800,000円

研究成果の概要（和文）：脳が、人工的に作成した肢部を自分自身のものとして自然に学習し、使えるようになるにはどのような条件が重要かを理解することを目的とした。1）人工物のどのような特性が、それが自分自身の一部であると脳に感じさせるのかを理解するための心理物理実験を実施した。2）神経信号で制御可能な、付加的な（第６の）指と感覚フィードバックシステムを開発した。3）人工肢部を制御するための「自由神経活動」を分離し、検証するための技術を開発した。4）当初の研究計画には含まれていなかった項目ではあるが、（１）の結果を拡張することにより、ロボットによる「身体化」の定義を初めて行い、ロボットにおける人間らしい道具の認識を可能にした

研究成果の概要（英文）：In this project we aimed to understand the key requirements for enabling a human brain to learn and use an artificial robot limb as naturally as one’s own limb? For this purpose: 1)We utilized psychophysical experiments to understand what characteristics of an artificial entity would make our brain feel as the entity is part of our self. 2)We developed a robotic extra (sixth) finger/ feedback system that can be controlled using neural signals and utilized it in experiments to test results in (1). 3)We developed a technique to isolate and verify the ‘free neural activity’ in the brain, that can be used to control artificial limbs. 5)Finally, though not initially in the project, we extended the results in (1) to define, for the first time, ‘embodiment’ by robots, and enable human-like tool cognition in robots.

研究分野：複合領域

キーワード：BMI　自然学習　機能拡張　可塑性

１．研究開始当初の背景

The ultimate brain machine interface (BMI) will be one that enables an individual to use a machine/robot, like say a prosthetic device, as if it were his own limb, with minimal attention and without requiring to imagine or behave in odd trained ways to do so. However, while our brain can readily learn to control new actions with our available effectors/limbs, the same cannot be said about learning of *new limbs* using BMI. While discrete BMI control of plans or tasks has been possible, online control has been very difficult and shown only for very slow movements. In this project we aimed to understand what these interfaces additionally require so that they can enable a human brain to learn and use an artificial robot limb as *naturally* as their own limb?

２．研究の目的

We hypothesized that there are two key requirements to enable an artificial limb to be learnt and used as one's own limb by humans. First, 'embodiment' of the limb is crucial: The limb movement should be controlled seamlessly using a neural signal form the human body/brain, and crucially, the movements should be associated with not only a visual, but also a proprioceptive/haptic feedback. Second, the limb needs to be controlled by a neural activity (from a user's body or brain) that is 'free' (we call this free neural activity, or FNA)and is not involved in the control of any other limb.

With these two hypothesis, we divided the research purpose into the following:

1) Understanding limb embodiment: examining how our brain defines our 'self' and what physical/functional characteristics of an artificial entity would make our brain feel as the entity is part of our self.
2) Developing a suitable additional limb (finger) and feedback system that we can control from neural signals and use to provide appropriate feedback to users
3) Utilize the finger system in experiments with users to test findings of (1)
4) FNA isolation: Develop a technique to isolate the FNA in the brain
5) Develop an artificial limb system: Utilize results of (1-4) to develop a artificial finger that users can use as their own.

In the project, in the available time we could achieve 1, 2, 3 and 4. We are still testing the method developed in (4) and have not yet reached to the last stage 5.

However, though not part of the project, we could utilize the result of the project for the development of AI in robotics. The results in (1) enabled us to define and develop, for the first time, the ability of embodiment in robots that enabled human-like tool cognition in robots (see research resukts for details).

３．研究の方法

1) Understanding limb embodiment: was developed using a series of psychophysical experiments using the rubber hand illusion, and also using artificial (robot) limbs and body.
2) Developing a suitable extra limb (finger) and feedback system was achieved as a Masters student project.
3) Utilize the finger system in experiments: We developed the first embodiment experiments with our sixth finger system.
4) FNA isolation: The FNA isolation was the most challenging problem of this project. The isolation and critically proving of the presence of FNA is a difficult mathematical problem. We utilized functional Magnetic Resonance imaging (fMRI), and starting with experiment to determine FNA in the visual cortex (as visual experiments are logistically easier to develop and control) we utilized machine learning to get the first estimates of the FNA in our brain.

４．研究成果

1)Understanding limb embodiment

With a post doctorate colleague, we performed a series of experiments to understand what features are key for the embodiment of artificial limbs by a human (brain). We started with experiments using the famous rubber hand illusion and later used robots to understand the embododiment of robotic(mechanical looking) limbs and bodies. These results were published as 5 international journal articles. Two key results of these experiments were 1) the discovery of the fact that the 'functionality' represented by a limb, rather than its physical features is key determinant of whether it can be embodied

Fig. 1: an experiment testing embodiment of a robot limb by a human.

By a human.2) Our clarification of how embodiment effect the motor-sensory mappings in the human body, such that users perceive sensory feedback variations form a embodied limb depending on whether they make the sensory stimulation or not.

2)Development of the additional (sixth) finger and feedback system

Fig. 2: top panel: the design of our sisth finger system. Bottom panels: the sixth finger device fixed on a users hand, with and with gloves.

With a Master's student of Dr. Yoichi Miyawaki, who is the collaborator in this project, we developed the design of a finger system that can be attached to a user's hand. The system can provide haptic feedback related to the movement to the side of the hand. We developed an actuation interface for this finger using electromyography (EMG) which enables a user to operate this finger independent of the other fingers, and without disturbing his other fingers.

