BioSystems 235 (2024) 105106

Contents lists available at ScienceDirect

BioSystems

journal homepage: www.elsevier.com/locate/biosystems

Fungal skin for robots

Antoni Gandia [a], Andrew Adamatzky [b,*]

[a] Institute for Plant Molecular and Cell Biology, CSIC-UPV, Valencia, Spain
[b] Unconventional Computing Laboratory, UWE, Bristol, UK

ARTICLE INFO

Keywords:
Fungi
Bio-electronics
Bio-wearables
Electrical activity
Spiking

ABSTRACT

Advancements in mycelium technology, stemming from fungal electronics and the development of living mycelium composites and skins, have opened new avenues in the fusion of biological and artificial systems. This paper explores an experimental endeavour that successfully incorporates living, self-regenerating, and reactive *Ganoderma sessile* mycelium into a model cyborg figure, creating a bio-cybernetic entity. The mycelium, cultivated using established techniques, was homogeneously grown on the cyborg model's surface, demonstrating robust reactivity to various stimuli such as light exposure and touch. This innovative merger points towards the future of sustainable biomaterials and the potential integration of these materials into new and existing technologies.

1. Introduction

The fusion of organic and inorganic materials is not a new concept in science. In fact, the pursuit of this fusion has been a driving force behind numerous technological innovations, from the development of bio-electronics to the creation of synthetic organisms (Meunier et al., 2010a,b; Vallet-Regí et al., 2011; Sicard et al., 2010; Maciel et al., 2021; Yoon et al., 2020; Bai et al., 2023; Yoon et al., 2019; Fallegger et al., 2020; Huang et al., 2020). However, the potential of harnessing the power of fungi, specifically their mycelium networks, sensorial fusion, information processing and decision making is a relatively novel exploration (Adamatzky, 2023; Adamatzky et al., 2022). The organic networks created by fungi have been shown to be highly adaptable and responsive to their environment, exhibiting electrical behaviours similar to that of neural networks (Adamatzky, 2022; Adamatzky and Gandia, 2021; Gandia and Adamatzky, 2022). By tapping into these inherent properties, we can start to envision a future where organic and inorganic materials coexist, creating a new breed of bio-cybernetic entities.

The field of fungal electronics (Adamatzky, 2023; Adamatzky et al., 2022) is a rapidly evolving research frontier, characterised by the development of electronic devices made of mycelium-bound composites and pure mycelium skins (Adamatzky et al., 2022; Danninger et al., 2022; Adamatzky et al., 2021a; Web article:, 2014; Bayer and McIntyre, 2014). These devices are capable of changing their impedance and generating spikes of electrical potential in response to external control parameters. The utility of fungal electronics extends to being embedded into fungal materials and wearables or serving as standalone sensing and computing devices (Adamatzky et al., 2021a,b; Vasquez and Vega, 2019).

The research into mycelium composites has led most of the advancements in mycelium technologies for the past decade (Jones et al., 2020b; Attias et al., 2020; Girometta et al., 2019). Such materials are not only eco-friendly but also exhibit a range of intriguing properties when kept alive. For instance, *Ganoderma resinaceum*, a type of filamentous polypore fungus, can colonise a variety of lignocellulosic substrates and react to physical stimuli, such as pressure from heavy weights (Adamatzky and Gandia, 2022). On the other hand, growing efforts are being poured into the development of pure mycelium materials aiming to replace animal and synthetic leather and textiles. Such materials, known as fungal-based biotextiles, mycoleather, or mycofabrics, are produced following different techniques such as liquid- and solid-state fermentation (Jeong et al., 2023; Gandia et al., 2021; Adamatzky et al., 2021a; Cartabia et al., 2021; Jones et al., 2020a) (Fig. 1).

The ability of the living fungal materials to respond to and interact with their environment (Dehshibi et al., 2021), as well as recent interest and investigation into self-healing properties (Elsacker et al., 2023; Web Article:, 2017, 2016), make the fungi in the genus Ganoderma prime candidates for integration into cyborg technologies.

Fungi are traditionally considered non-excitable organisms, unlike animals and some plants, which have well-defined electrical signalling systems. However, recent studies have revealed intriguing aspects of electrical behaviour in certain fungal species. Here are some key points. Fungi have been observed to display electrical potentials during hyphal growth. Namely, an electrical current is initiated by a hypha:

---

* Corresponding author.
E-mail address: andrew.adamatzky@uwe.ac.uk (A. Adamatzky).

https://doi.org/10.1016/j.biosystems.2023.105106
Received 25 November 2023; Received in revised form 16 December 2023; Accepted 16 December 2023

Fig. 1. Example of living floating fungal mat grown on MEB liquid medium.

positive current, more likely carried by protons (McGillviray and Gow, 1987), enters the tip of a growing hypha (Gow, 1984; Harold et al., 1985). The reported current density is documented to reach up to 0.6 μA/cm^2(McGillviray and Gow, 1987). Electrostatic repulsion of charged basidiospores propels the spores away from similarly charged basidia (Savile, 1965; Leach, 1976). The involvement or association of electrical current with the translocation of material is reported to occur concurrently with hydraulic pressure (Rayner, 1991). There is evidence suggesting the participation of electrical current in the interactions between mycelium and plant roots during the formation of mycorrhiza (Berbara et al., 1995). In 1976, Slayman, Long, and Gradmann identified action potential-like spikes through intracellular recordings in the mycelium of *Neurospora crassa* (Slayman et al., 1976). Two decades later, Olsson and Hansson demonstrated spontaneous action potential-like activity in the hyphae of *Pleurotus ostreatus* and *Armillaria bulbosa* using intracellular recordings with a reference electrode in the agar substrate (Olsson and Hansson, 1995).

The interest to electrical activity of fungi resurrected in 2018, when we reported on action-potential like spiking in oyster fungi (Adamatzky, 2018). This followed by a series of discoveries on complexity of electrical spiking (Dehshibi and Adamatzky, 2021; Adamatzky, 2022) and mapping of the tactile, chemical and optical stimuli to distinctive patterns of electrical activity (Dehshibi et al., 2021; Adamatzky et al., 2021b; Adamatzky and Gandia, 2022).

