科学研究費助成事業　　研究成果報告書

令和　３ 年　 ４ 月 ２７ 日現在

機関番号：１４４０１
研究種目：若手研究
研究期間：2019～2020
課題番号：１９Ｋ２０３２１

研究課題名（和文）3Dプリンタの柔らかさ表現能力を拡張する計算論的ファブリケーション研究

研究課題名（英文）Computational Fabrication Approach to Extend the Softness Capabilities of 3D Printers

研究代表者
プンポンサノン　パリンヤ（PUNPONGSANON, PARINYA）

大阪大学・基礎工学研究科・助教

研究者番号：９０８１２２２２

交付決定額（研究期間全体）：（直接経費）　　3,200,000円

研究成果の概要（和文）：3Dプリンターで出力した際の硬さ・柔らかさの知覚には、粗さの知覚（注：先行研究）に加えて、内部構造（充填率を一定にした場合）と表面微細構造が影響することがわかりました。しかし、内部の充填率に比べて、表面の微細構造は硬さや柔らかさの知覚に影響を与えないことも示唆されました。これらの結果は、微細構造を操作した場合の知覚的な粗さや知覚的な柔らかさとは一致したが、知覚的な粗さとは強く一致しなかった。これらの実験結果をもとに、3Dプリントされた物体の知覚された粗さに応じて、知覚された柔らかさを推定・予測する計算モデルを開発した。最後に，インバースモデリング法を用いて，任意のパラメータでモデルを検証した。

研究成果の学術的意義や社会的意義
本研究の成果は、標準的な既製の3Dプリンターに加えて、同じ3Dプリンティング・フィラメントを使用して、知覚される材料特性（例えば、柔らかさや硬さ）を拡張するために使用することができます。したがって、本研究で提案した方法は、必要な柔らかさに応じて微細構造を操作することで、3Dプリンターに必要な代替材料の数を減らすことができます（例えば、数種類の柔らかい材料を印刷する場合など）。また、知覚された柔らかさと粗さの対応関係も示唆されており、今後も様々な研究分野での展開が期待されます。

研究成果の概要（英文）：We found that in addition to the perception of roughness (note: previous research), the internal structure (when the filling rate is kept constant) and the surface microstructure affect the perception of hardness and softness when output by a 3D printer. However, the results also suggested that the surface microstructure had less influence on the perception of hardness and softness compared to the internal fill rate (e.g., infill ratio). These results were in agreement with perceived roughness and perceived softness when microstructure was manipulated, but not in strong agreement with perceived roughness. Based on these experimental results, we developed a computational model to estimate and predict the perceived softness of 3D printed objects according to their perceived roughness. Finally, we also verified the model with arbitrary parameters using inverse modeling method.

研究分野：ヒューマン・コンピュータ・インタラクション

キーワード：デジタルファブリケーション　3Dプリンター出力　柔らかさ・硬さ

１．研究開始当初の背景

3D printing has enabled **massive creativity** in product design both personal and industrial. The use of 3D printing technologies to increase usability and accessibility of the products to meet each individual requirement **increased at** a **dramatic rate**. For example, the use of 3D printer to fabricate vehicles allows the customer to customize its design to fit the personal lifestyle or the printed footwear that fit individual foot arch types. While these emerging technologies excel at realizing a **personal shape or form**, these objects **lack the personal desired of softness by users**, limited the **perceptual desired**. Therefore, **adding the desired softness** is one of an **important factor** to enhance the capability of the 3D printers as it is directly related to how human recognized the objects. In my previous work, I have explored the technique to tackle such issues by enabling visually haptic design [2] in an arbitrary object. My previous work realized a technique to **manipulate the softness of physical objects using a projection-mapping** technique. However, the proposed method only allows the user to simulate the various softness **without actually fabricated** physical object. Solving such limitation of fabricated object usually done by extending the number of materials or using an expensive hardware. As the range of materials used by current 3D printing is **more limited**, softness and other haptic properties often must be **controlled with geometry variation**, rather than with the choice of physical material.