3)Utilizing the finger system in experiments

Utilizing the finger system driven by EMG, we developed the first experiments to test how the presence of 'agency', the ability to

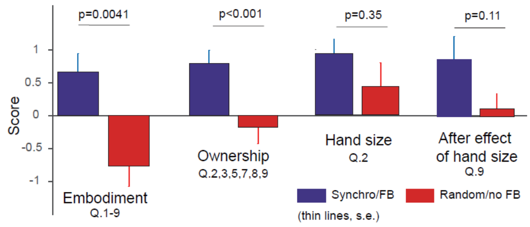

Fig 3: the subjective scores on different questions in the presence of agency and feedback (blue) and in their absence (red).

control the finger, and feedback affects the feeling that the artificial finger is part of one's own body. These results were presented in a local conference this year.

4)FNA isolation

This part of the project is still ongoing. We utilized fMRI experiments and examined the brain activations during the viewing of a video by participants to isolate brain regions that may represent the FNA. We have now developed a procedure to check the validity of the FNA isolation and are continuing experiments on this at the moment.

5)Extension to Robotic

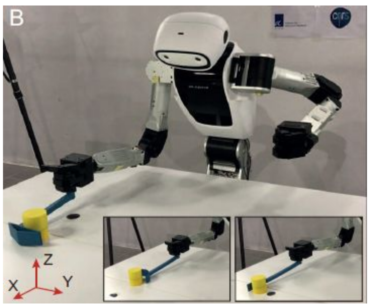

Fig.4: A video grab of our experiment in which we used the results of our embodiment experiment to enable robots to 'embody' and use tools.

We were also able to extend the results of our embodiment studies with humans to address an important issue in robotics- that of enabling tool use by robots. Tool use by humans is considered to be possible to their ability to embody tools. Our results last year gave new details about the embodiment abilities of humans, and specifically the relation between the functionality and embodiment. This enabled us to develop an algorithm that enables robots to recognize previously unseen objects as tools and use them immediately for tasks, without requiring any learning. This result was published in the largest Robotics conference (ICRA) in 2018.

５．主な発表論文等
（研究代表者、研究分担者及び連携研究者には下線）

〔雑誌論文〕（計　5　件）

L. Aymerich-Franch, D. Petit, G. Ganesh, A. Kheddar (2017). Object touch by a humanoid robot avatar induces haptic sensation in the real hand. Journal of Computer Mediated Communication. 22(4):215:230.

L. Aymerich-Franch, D. Petit, G. Ganesh, A. Kheddar (2017). Non-human looking robot arms produce illusion of embodiment. International Journal of Social Robotics.1-12.

L. Aymerich-Franch, D. Petit, G. Ganesh, A. Kheddar (2016). The second me: seeing the real body during humanoid embodiment produces an illusion of bi-location. Consciousness and Cognition. 46:99-109. doi: 10.1016/j.concog.2016.09.017.

L. Aymerich-Franch, D. Petit, A. Kheddar, G. Ganesh (2016). Forward modelling the rubber hand: illusion of ownership reorganizes the motor-sensory predictions by the brain. Royal Society Open Science. DOI:10.1098/rsos.160407

L. Aymerich-Franch, G. Ganesh (2016). The role of functionality in the body model for self-attribution. Review in Neuroscience Research. 104:31-7. doi: 10.1016/j.neures.2015

〔学会発表〕（計 3　件）

K.P. Tee, J. Li, L.T.P. Chen, K.W. Wan, G. Ganesh (2018).Towards Emergence of Tool Use in Robots: Automatic Tool Recognition and Use without Prior Tool Learning. *IEEE International Conference on Robotics and Automation, ICRA* 2018.

Y. Suzuki, G. Ganesh, Y. Miyawaki (2018). Investigation of the change in body representation due to a sixth finger. 17th Winter workshop on the mechanisms of brain and mind, *January 2018*.

G. Ganesh (2017). Functionality as the key determinant of limb/body ownership: a discussion. Invited *Talk at the Symposium of the Special Interests Group on Tele-existence, 12the December 2017*.

〔図書〕（計　1　件）

T. Ikegami, H. Nakamoto, G. Ganesh. Action and Prediction driven contagions in human actions. Book chapter in press in the MIT press Handbook on *Embodied Cognition and Sports Psychology*.

〔産業財産権〕

○出願状況（計　　件）

名称：
発明者：
権利者：
種類：
番号：
出願年月日：
国内外の別：

○取得状況（計　　件）

名称：
発明者：
権利者：
種類：
番号：
取得年月日：
国内外の別：

〔その他〕
ホームページ等

６．研究組織

(1)研究代表者

ＧＯＷＲＩＳＨＡＮＫ　ＡＲ．Ｇ

(GOWRISHANKAR Ganesh)

国立研究開発法人産業技術総合研究所・情報・人間工学領域・国際客員研究員

研究者番号：10570244

(2)研究分担者

宮脇　陽一　　(MIYAWAKI Yoichi)

電気通信大学・先端領域教育研究センター・教授

研究者番号： 80373372

(3)連携研究者

(　　)

研究者番号：

(4)研究協力者

(　　)