Building upon these principles, we attempted to create a living, self-regenerating, and reactive mycelium skin by growing the mycelium of the fungus *G. sessile* on a cyborg figure. An 18 cm tall T-800 Terminator model served as a physical structure that could be enhanced with the biological capabilities of the mycelium. The experiment aimed to demonstrate the potential of mycelium as a functional, responsive interface for cybernetic systems, thereby inspiring a new step towards a new class of bio-organic technologies.

The experiment involving living fungal skin holds specific interest for design and engineering applications, particularly in the realm of cyborg technologies. The potential benefits and areas of interest include: adaptive and responsive design, biohybrid sensing systems, self-healing robotic structures, morphable and flexible robotics, human–machine interaction and interfaces, environmental sensing and monitoring, biocompatible and biodegradable materials.

2. Methods

To create the mycelial cyborg, we utilised a two-pronged approach: firstly, we cultivated a minimal viable amount of *G. sessile* mycelium using a suitable liquid medium and proper environmental conditions. Secondly, we established a methodology for embedding the mycelium onto the surface of a model figure, a scale 1:10 T-800 Terminator endoskeleton (NECA, USA), effectively creating a functional living fungal exoskin.

Our choice of fungus for this experiment was *Ganoderma sessile*, selected for its robust growth and adaptability based in literature (Viceconte et al., 2021; Attias et al., 2021, 2020; Loyd et al., 2018). A living culture of *G. sessile* was provided by MOGU S.r.l. (Inarzo, Italy) with collection code 95-19 pv5. The mycelium was sub-cultured on Potato Dextrose Agar (VWR Chemicals, USA) in 90 mm Petri dishes. To promote optimal growth, the culture was kept in darkness at an ambient room temperature of circa 22–23 °C for 5 days (Fig. 2a).

A mycelial plug from an active colony grown on PDA was transferred to a 1L liquid culture bottle filled with sterile malt extract broth (MEB). The liquid culture was then incubated for 7 days under stirring conditions, and homogenised with a laboratory blender before use (Waring, USA). The cyborg figure model, made from plastic resin, was subsequently prepared to accommodate the mycelium growth. The figure surface was pre-treated with a commercial sporicide (Ecolab, DE) and with ethanol 70%, and washed repeatedly with sterile demiwater (Fig. 2b). To allow the fungal tissue to grow on the surface, the cyborg model figure was coated with a thin layer of malt extract agar (MEA). Once the MEA coating gelatinised, the figure was briefly submerged in the homogenised liquid culture previously prepared to allow the fungal hyphae to attach. The model was then placed in a PP5 filter-patch microbox container (SaCO2, Belgium) under controlled environmental conditions, and incubated for an additional 7 days at a constant ambient temperature of 22°C and in absence of light. Once the mycelium was fully established on the surface of the model figure, we proceeded to conducting the electrical recordings.

Electrical activity was recorded using iridium-coated stainless steel sub-dermal needle electrodes (Spes Medica S.r.l., Italy). Four pairs of electrodes were inserted into the neck (channel 1–2), the back (channel 3–4), and the two arms (channel 5–6 in the right arm and channel 7–8 in the left arm) of the mycelium-covered model (Fig. 2cd and Fig. 3) with distances between electrodes ranging of approx. 1 cm.

The high-resolution data logger ADC-24 (Pico Technology, UK) was used to record electrical activity, averaging as many measurements as possible (600 per second). The signals have been analysed in a semi-automatic mode and using algorithm proposed in Adamatzky (2022). The signal quality is contingent upon the positioning of electrodes relative to the hyphal network. Consequently, signals may exhibit variations, at times presenting as noise while in other instances appearing clearer. Although signal quality enhancement can be achieved through averaging and filtering techniques, we opt to present raw data to readers in the interest of transparency.

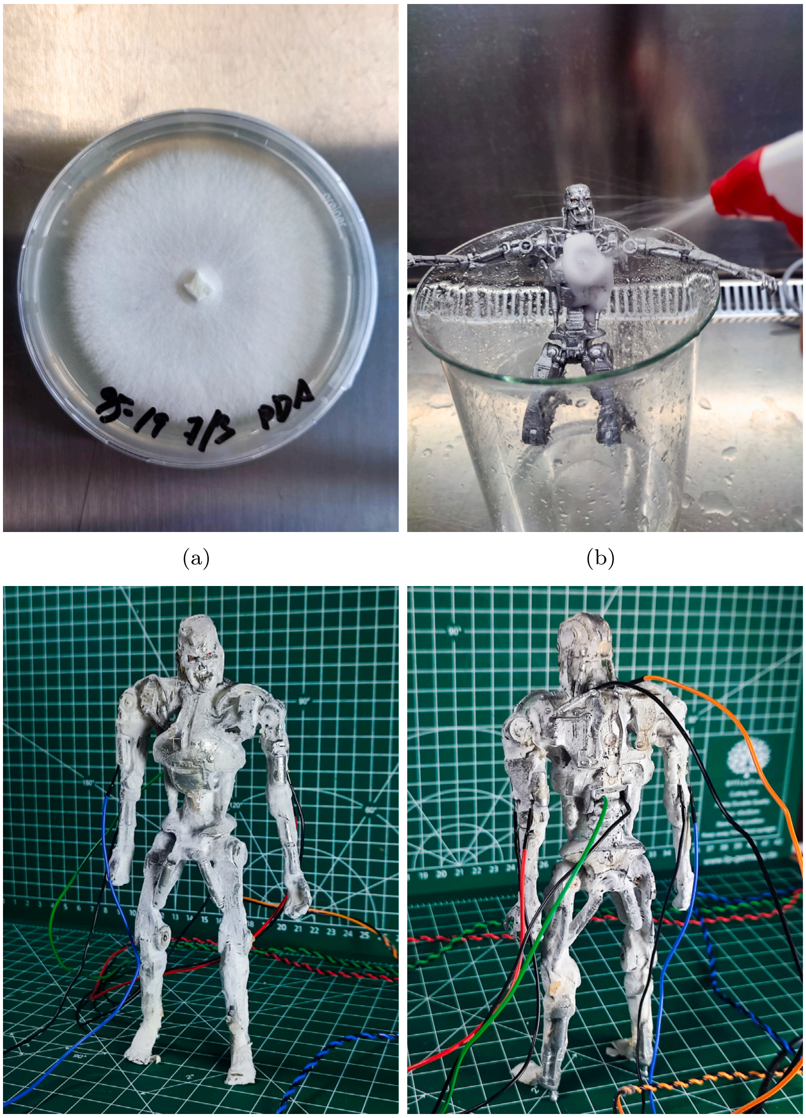
The environmental relative humidity in the recording chamber was maintained between 70%–80%.

