Applied Physics A (2021) 127:181
https://doi.org/10.1007/s00339-021-04310-5

Applied Physics A
Materials Science & Processing

T.C. BIOLOGICAL AND BIOMIMETIC MATERIALS

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Spiky-joint: a bioinspired solution to combine mobility and support

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Received: 14 November 2020 / Accepted: 15 January 2021 / Published online: 11 February 2021

Abstract

Mobility and support are two structural properties that are often mutually exclusive. However, combining them could enhance the performance of mechanical components, and offer novel technical applications. Here through the implementation of a bioinspired interlocking mechanism in the design of a supportive, yet mobile, wrist splint, we tackled the conflicting combination of the two properties. We elaborated our design into a technology readiness level and, using 3D printing, directly converted it into a real-life application. In contrast to the existing splints, our bioinspired splint supports human wrist without impairing its movements. Hence, it can be used to prevent hyperextension injuries without hindering wrist function. By being interlocked at the maximum wrist extension, our splint could be an ideal wrist support for athletes, especially weightlifters. By restricting the wrist mobility, it could also be used as a support device to treat less severe medical issues, such as sprain, strain, or even for the recovery after cast removal, during which full immobilization may result in muscle atrophy. Our design strategy is purely structural; hence, it can be easily modified and implemented in other engineering applications. The simple, yet efficient, solution developed in this study offers a universal paradigm for developing engineering systems that pursuit both mobility and support.

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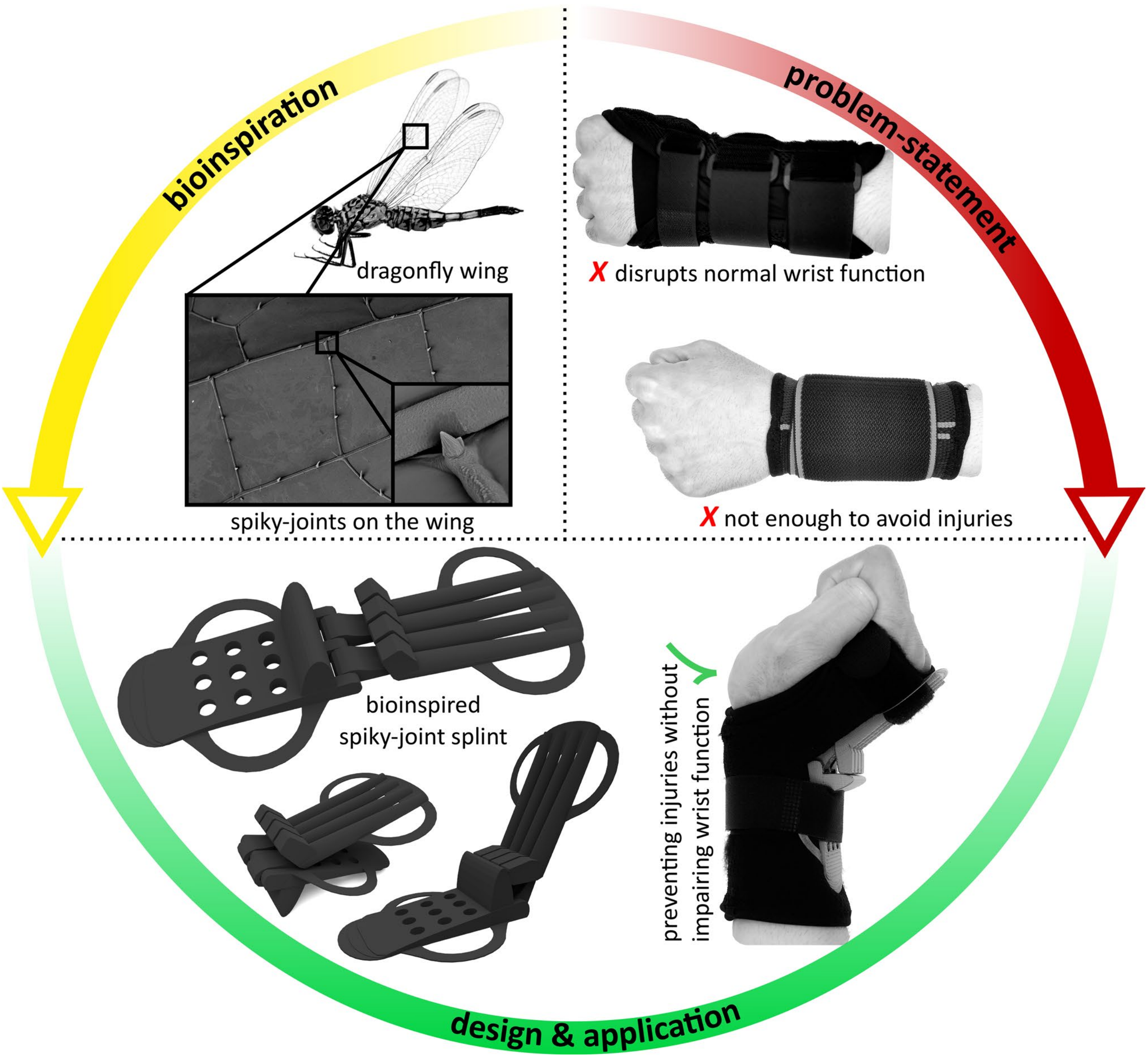
Graphic abstract