２．研究の目的

While the objects' softness is **varying among individual**, prior work shows that modify either hardware component of fabrication machine or even adding air to the 3D printed output could manipulate the stiffness properties of the objects. However, such methods are **requiring special materials** and **not possible to apply to a standard 3D printer**, which usually available at home and personal use, but only work with manufacturing printers. This leads to a number of research challenges represented as the **key scientific question** —how to **fabricate a 3D printed** object **using a single material with varying softness properties**? —To answer the above scientific question, I will focus on **exploring the 'softness perception'** for 3D printing to fulfill the personal preference due to the number of materials and printing constraints.

Fabricating the haptics sensation in 3D printed object could contribute to both functional and aesthetic value of the product, and serve a personal requirement. In this proposal, I propose a technique to **print a soft object** from an **existing 3D printing materials** through **computational fabrication** based on end-end fabrication process to manipulate the printing soft objects that meet a personal need (Figure 1). In particular, this proposal evaluating a new method, **computational approach**, to tackle softness printing challenge based on the **correlation** between **available number of materials**, **printing parameters** (surface texture and internal structure), and **target human perception** in order to obtain a computational model that allows to predict the printing parameters from the desired softness input by user. To summarize, this proposal aims to investigate a **new technique to fabricate a soft object** with 3D printer based on the **personal need**, with a hardware constraint (personal 3D printer), and within an available number of materials.

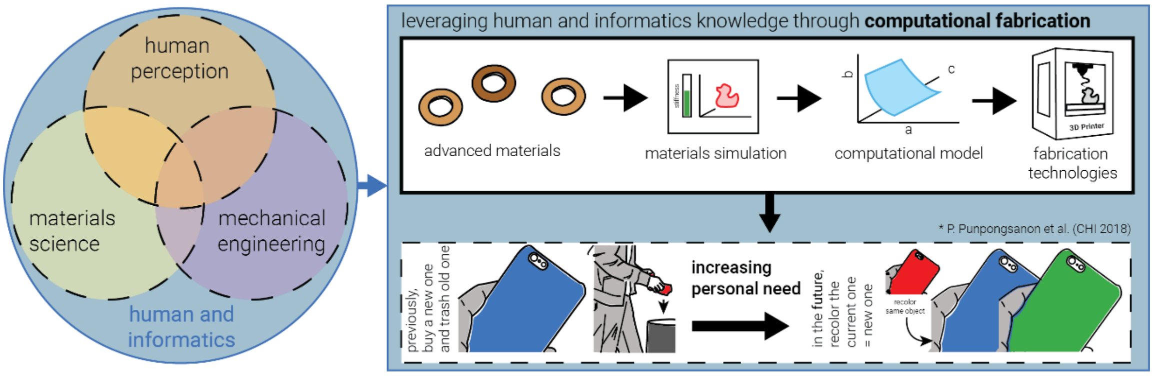

Figure 1 This proposed research aims to integrate the advanced materials, human perception, and fabrication technologies as an approach to realize everyday objects that match personal need.

３．研究の方法

Although various infill densities (i.e., the volume inside the 3D printed object) can modify the perceived softness, it is unclear whether the indentation and contact area of pits that modify perceived roughness could also contribute to the softness sensation. On the other hand, modifying the contact area used in the roughness perception model may change the perceived softness, but no such investigation has been conducted thus far. This work is the first to explore haptic softness perception from a given roughness perception in an FDM. Therefore, I conducted the first experiment to **investigate the best infill structure** that would allow to change the softness of fabricated 3D objects in the widest softness perception range. Then, I conducted the second experiment to **investigate the effect of contact area on softness sensation** by controlling pits density in addition to infill density.