With the electrodes in place, two different experiments were conducted to stimulate the fungal tissue mechanically and optically. In the first experiment, mechanical stimulation in form of slight touch was applied to the fungal tissue using a non-conductive wooden stick. In the second experiment, the fungal tissue was stimulated optically using a white LED lamp placed at a distance of approx. 60 cm from the surface of the myceliated figure.

3. Results

The *G. sessile* mycelium showed robust growth on the agar-coated surface of the cyborg model. It successfully colonised the entire surface of the model in 5 days, creating a fully organic layer that intertwined with the inorganic substrate of the model. This resulted in a visually striking juxtaposition of the organic mycelium and the inorganic cyborg model, symbolising the fusion of biology and technology.

An example of high-frequency spiking is shown in Fig. 4. Average distance between spikes is 25 s (median 13 s, $\sigma = 65$) (Fig. 4b).



(a) (b)

(c) (d)

Fig. 2. Experimental procedure; (a) culture plate of *Ganoderma sessile* used in the experiments, (b) sanitisation of the model figure with sporicide and ethanol 70%, (c) close-up view of the myceliated model figure, (d) exemplar locations of electrodes on the living mycelium exoskin.

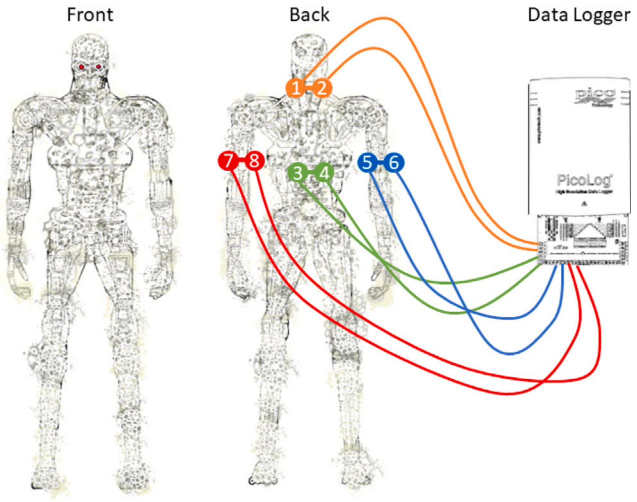


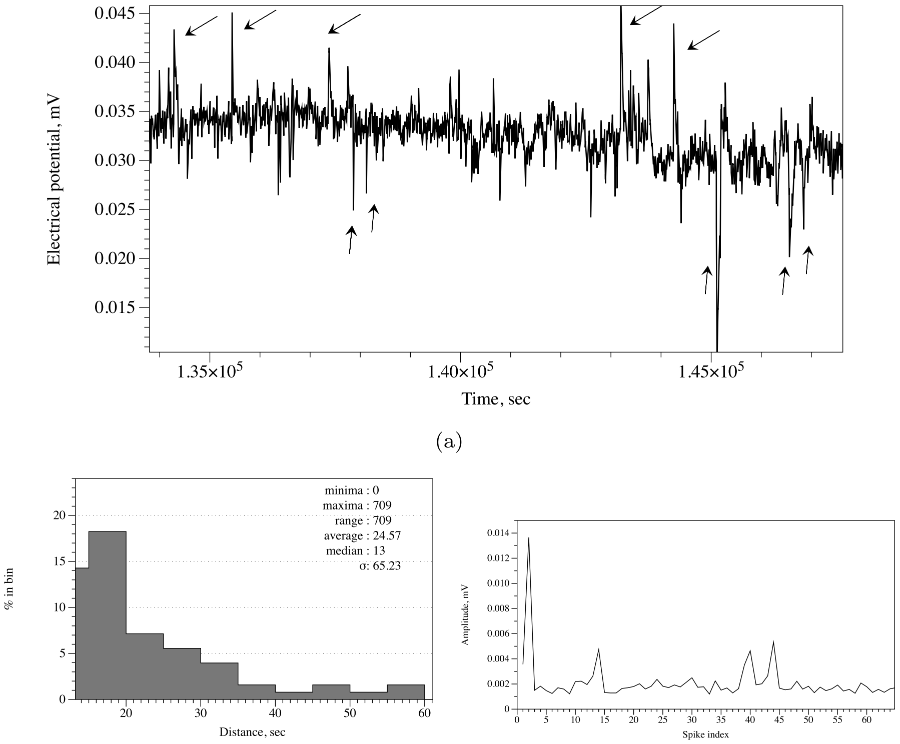
Fig. 3. Schematic placement of the electrode pairs inserted on the back side of the living mycelium exoskin grown on a T-800 Terminator model figure.

Amplitudes of fast spikes are strongly around average 0.0021 mV (median 0.0017, σ = 0.0016) Fig. 4c.

Example of a very low frequency oscillations of electrical potential are shown in Fig. 5a. Slow oscillations are characterised by the following parameters. Average width of a spike is 125 min (median 119 min, σ = 41) (Fig. 5b), average amplitude of spikes is 0.03 mV (median 0.03 mV, σ = 0.01) (Fig. 5c), average distance between spikes is 155 min (median 157 min, σ = 48) (Fig. 5d).

A 'train of spikes' denotes a series of spikes that occur sequentially over a period. In this context, each spike is succeeded by another spike, and the distance between them does not surpass twice the width of a single spike. (Dehshibi and Adamatzky, 2021; Adamatzky, 2022). We have observed trains of spikes in the intact fungal skin, as illustrated in Fig. 6. A number of spikes in a train can vary from 2 to 7 but typically 3-4. In contrast to our previous study we did not observe a sufficient number of train to collect statistics.