Keywords 3D printing · Hyperextension · Wrist support · Wearable device · Orthotic

Media summary

Here we introduce the concept of 'variable mobility', which is borrowed from elaborated joints of insect wings. We translate this concept into a marketable technology: a supportive, but mobile, wrist splint. Our 3D printed PLA splint has a load-bearing capacity of ~30 kg and is particularly suitable for wrist protection in sports, such as handball, basketball and weightlifting. If manufactured by stronger materials, such as stainless steel, our bioinspired splint can withstand weights more than 450 kg, far beyond the world record of weightlifting.

Highlights

- Inspired by the interlocking mechanism of vein joints on insect wings, we developed the concept of variable mobility and implemented it into the design of a supportive, yet mobile, wrist splint.
- By being interlocked at the maximum wrist extension, our developed splint could be an ideal wrist support

against hyperextension injury for athletes, especially weightlifters.

- The developed splint here, allowed us to achieve the desired supportive function where and only when it is locally needed.
- In contrast to the existing splints, our bioinspired splint securely protects human wrist without sacrificing wrist functions.
- The level of the wrist mobility could be further adjusted by solely structural changes (i.e. changing the size of the spikes and their location on the splint).
- The developed concept here offers a simple, yet an efficient solution for developing engineering structures that pursuit both mobility and support.