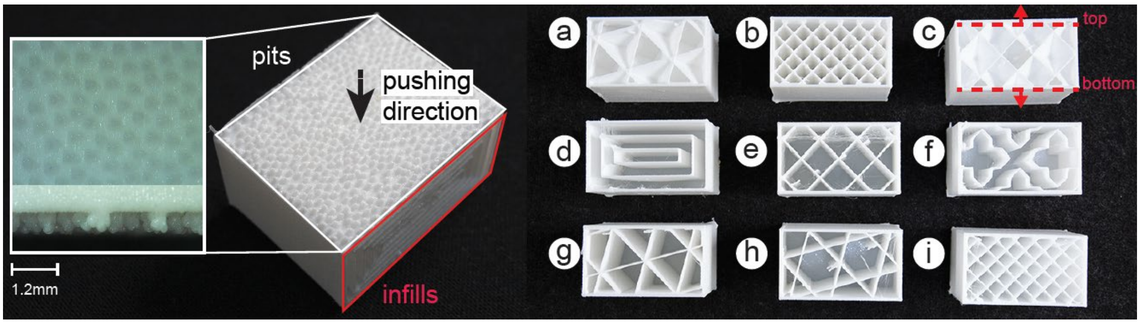

Figure 2 A sample 3D printed object with pits and concentric infill structure used in the experiment 1 and 2. I prepared (a) cubic (CU), (b) line (LI), (c) octet (OC), (d) concentric (CO), (e) grid (GR), (f) cross (CR), (g) triangle (TR), (h) tri-hexagon (TH), and (i) zigzag (ZI) infill structures as the stimuli to explore the perceived softness. The samples show the cut 3D printed object to display the internal structure on the side (i.e., user touch the object from the top shown in red line).

Unlike previous work, the pits and slab were made by an FDM 3D printer (Ultimaker 3, 0:4 mm nozzle resolution) using TPU material (Ultimaker TPU95A filament, 2.8mm diameter). Since the previously investigated pits model for roughness perception was fabricated using a high-resolution industrial 3D printer, I set the pits resolution at one compatible with that of the FDM 3D printer from the preliminary experiment [1]. The mechanical softness of 3D printed objects was measured by a standard elastic SHORE TYPE A/ISO 7619 using an off-the shelf durometer (TECLOCK GS-709N). The 3D printed objects were made without modifying the 3D printing parameters or enhanced the printer except for the infill density parameter (Figure 2). 1) Slab: The slab was printed with a square shape, W350 mm x H350 mm x D200 mm in size. The infill density was set at 5% after considering the standard FDM 3D printing recommended minimum. The infill structure was varied; cubic (CU), line (LI), octet (OC), concentric (CO), grid (GR), cross (CR), triangle (TR), tri-hexagon (TH), and zigzag (ZI). I selected the infill structure patterns from the standard set of pattern frequently used by FDM 3D printers and considering the printable structure without any support materials [3]. 2) Pits: I prepared five sparse pits by adapting the distance between each pit λ parameter from previous findings on roughness perception in 3D printed objects. Each pit was printed as a cone shape, 3 mm in diameter and 1 mm height. I conducted the pilot study to verify the adapted λ was compatible with the FDM 3D printer [28]. I decided on λ-values of 0:685 mm, 0:815 mm, 0:935 mm, 1:063 mm, and 1:250 mm, respectively, for this study. In the follow section, I explore infill structures that provide a soft perception. Then, I used these results to expand the softness domain to the roughness perception model (Figure 3).

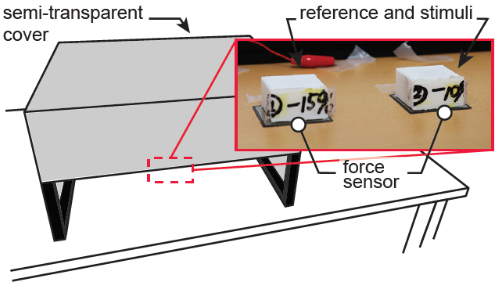

Figure 3 Experiment setup: a semi-transparent cover set over the experiment to prevent participants from seeing the stimuli while still allowing them to estimate the touch location.