Our experiments showed that the fungal skin responded to the mechanical and optical stimulation by exhibiting changes in its electrical activity. An exemplar recording of the electrical activity during stimulation is shown in Fig. 7. A typical response to illumination is characterised by a substantial (0.02 mV to 2 mV) drift of the electrical potential away from the based level of intact activity (Fig. 8a).



(a)

(b)

(c)

Fig. 4. High frequency oscillations of electrical potential. (a) Exemplar of spikes with amplitude 0.01 mV or more are shown by arrows. (b) Distribution of distances between spikes, bin size 550.

Response to light stimulation is manifested equally on all electrode pairs due to the fact the myceliated model figure was illuminated from above, so most parts of the fungal skin were exhibited to the stimulus.

The potential returns to near baseline intact potential after the light is switched off. Fungal skin response to momentary tactile stimulation is manifested by single spikes of electrical potential (Fig. 8b). In the exemplar response, we see that the amplitude of the responses does not depend on the distance from the stimulus. Recall that the figuring was touched for c. 20 ms, by a non-conductive and non-charged wooden stick. Electrodes attached to the neck recorded a response with the amplitude 0.3 mV lasting 12 s (orange line in Fig. 8b). With a delay of 6 s responses were registered at other electrode pairs. The electrodes attached to the neck recorded a spike 0.1 mV for 5 s (green line in Fig. 8b). The neck's response is followed by relatively high-amplitude responses on arms with amplitudes 1.3 mV and 0.8 mV lasting for 36 s and 44 s (blue and red lines in Fig. 8b).

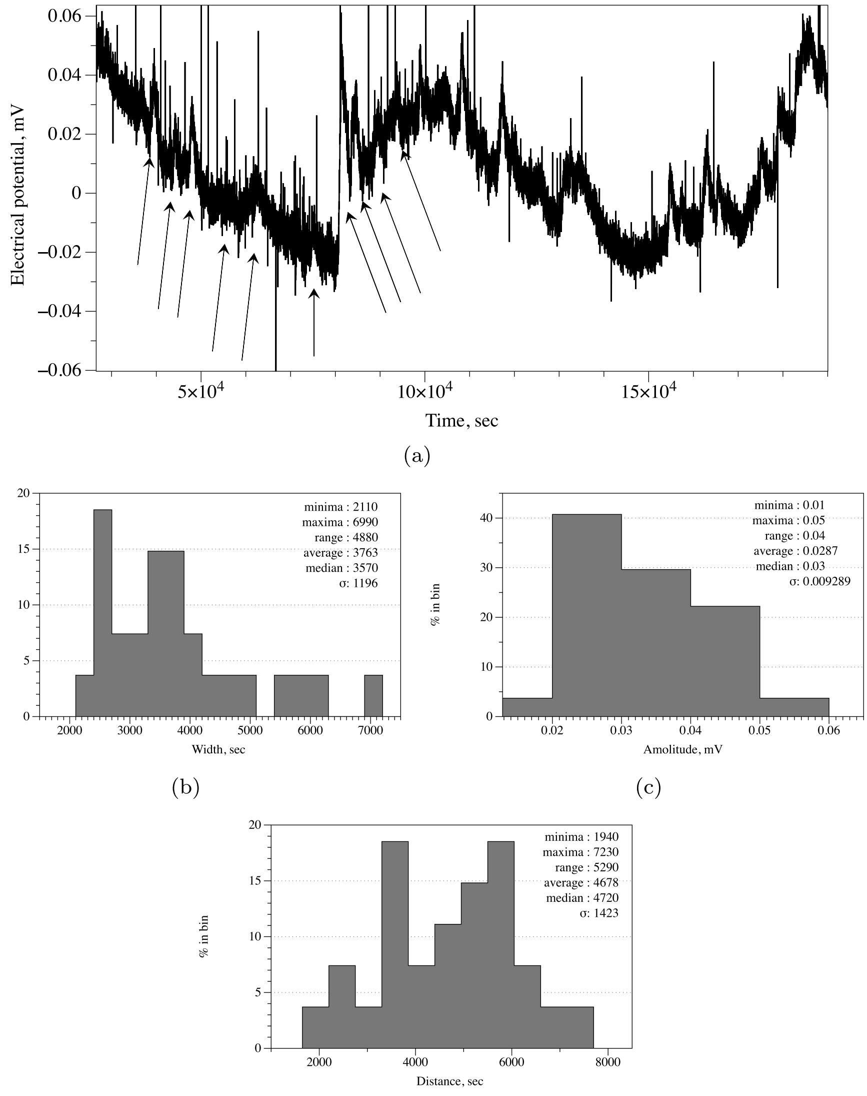
4. Discussion

The emergence of fungal-infused bio-cybernetics offers a novel avenue in our approach to integrating biology with technology. Through the utilisation of the unique properties of fungal hyphae, we can generate bio-cybernetic entities that are alive, responsive, and adaptive. The cyborg model in this study, en-sheathed in a layer of living mycelium, represents a symbol of this new frontier.

The observed electrical responses of the mycelium to external stimuli demonstrate the potential of mycelium as a natural sensor. As a form of biotechnology, this functionality could have far-reaching applications. For instance, creating robotics with a new level of tactile sensing, which could improve their performance in different applications, such as grasping delicate objects or working in unknown or unstructured environments. We could also raise buildings constructed with mycelium-infused materials that could self-regulate and respond to environmental changes, enhancing sustainability and energy efficiency. Similarly, mycelium-based wearables could monitor bodily conditions and react in real-time, creating a new paradigm for personalised medicine and self-preservation. Moreover, integrating fungal components into computing arrays could lead to hybrid systems that merge biological and technological functionalities. These systems might offer capabilities such as self-repair, adaptation to changing conditions, or even bio-assisted decision-making.

We acknowledge that the envisioned experimental methodology comes with certain constraints that warrant future consideration and refinement. One such constraint pertains to the necessity of maintaining the mycelium in an environment characterised by elevated humidity levels. This particular requirement underscores a potential limitation in the experimental setup that merits further investigation and potential optimisation in subsequent phases of the study. Additionally, another noteworthy limitation lies in our current lack of understanding regarding how the fungal skin will respond to the movement of the robot. This aspect introduces a degree of uncertainty, necessitating future research efforts to elucidate and address potential challenges associated with the dynamic interaction between the fungal skin and the robotic system. Resolving these uncertainties will contribute to a more comprehensive understanding of the proposed experimental approach and enhance its efficacy in practical applications.