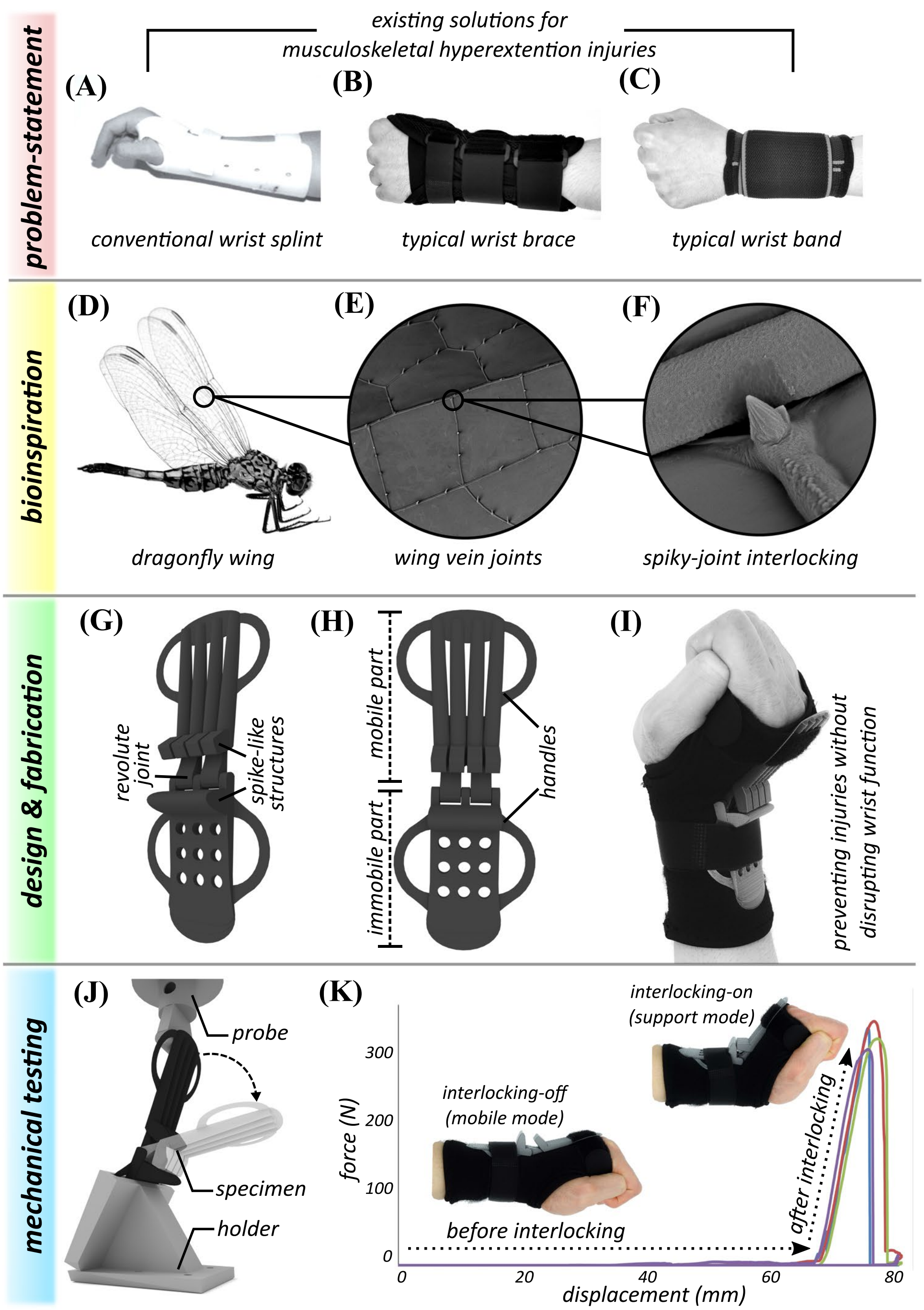


Fig. 1 From problem statement to a bioinspired design. **a** A rigid conventional splint [5]. **b** A common compressive wrist support that interrupts the normal wrist function. **c** A common compressive wrist support that does not provide enough protection against injuries. **d** The wing of a dragonfly as the source of inspiration [27]. **e** A scanning electron microscope (SEM) image showing the distribution of vein joints in a part of the wing. **f** A SEM image of a vein joint on the wing with a spike that restricts joint mobility by an interlocking effect. **g** A perspective view of our bioinspired splint with the spikes and revolute joints. **h** A top view of our splint that shows the mobile and immobile parts. **i** Application of our 3D-printed splint on the wrist showing the splint in the interlocking position. **j** Mechanical testing set-up of the splints at the initial and final positions. **k** Force–displacement curves of the splints, showing the load-bearing capacity before and after interlocking with an illustration of the splints on human wrist in the representative mobile and support modes. Each colour represents data from a different specimen

1 Introduction

Musculoskeletal injuries refer to the damage of muscular or skeletal system. They affect muscles, bones, joints, and thereby locomotion. Musculoskeletal injuries are one of the most common reasons for the injury-related visits to physicians [22]. In the USA and UK, as an example, 15% of the population experience one type of musculoskeletal disorders per year [14]. Around 80% of sport-related injuries are associated with the musculoskeletal system [21]. There are different types of musculoskeletal injuries, such as ligament sprain, muscle strain, bone fractures, etc. However, hyperextension is one of the most common types, which often occurs in falls and heavy sports, such as bodybuilding and weightlifting [16, 28, 30].