4．研究成果

The result in Figure 4 shows the average perceived softness of each stimulus (e.g., the 3D printed objects with various infill patterns). The participants felt softer with concentric (avg. 128.33) infills than line (avg. 144.16), octet (avg. 144.16), cubic (avg. 153.91), cross (avg. 165.67), grid (avg. 177.33), triangle (avg. 177.16), zigzag (avg. 180.41) and tri-hexagon (avg. 182.00), respectively. I performed a one-way ANOVA and found the main effect of infill density (F(8; 107)

= 19.452, $p = 0.001$). From the experiment result, I found that concentric infill pattern (Figure 2d) provided the softer perception compared to other infill patterns. Therefore, I will use CO as the internal structure in the following experiment.

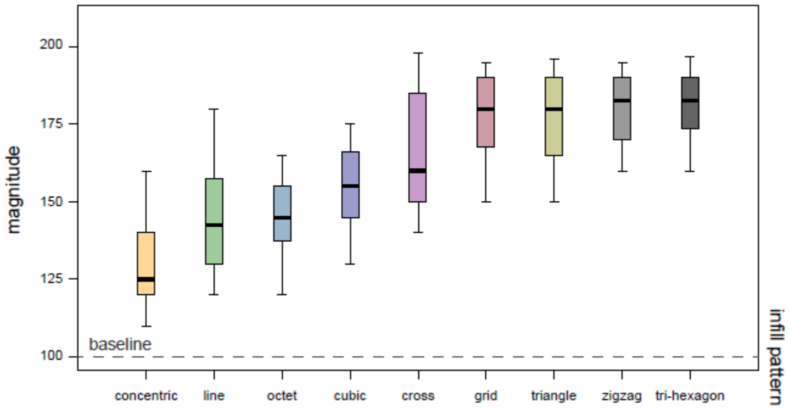

Figure 4 Boxplotof subjective magnitudes of perceived softness for each infill pattern. The whiskers represent the highest and lowest values within 1.5 and 3 times the interquartile range without outliers. The baseline shows the magnitudes of perceived softness for the reference object.

The participants felt stimuli softer with 5% infill and λ = 1:25 (118) than 1.063 (119.5), 0.933 (133.5), 0.873 (139.5), and 0.688 (159), respectively. Similarly, for the 10% infill, the participants felt the stimuli softer with λ = 1:25 (162) than 1.063 (187), 0.933 (174), 0.873 (172), and 0.688 (204), respectively. However, from the result, I could not find a clear relationship between softness perception and pits parameters with 15%, 20%, and 25% infills. I intentionally performed a Tukey's Hinges method to identify and remove outliers. Therefore, the following analysis was performed on the data that did not include outliers. I also conducted a Shapiro-Wilk test to verify normality and a Mauchly's test to check the sphericity criteria ($p <$ 0:05) before identify the effect of infill and pits conditions in both tasks. Then, I performed a two-way repeated ANOVA. with the factors of infills and pits for each exploration task to identify the interaction effect on the between initial and intervention tasks. The results show that there was a significant main effect of the infills and pits conditions in the initial task ($F(24; 239) = 5:834$, $p = 0:003$) and a significant main effect in the intervention task ($F(24; 239) = 5:061$, $p = 0:002$). There was no significant interaction effect between the two tasks ($F(576; 239) = 1:013$, $p = 0:451$).

I used a dependent t-test to identify the significant effect of pits among the same infills. As shown in Figure 5, I found significant differences in the following conditions. For 5% infills: 0.688mm – 0.873mm ($t = 2.847$,$p < 0.05$), 0.688mm – 0.938mm ($t = 3.484$,$p < 0.01$), 0.688mm – 1.063mm ($t = 3.990$; $p < 0.01$), and 0.688mm – 1.25mm ($t = 3.993$; $p < 0.01$). For 10% infills: 0.688mm – 0.873mm ($t = 2.725$; $p < 0.05$), and 0.688mm – 1.25mm ($t = 2.661$; $p < 0.01$). For 20% infills: 0.688mm – 0.873mm ($t = 3.011$; $p < 0.05$), 0.873mm – 0.938mm ($t = -3.362$; $p < 0.01$), and 0.873mm – 1.063mm ($t = - 2.939$; $p < 0.05$). Then, I conducted the Pearson product-moment correlation coefficient (i.e., Pearson's correlation) and performed a regression analysis to predict the value of infill and pits density outside the scale of printing parameters.