The variability observed in response amplitudes following a mechanical stimulus could potentially be attributed to the heterogeneous structure of the mycelium network that forms the fungal skin. This heterogeneity may influence the distribution and strength of hyphae within the network. Additionally, the positions of electrodes in relation to the most robust hyphae could play a crucial role in shaping the recorded responses. The spatial arrangement of these electrodes in proximity to key elements of the mycelial structure might contribute to the observed variations in signal amplitudes. Hence, understanding both the intricate architecture of the mycelium network and the strategic placement of electrodes becomes essential for comprehending the nuances of the recorded responses.



(a)

(b)

(c)

(d)

Fig. 5. Low frequency oscillations of electrical potential. (a) Exemplar spikes are shown by arrows. (b) Distribution of spike width, bin size 300. (c) Distribution of spike amplitudes, bin size 0.01. (d) Distribution of distances between spikes, bin size 550.

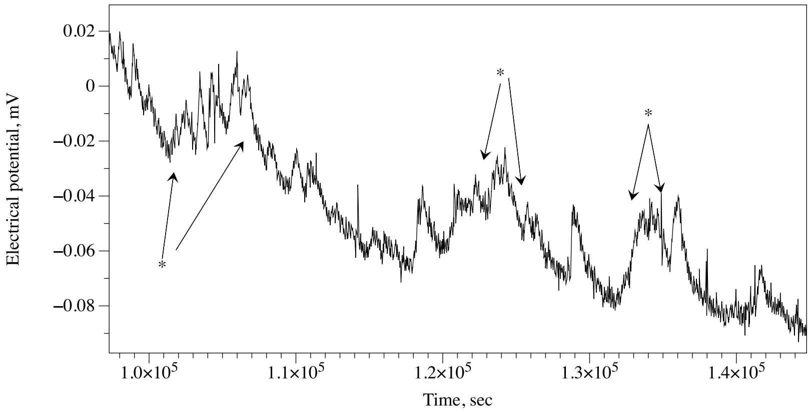


Fig. 6. Trains of spikes of electrical potential. Exemplar trains are shown by arrows with asterisk.

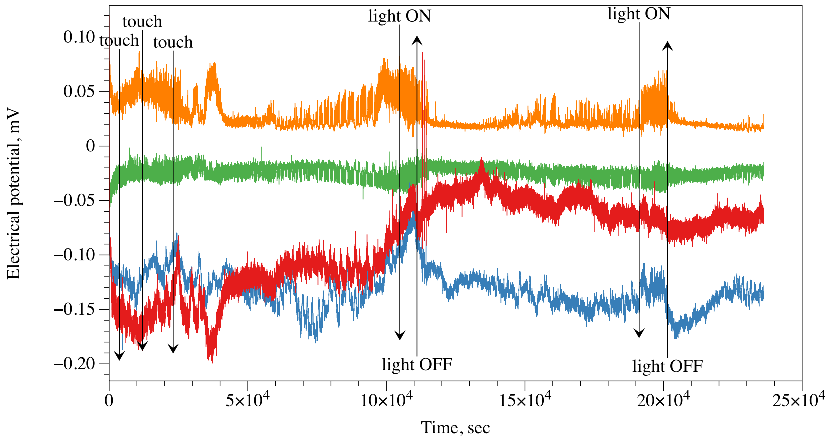


Fig. 7. Recording of electrical activity of fungal skin in response to tactile and light stimulation. Orange is channel 1–2, green channel 3–4, blue channel 5–6, red channel 7–8.

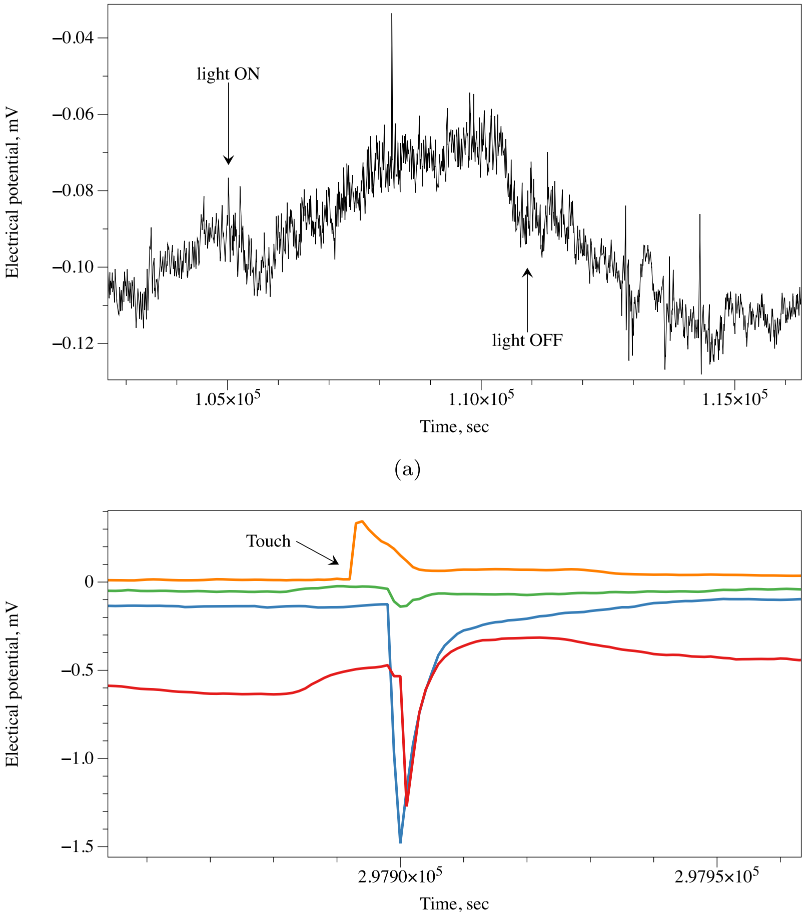


Fig. 8. Responses of fungal skin to (a) optical and (b) tactile stimulation. Orange is channel 1–2, green channel 3–4, blue channel 5–6, red channel 7–8.