Conventional plaster casts and splints are still the most common tools that are used to treat musculoskeletal injuries worldwide [13] (Fig. 1a). Casts provide full support for an injured or broken limb. In contrast, splints, which are also known as half-casts, provide less mechanical support than casts; they are not completely wrapped around the injured body part and can be removed or adjusted. Regardless of the worldwide use of the conventional casts and splints, there are several issues associated with them. These include high weight, poor ventilation, difficult removal, discomfort, rigidity and non-recyclability [10]. The latter, i.e. non-recyclability, results in an average of 670,000 kg waste per year [15].

2 Unconventional casts and splints

Nowadays, 3D printing has enabled the fabrication of complex 3D objects. The state-of-the-art 3D printing technology offers alternative solutions to overcome the problems associated with the conventional splints. In the last decade, there have been several efforts to improve the design of the existing splints [10]. So far, to some extent, the developed designs have achieved the purpose of being lightweight, breathable, removable and aesthetically better looking than the conventional plaster casts and splints. However, most of the existing splints are fully rigid structures, which allow no mobility.

Why mobility should be included into the design of splints? First, because an ideal splint should not hinder the limb function. In other words, it should not interfere with the mobility of the joints, but should only prevent 'undesired' movements. Second, because in the case of less severe injuries, such as sprains and strains, or during the recovery period after cast removal, limbs should only be partially immobilized. The excessive immobilization can lead to joint stiffness, chronic pain, muscle atrophy or more severe complications [3]. Third, a supporting splint with limited mobility could also be used as a safety support device in sports, which allows mobility in desired directions while provides support in other directions. To sum up, the aim of splints can vary significantly from stabilizing the affected joints and providing support to promoting mobility in a controlled manner. However, the mobility and support are two conflicting characteristics that are not likely to be combined together in the same structure.

3 The concept of 'variable mobility'

Although mobility and support are mutually exclusive, it is possible to use different design strategies to develop structures that change their level of mobility. The structures with variable mobility are of particular interest to structural engineers, because of their potential to adapt to applied loads [18]. There is an increasing interest in such structures in robotics and biomedical applications [4, 31].

Recent studies have offered solutions to develop structures with variable mobility [12]. These solutions are often based on complicated strategies, which include layer jamming [9, 18], prestretched sandwiched layers of multiple materials [17] and kinematic interaction of multiple surfaces [7]. In contrast to the existing engineering solutions, Nature provides us with simple, yet efficient, solutions. There are many examples of structures with variable mobility among plants and animals that tune their mobility depending on the loads, to which they are subjected [2]. Insect wings, for instance, represent remarkable examples of such a feature (Fig. 1d–f). The key to this lies in the presence of vein joints, which consist of stiff cuticular spikes and flexible resilin patches [6, 8, 23] (Fig. 1e, f). While the latter, i.e. resilin patches, provide the joints with mobility, the former, i.e. cuticular spikes, improve their structural support [24].

Inspired by insect wings, here we develop a strategy to design and fabricate engineering structures with variable mobility. Using an example of a wrist splint, we apply our bioinspired strategy to a real-life application. We fabricated our splint using 3D printing and demonstrated its use in prevention of hyperextension injuries without hindering normal wrist function. The 3D-printed splint developed in this study is a patented design [11] and represents a bioinspired engineering structure that utilizes an interlocking mechanism to fulfil the concept of variable mobility. Our design represents a simple, yet efficient, solution for the pursuit of both mobility and support in engineering structures.