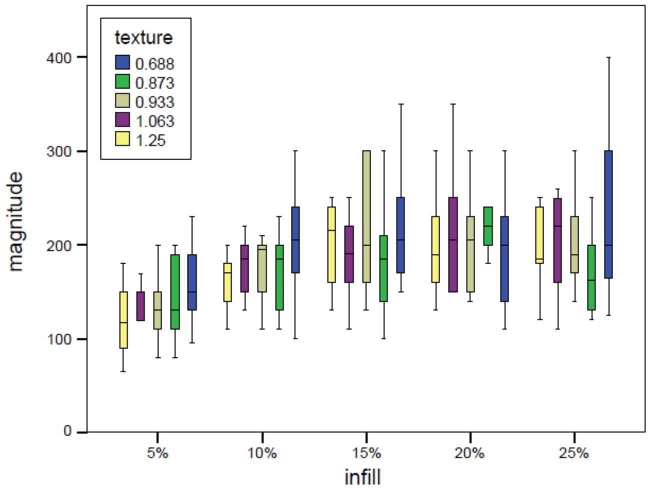

Figure 5 Boxplot of subjective magnitudes of perceived softness for each infill and pit parameter. The whiskers represent the highest and lowest values within1.5 and 3 times the interquartile range without outliers.

The results show that both infills and pits density significantly impact perceived softness and roughness sensations. The psychophysical experiment confirmed that the infills and pits density parameters significantly affect the perceived amount of softness, especially in the range between 5% and 10% infill densities. The results correspond to previous findings, which suggested a significant connection between the contact area between the finger and target objects and to the perceived roughness and haptic softness.Furthermore, this work found another dimension—softness perception from the given perceived roughness. The computational model can estimates the FDM 3D printing parameter and infill density by giving target perceived softness and target perceived roughness. Therefore, to create the 3D printed objects with a specific desired softness experience, the designer needs to carefully determine the appropriate infill density that will result in the desired softness perception given a target roughness perception.

From the above results, I proposed a soft display system that has both low production cost and high ability to express softness. The system allows the expression of softness by controlling the rigidity of a mixed material and the deformation of a surface to additively allow to design the softness of 3D printed object before actual fabrication [4].

＜引用文献＞

[1] 三好幹，プンポンサノン・パリンヤ，岩井大輔，佐藤宏介．3Dプリンタ出力に対して知覚される硬軟度操作のための表面微細形状と内部構造設計．第63回システム制御情報学会研究発表講演会，2019，1203-1207.

[2] Parinya Punpongsanon et al. SoftAR: Visually Manipulating Haptic Softness Perception in Spatial Augmented Reality. IEEE TVCG, 2015.

[3] Motoki Miyoshi, Parinya Punpongsanon, Daisuke Iwai, and Kosuke Sato. Preliminary Study on Surface Texture to Manipulate perceived Softness of 3D Printed Objects. In Proceedings of International Conference on Artificial Reality and Telexistence with Eurographics Symposium on Virtual Environments (ICAT-EGVE) 2019, pp. 17-18. 2019.

[4] Motoki Miyoshi, Parinya Punpongsanon, Daisuke Iwai, and Kosuke Sato. Investigation of Soft Display using Digital Fabrication and Phase-change Material. In Proceedings of 2021 IEEE 3rd Global Conference on Life Sciences and Technologies (LifeTech), pp. 513-514. 2021.