The concept of utilising living fungal skin for robots presents intriguing possibilities across various fields. Here are some potential applications. First, is a biodegradable robotics (Rossiter et al., 2016; Wiesemüller et al., 2021; Zarei et al., 2023). Fungal materials are biodegradable. Incorporating living fungal skin into robot components could contribute to the development of environmentally friendly and biodegradable robots, which could be particularly useful in applications where traditional materials may pose ecological concerns. Second potential application is environmental monitoring (Dunbabin and Marques, 2012; Trincavelli et al., 2008; Dhariwal et al., 2004). Robots equipped with fungal skin could serve as environmental sensors. The living skin might react to specific environmental conditions, such as pollutants or changes in humidity, providing real-time data for environmental monitoring. Third is a self-healing robotics (Bilodeau and Kramer, 2017; Tan et al., 2021). Fungi have natural regenerative capabilities. Integrating fungal skin into robot structures could enable self-healing mechanisms, allowing the robot to repair minor damages autonomously and prolonging its operational lifespan. Fourth is biological interaction and sensing (Romano et al., 2019; Kaur et al., 2021; Murphy, 1996). Living fungal skin could be designed to interact

Fig. 9. "I'll be back".

with biological entities, such as plants or microorganisms. This could find applications in agriculture and forestry, where robots with fungal skin may sense and respond to plant health or assist in pollination processes. Fifth is soft robotics and morphable structures (Whitesides, 2018; Kim et al., 2013; Fu et al., 2020; Cicconofri et al., 2020). Fungal materials are inherently flexible. Incorporating fungal skin could lead to the development of soft robotics with morphable structures, allowing robots to navigate complex and dynamic environments more effectively. Sixth is biological energy sources. Some fungi can participate in bioelectrochemical processes. Living fungal skin might be employed in robots to harness biological energy sources, potentially enabling sustained operation without the need for traditional power supplies. Seventh is human–robot interaction and assistive devices (Sheridan, 2016; Goodrich et al., 2008). Fungal skin could enhance the tactile and sensory capabilities of robots, making them more suitable for human–robot interaction. This could be particularly valuable in the development of assistive devices for healthcare or daily living assistance. Eights is space exploration (Jemison and Olabisi, 2021; Gelinsky, 2020; Williams, 2022). The adaptability and resilience of fungal organisms make them potential candidates for robots designed for space exploration. Living fungal skin could help robots withstand harsh environmental conditions and contribute to the sustainability of long-duration missions.

In conclusion, our study showcases the potential of mycelium as a foundational element in the development of bio-cybernetic systems. However, it also illuminates the need for further research to better understand and harness these capabilities. Future investigations should focus on further elucidating the mechanisms underlying the electrical responses and habituation of mycelium to different stimuli, as well as the potential applications of mycelium-based electronics in various fields. Furthermore, the challenges of scaling up and maintaining fungal cultures alive during the intented operational time also need to be addressed before this technology can be fully implemented in practical applications. As we continue to push the boundaries of what is achievable with mycelium, solving these question marks will make us step closer to a future where bio-cybernetic systems are a part of our everyday lives (Fig. 9).

CRediT authorship contribution statement

Antoni Gandia: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Andrew Adamatzky:** Writing – review & editing, Writing – original draft, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare no conflicting interests.

Data availability

Data will be made available on request.

Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation programme FET OPEN "Challenging current thinking" under grant agreement No 858132. We extend our gratitude to James Cameron and Gale Anne Hurd for their inspirational role in shaping the direction of our research for this paper.

References

Adamatzky, Andrew, 2018. On spiking behaviour of oyster fungi *Pleurotus djamor*. Sci. Rep. 8 (1), 1–7.

Adamatzky, Andrew, 2022. Language of fungi derived from their electrical spiking activity. Royal Soc. Open Sci. 9 (4), 211926.

Adamatzky, Andrew (Ed.), 2023. Fungal machines: Sensing and computing with fungi. Springer.

Adamatzky, Andrew, Ayres, Phil, Beasley, Alexander E., Chiolerio, Alessandro, Dehshibi, Mohammad M., Gandia, Antoni, Albergati, Elena, Mayne, Richard, Nikolaidou, Anna, Roberts, Nic, Tegelaar, Martin, Tsompanas, Michail Antisthenis, Phillips, Neil, Wösten, Han A.B., 2022. Fungal electronics. Biosystems 212, 104588.

Adamatzky, Andrew, Gandia, Antoni, 2021. On electrical spiking of *Ganoderma resinaceum*. Biophys. Rev. Lett. 16 (04), 133–141.

Adamatzky, Andrew, Gandia, Antoni, 2022. Living mycelium composites discern weights via patterns of electrical activity. J. Biores. Bioprod. 7 (1), 26–32.

Adamatzky, Andrew, Gandia, Antoni, Chiolerio, Alessandro, 2021a. Fungal sensing skin. Fungal Biol. Biotechnol. 8 (1), 1–6.

Adamatzky, Andrew, Nikolaidou, Anna, Gandia, Antoni, Chiolerio, Alessandro, Dehshibi, Mohammad Mahdi, 2021b. Reactive fungal wearable. Biosystems 199, 104304.

Attias, Noam, Danai, Ofer, Abitbol, Tiffany, Tarazi, Ezri, Ezov, Nirit, Pereman, Idan, Grobman, Yasha J., 2020. Mycelium bio-composites in industrial design and architecture: Comparative review and experimental analysis. J. Clean. Prod. 246, 119037.

Attias, Noam, Reid, Michael, Mijowska, Sylwia Carolina, Dobryden, Illia, Isaksson, Marcus, Pokroy, Boaz, Grobman, Yasha J., Abitbol, Tiffany, 2021. Biofabrication of nanocellulose–mycelium hybrid materials. Adv. Sustain. Syst. 5, 2000196.

Bai, Hedan, Hu, Ziying, Rogers, John A., 2023. Hybrid materials approaches for bioelectronics. MRS Bull. 1–15.

Bayer, Eben, McIntyre, Gavin, 2014. Method of Growing Electrically Conductive Tissue. US Patent 0097008A1.