4 Design, fabrication and testing of a bioinspired wrist splint

In order to translate the concept of variable mobility from insect wings into a real-life application, we designed and fabricated a wrist splint. To this end, we combined computer aided design (3D computer graphics software Blender v. 2.79) and 3D printing (Prusa i3 MK3). The designed splint consisted of a mobile part and an immobile part (Fig. 1h). The mobile part had four tubular elements that were connected to each other at both ends. At one end, a spike-like structure was situated on each tubular element. The mobile part was connected to the immobile part using two revolute joints (Fig. 1g). The immobile part of the splint was a rectangular block, which was equipped with one large spike-like protrusion at one end. The spike acts as a mechanical 'stopper' that restricts undesired rotations by coming in contact with the spikes on the mobile part. The immobile part was made perforated, in order to increase breathability. Four handles were added to the lateral sides of the splint to fit it to the hand by using Velcro tapes (Fig. 1h). We 3D-printed the splints using polylactic acid (PLA) filament (filament diameter 1.75 mm, printing temperature 190–220 °C, AMOLEN) and polylactic acid/polyhydroxyalkanoate (PLA/PHA) filament (filament diameter: 1.75 mm, printing temperature: 195–220 °C, ColorFabb). The splints were 3D-printed in 100% infill density with a layer height of 0.2 mm. The 3D printing of the splint took about 1.5 h. In dimensions of $14 \times 3 \times 2$ cm^3, the splint has a mass of ~ 23 g.

The 3D-printed splints were fit and tested on human wrist (Fig. 1i). In order to characterize their mechanical behaviour, in particular load-bearing capacity, we performed static bending tests using a ZwickiLine uniaxial testing machine (ZwickRoell). Figure 1j illustrates the experimental set-up and the specimen at the beginning and the end of the loading. The loading velocity was 1 mm/s. The immobile part of the splint was inserted into a customized holder. Then, using a customized probe a displacement of 8 cm was applied to the tubular elements of the mobile part of the splint. This enabled us to measure the force that the splint can withstand before fracture.

The force–displacement curves presented in Fig. 1k show the response of the 3D-printed splints from the start of the loading until fracture. Application of a displacement up to 6.7 cm (equal to a rotation of ~ 70°) does not result in an increase in the force. This indicates that the mobile part of the splint could freely rotate about the joint. At this point, the spike-like structures on the mobile and immobile part contact each other. Due to their mechanical contact, the force rapidly increases at the application of larger displacements. The linear increase in the force finally results in the fracture of the splint. Prior to failure the splint could withstand an average force of ~ 320 N.

5 Discussions and future directions

The 3D-printed splint introduced in this study is a patented design [11] that is intended to protect human wrist by partially restraining its mobility in extension, but not in flexion. This feature was achieved by an interlocking effect that restricts the wrist joint mobility at a threshold. The bioinspired 'spiky-joint' splint developed in this study can be used as a protective support device in sports, such as weightlifting and fitness, to prevent hyperextension wrist injuries (Fig. S1). The splint could also be used to treat less severe medical issues, such as sprain, strain or for the recovery period after cast removal, during which limb flexions or extensions only up to a certain point are allowed. To this end, a similar design of the splint has also been developed for knee and elbow (Fig. S2). A clinical study of the efficiency of the developed wrist splint, however, is out of the scope of the current study.