５．主な発表論文等

〔雑誌論文〕　計5件（うち査読付論文　5件／うち国際共著　5件／うちオープンアクセス　0件）

１．著者名 Motoki Miyoshi, Parinya Punpongsanon, Daisuke Iwai, Kosuke Sato	４．巻 1727
２．論文標題 Preliminary Study on Surface Texture to Manipulate Perceived Softness of 3D Printed Objects	５．発行年 2019年
３．雑誌名 International Conference on Artificial Reality and Telexistence and Eurographics Symposium on Virtual Environments 2019	６．最初と最後の頁 17-18
掲載論文のDOI（デジタルオブジェクト識別子） 10.2312/egve.20191296	査読の有無 有
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 該当する

１．著者名 Ying-Ju Lin, Parinya Punpongsanon, Xin Wen, Daisuke Iwai, Kosuke Sato, Marianna Obrist, Stefanie Mueller	４．巻 294
２．論文標題 FoodFab: Creating Food Perception Illusions using Food 3D Printing	５．発行年 2020年
３．雑誌名 ACM CHI Conference on Human Factors in Computing Systems 2020	６．最初と最後の頁 294:1-294:13
掲載論文のDOI（デジタルオブジェクト識別子） 10.1145/3313831.3376421	査読の有無 有
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 該当する

１．著者名 Haruki Takahashi, Parinya Punpongsanon, Jeeeun Kim	４．巻 0
２．論文標題 Programmable Filament: Printed Filaments for Multi-material 3D Printing	５．発行年 2020年
３．雑誌名 The 33rd Annual ACM Symposium on User Interface Software and Technology	６．最初と最後の頁 1209-1221
掲載論文のDOI（デジタルオブジェクト識別子） 10.1145/3379337.3415863	査読の有無 有
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 該当する

１．著者名 Pat Pataranutaporn, Ali Shtarbanov, Glenn Fernandes, Jingwen Li, Parinya Punpongsanon, Joe Paradiso, Pattie Maes	４．巻 0
２．論文標題 Wearable Sanitizer: Design and Implementation of an Open-source, On-body Sanitizer for a Post-Pandemic	５．発行年 2020年
３．雑誌名 ACM SIGGRAPH Asia 2020: Emerging Technologies (eTech)	６．最初と最後の頁 1:1-1:3
掲載論文のDOI（デジタルオブジェクト識別子） 10.1145/3415255.3422897	査読の有無 有
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 該当する

1．著者名 Motoki Miyoshi, Parinya Punpongsanon, Daisuke Iwai, Kosuke Sato	4．巻 1255
2．論文標題 Investigation of Soft Display using Digital Fabrication and Phase-change Material	5．発行年 2021年
3．雑誌名 2021 IEEE 3rd Global Conference on Life Sciences and Technologies (LifeTech)	6．最初と最後の頁 510-511

掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/LifeTech52111.2021.9391833	査読の有無 有
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 該当する

〔学会発表〕　計3件（うち招待講演　0件／うち国際学会　1件）

1．発表者名 三好幹，プンポンサノンパリンヤ，岩井大輔，佐藤宏介
2．発表標題 3Dプリンタ出力に対して知覚される硬軟度操作のための表面微細形状と内部構造設計
3．学会等名 第63回システム制御情報学会研究発表講演会
4．発表年 2019年

1．発表者名 Parinya Punpongsanon, Ying-Ju Lin, Xin Wen, Daisuke Iwai, Kosuke Sato, Marianna Obrist, Stefanie Mueller
2．発表標題 Demonstration of FoodFab: Creating Food Perceptual Illusions using Food 3D Printing
3．学会等名 ACM CHI Conference on Human Factors in Computing Systems 2020（国際学会）
4．発表年 2020年

1．発表者名 堀 悠太郎，平木 剛史，プンポンサノン パリンヤ，岩井 大輔，川原 圭博，佐藤 宏介
2．発表標題 双安定性サーモクロミックインクの選択的加熱を用いた造形後に表面色・模様を制御可能な立体物造形手法
3．学会等名 情報処理学会 インタラクション2021
4．発表年 2021年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

－

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