Berbara, R.L.L., Morris, B.M., Fonseca, H.M.A.C., Reid, B., Gow, N.A.R., Daft, M.J., 1995. Electrical currents associated with arbuscular mycorrhizal interactions. New Phytol. 129 (3), 433–438.

Bilodeau, R. Adam, Kramer, Rebecca K., 2017. Self-healing and damage resilience for soft robotics: A review. Front. Robotics AI 4, 48.

Cartabia, Marco, Girometta, Carolina Elena, Milanese, Chiara, Baiguera, Rebecca Michela, Buratti, Simone, Branciforti, Diego Savio, Vadivel, Dhanalakshmi, Girella, Alessandro, Babbini, Stefano, Savino, Elena, Dondi, Daniele, 2021. Collection and characterization of wood decay fungal strains for developing pure mycelium mats. J. Fungi 7.

Cicconofri, Giancarlo, Arroyo, Marino, Noselli, Giovanni, DeSimone, Antonio, 2020. Morphable structures from unicellular organisms with active, shape-shifting envelopes: Variations on a theme by Gauss. Int. J. Non-Linear Mech. 118, 103278.

Danninger, Doris, Pruckner, Roland, Holzinger, Laura, Koeppe, Robert, Kaltenbrunner, Martin, 2022. MycelioTronics: Fungal mycelium skin for sustainable electronics. Sci. Adv. 8, 7118.

Dehshibi, Mohammad Mahdi, Adamatzky, Andrew, 2021. Electrical activity of fungi: Spikes detection and complexity analysis. Biosystems 203, 104373.

Dehshibi, Mohammad Mahdi, Chiolerio, Alessandro, Nikolaidou, Anna, Mayne, Richard, Gandia, Antoni, Ashtari-Majlan, Mona, Adamatzky, Andrew, 2021. Stimulating fungi pleurotus ostreatus with hydrocortisone. ACS Biomater. Sci. Eng. 7 (8), 3718–3726.

Dhariwal, Amit, Sukhatme, Gaurav S., Requicha, Aristides A.G., 2004. Bacterium-inspired robots for environmental monitoring. In: IEEE International Conference on Robotics and Automation, 2004. Proceedings, Vol. 2. ICRA'04. 2004, IEEE, pp. 1436–1443.

Dunbabin, Matthew, Marques, Lino, 2012. Robots for environmental monitoring: Significant advancements and applications. IEEE Robot. Autom. Mag. 19 (1), 24–39.

Elsacker, Elise, Zhang, Meng, Dade-Robertson, Martyn, 2023. Fungal engineered living materials: The viability of pure mycelium materials with self-healing functionalities. Adv. Funct. Mater. 33, 2301875.

Fallegger, Florian, Schiavone, Giuseppe, Lacour, Stéphanie P, 2020. Conformable hybrid systems for implantable bioelectronic interfaces. Adv. Mater. 32 (15), 1903904.

Fu, Haoran, Bai, Ke, Huang, Yonggang, Zhang, Yihui, 2020. Recent progress of morphable 3D mesostructures in advanced materials. J. Semicond. 41 (4), 041604.

Gandia, Antoni, Adamatzky, Andrew, 2022. Electrical spiking of psilocybin fungi. Commun. Integrat. Biol. 15, 226–231.

Gandia, Antoni, van den Brandhof, Jeroen G., Appels, Freek V.W., Jones, Mitchell P., 2021. Flexible fungal materials: Shaping the future. Trends Biotechnol. 39, 1321–1331.

Gelinsky, Michael, 2020. Latest advances of bioprinting in space: an interview with Michael Gelinsky. J. 3D Print Med. 4 (1), 1–4.

Girometta, Carolina, Picco, Anna Maria, Baiguera, Rebecca Michela, Dondi, Daniele, Babbini, Stefano, Cartabia, Marco, Pellegrini, Mirko, Savino, Elena, 2019. Physico-mechanical and thermodynamic properties of mycelium-based biocomposites: A review. Sustainability (Switzerland) 11.

Goodrich, Michael A., Schultz, Alan C., et al., 2008. Human–robot interaction: a survey. Found. Trends Human–Comput. Interact. 1 (3), 203–275.

Gow, Neil A.R., 1984. Transhyphal electrical currents in fungi. Microbiology 130 (12), 3313–3318.

Harold, Franklin M., Kropf, Darryl L., Caldwell, John H., 1985. Why do fungi drive electric currents through themselves? Experim. Mycol. 9 (3), 3–86.

Huang, Xueying, Wang, Liu, Wang, Huachun, Zhang, Bozhen, Wang, Xibo, Stening, Rowena Y.Z., Sheng, Xing, Yin, Lan, 2020. Materials strategies and device architectures of emerging power supply devices for implantable bioelectronics. Small 16 (15), 1902827.

Jemison, Mae, Olabisi, Ronke, 2021. Biomaterials for human space exploration: a review of their untapped potential. Acta Biomater. 128, 77–99.

Jeong, Yong Hyeon, Kim, Da Song, Shin, Hyun Jae, 2023. Trametes orientalis mycelium mat, can be used as an alternative to elastomers? Biotechnol. Bioprocess Eng. 1–10.

Jones, Mitchell, Gandia, Antoni, John, Sabu, Bismarck, Alexander, 2020a. Leather-like material biofabrication using fungi. Nat. Sustain. 1–8.

Jones, Mitchell, Mautner, Andreas, Luenco, Stefano, Bismarck, Alexander, John, Sabu, 2020b. Engineered mycelium composite construction materials from fungal biorefineries: A critical review. Mater. Des. 187, 108397.

Kaur, Manpreet, Kim, Tae-Ho, Kim, Woo Soo, 2021. New frontiers in 3D structural sensing robots. Adv. Mater. 33 (19), 2002534.

Kim, Sangbae, Laschi, Cecilia, Trimmer, Barry, 2013. Soft robotics: a bioinspired evolution in robotics. Trends Biotechnol. 31 (5), 287–294.

Leach, Charles M., 1976. An electrostatic theory to explain violent spore liberation by *Drechslera turcica* and other fungi. Mycologia 63–86.

Loyd, Andrew L., Held, Benjamin W., Linder, Eric R., Smith, Jason A., Blanchette, Robert A., 2018. Elucidating wood decomposition by four species of Ganoderma from the United States. Fung. Biol. 122 (4), 254–263.

Maciel, Marta M., Correia, Tiago R., Gaspar, Vítor M., Rodrigues, João M.M., Choi, Insung S., Mano, João F., 2021. Partial coated stem cells with bioinspired silica as new generation of cellular hybrid materials. Adv. Funct. Mater. 31 (29), 2009619.

McGillviray, Ann M., Gow, Neil A.R., 1987. The transhyphal electrical current of *Neuruspua crassa* is carried principally by protons. Microbiology 133 (10), 2875–2881.

Meunier, Christophe F., Dandoy, Philippe, Su, Bao-Lian, 2010a. Encapsulation of cells within silica matrixes: Towards a new advance in the conception of living hybrid materials. J. Colloid Interface Sci. 342 (2), 211–224.

Meunier, Christophe F., Rooke, Joanna C., Léonard, Alexandre, Xie, Hao, Su, Bao-Lian, 2010b. Living hybrid materials capable of energy conversion and CO 2 assimilation. Chem. Commun. 46 (22), 3843–3859.

Murphy, Robin R., 1996. Biological and cognitive foundations of intelligent sensor fusion. IEEE Trans. Syst. Man Cybern. A 26 (1), 42–51.

Olsson, S., Hansson, B.S., 1995. Action potential-like activity found in fungal mycelia is sensitive to stimulation. Naturwissenschaften 82 (1), 30–31.

Rayner, Alan D.M., 1991. The challenge of the individualistic mycelium. Mycologia 48–71.

Romano, Donato, Donati, Elisa, Benelli, Giovanni, Stefanini, Cesare, 2019. A review on animal–robot interaction: from bio-hybrid organisms to mixed societies. Biol. Cybern. 113, 201–225.

Rossiter, Jonathan, Winfield, Jonathan, Ieropoulos, Ioannis, 2016. Here today, gone tomorrow: biodegradable soft robots. In: Electroactive Polymer Actuators and Devices (EAPAD) 2016, Vol. 9798. SPIE, pp. 312–321.

Savile, DBO, 1965. Spore discharge in *Basidiomycetes*: a unified theory. Science 147 (3654), 165–166.

Sheridan, Thomas B., 2016. Human–robot interaction: status and challenges. Human factors 58 (4), 525–532.

Sicard, Clémence, Brayner, Roberta, Margueritat, Jérémie, Hémadi, Miryana, Couté, Alain, Yéprémian, Claude, Djediat, Chakib, Aubard, Jean, Fiévet, Fernand, Livage, Jacques, et al., 2010. Nano-gold biosynthesis by silica-encapsulated micro-algae: a "living" bio-hybrid material. J. Mater. Chem. 20 (42), 9342–9347.

Slayman, Clifford L., Long, W. Scott, Gradmann, Dietrich, 1976. "Action potentials" in *Neurospora crassa*, a mycelial fungus. Biochim. Biophys. Acta. 426 (4), 732–744.

Tan, Yu Jun, Susanto, Glenys Jocelin, Anwar Ali, Hashina Parveen, Tee, Benjamin C.K., 2021. Progress and roadmap for intelligent self-healing materials in autonomous robotics. Adv. Mater. 33 (19), 2002800.

Trincavelli, Marco, Reggente, Matteo, Coradeschi, Silvia, Loutfi, Amy, Ishida, Hiroshi, Lilienthal, Achim J., 2008. Towards environmental monitoring with mobile robots. In: 2008 IEEE/RSJ International Conference on Intelligent Robots and Systems. IEEE, pp. 2210–2215.

Vallet-Regí, María, Colilla, Montserrat, González, Blanca, 2011. Medical applications of organic–inorganic hybrid materials within the field of silica-based bioceramics. Chem. Soc. Rev. 40 (2), 596–607.

Vasquez, Eldy S. Lazaro, Vega, Katia, 2019. Myco-accessories: Sustainable wearables with biodegradable materials. In: Proceedings - International Symposium on Wearable Computers. ISWC, Association for Computing Machinery, pp. 306–311.

Viceconte, Fátima R., Diaz, Marina L., Soresi, Daniela S., Lencinas, Ileana B., Carrera, Alicia, Prat, María Inés, Gurovic, María Soledad Vela, 2021. Ganoderma sessile is a fast polysaccharide producer among Ganoderma species. Mycologia 113 (3), 513–524.

Web article:, 2014. Prototyping a biological UAV. The 2014 Stanford-Brown-Spelman iGEM Team, iGEM.com.

Web Article:, 2016. Living structural materials could open new horizons for engineers and architects. DARPA.mil.

Web Article:, 2017. Ecovative design awarded 9.1 million USD to develop and scale a new generation of living building materials. Grow.bio.

Whitesides, George M., 2018. Soft robotics. Angew. Chem., Int. Ed. Engl. 57 (16), 4258–4273.

Wiesemüller, Fabian, Miriyev, Aslan, Kovac, Mirko, 2021. Zero-footprint eco-robotics: A new perspective on biodegradable robots. In: 2021 Aerial Robotic Systems Physically Interacting with the Environment. AIRPHARO, IEEE, pp. 1–6.

Williams, Tiffany S., 2022. Advancing research efforts in biomimicry to develop nature-inspired materials, processes for space exploration and more efficient aircraft. In: Biomimicry Aerosp.. Elsevier, pp. 385–421.

Yoon, Jinho, Lee, Taek, Choi, Jeong-Woo, 2019. Development of bioelectronic devices using bionanohybrid materials for biocomputation system. Micromachines 10 (5), 347.

Yoon, Jinho, Shin, Minkyu, Lim, Joungpyo, Kim, Dong Yeon, Lee, Taek, Choi, Jeong-Woo, 2020. Nanobiohybrid material-based bioelectronic devices. Biotechnol. J. 15 (6), 1900347.

Zarei, Mohammad, Lee, Giwon, Lee, Seung Goo, Cho, Kilwon, 2023. Advances in biodegradable electronic skin: Material progress and recent applications in sensing, robotics, and human–machine interfaces. Adv. Mater. 35 (4), 2203193.