The developed wrist splint in this study combines mobility and support: it is mobile at the beginning to allow a user to extend the wrist freely, and becomes immobile, i.e. supportive, after the spike interlocking. This is in contrast to existing wrist support devices that are either compressive wrist supports, and do not provide enough support to avoid injuries, or are supportive, but disrupt the normal wrist mobility (Fig. 1b, c). The splint developed here enabled us to obtain the desired supportive function where and only when it is locally needed. This results in securely protecting a limb without sacrificing its function. More importantly, the level of the wrist mobility could be further adjusted by changing the size of the spikes and their location. Depending on the level of spike activation, the splint shifts between the functions of protection and support. The function of protection is achieved by letting the spikes activate at the maximum allowed wrist extension (i.e. 70–80°) to prevent hyperextension. The function of support can be reached by activating the spikes at earlier stages than the maximum wrist extension, to let them partially carry loads and reduce the load applied to the wrist.

The novel design developed here is also a suitable candidate for robotic applications. This is particularly due to two main reasons. First, as observed in the mechanical tests, there is no time delay in the process of transition from the mobile mode, in which the load-bearing is almost equal to zero, to the support mode, in which the load-bearing capacity abruptly increases (to ~ 320 N). This is also obvious in the radical difference between the stiffness of the two modes, which reaches ~ 50,000 times (~ 37 kN/m vs. ~ 0.75 N/m). Second, our developed design had a high load-bearing capacity. The splint could withstand loads more than 1,400 times its own weight. The two features mentioned earlier are the key requirements of structures that are used in adaptive morphing structures with robotic applications [31].

Considering the direct effect of material stiffness on the load-bearing capacity of our developed structure, when manufactured by stronger materials, our bioinspired splint can withstand forces much higher than the current one (i.e. ~ 320 N). For instance, stainless steel has a yield strength of ~ 600 MPa [29] which is ~ 14 times that of PLA (~ 43 MPa) [20]. The use of the stainless steel, therefore, is expected to increase the load-bearing capacity of our split to ~ 4500 N.

In addition to our main aim to apply the latest findings on insect wings into an engineering design, our results could also provide some biological insights into the field of wing functional morphology and wing biomechanics. Here we showed that an interlocking effect achieved by spikes notably enhanced the load-bearing capacity of a structure, while still allowing it to deform to some extent. This resembles the spike-containing flexible joints in insect wings, which passively control wing deformations in flapping flight and provide them with combination of deformability and stiffness [25, 32, 33]. Our findings, therefore, confirm the results of previous studies, which suggested the key role of spike-containing joints in enhancing the load-bearing of the insect wings [6, 23, 24].

Although the interlocking of the spiky-joints limits the deformability of insect wings, it does not result in a hard stop, as intended in our design. This can be attributed to a few reasons. First, the presence of flexible resilin patches at the proximity of the joints in the wings still allows some levels of deformability after the interlocking is reached. This phenomenon was observed in a previous study, in which the interlocking effect was simulated using finite element method [26]. Second, there are plenty of joints in the wings, both of the same and different types [1, 6, 19, 24, 34]. These joints have different geometries and are distributed all over the wing. The interlocking of the joints does not take place at the same time; while some of the joints are interlocked, many others can still move freely. Therefore, it is unlikely that such a dramatic change in stiffness ever occurs in insect wings.

Structures with variable mobility offer promising solutions for biomedical, robotics and aerospace applications due to their multifunctional advantage and ability to adapt themselves to their circumstances with regard to external loads [9, 18, 31]. Hence, many efforts have been made, during the last years, to employ different design strategies to achieve this feature in engineering systems. In contrast to existing complicated strategies, here we developed an efficient, yet simple, bioinspired solution.

Our developed design was used to tackle a non-trivial, previously unsolved problem, i.e. a supportive, but mobile, wrist splint. The design developed in this study offers a universal paradigm for the pursuit of both mobility and support in engineering structures and, therefore, is applicable to numerous other systems with similar objectives. Future studies can focus on the development of more complex joints with two or more degrees of freedom where different spike profiles could direct and control dynamic movements.

A summary of this study for non-expert, general audience is presented in **Video S1**.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00339-021-04310-5.

Acknowledgements We would like to thank Halvor T. Tramsen for his helpful discussions.

Author contributions HR and SNG were involved in conceptualization; HR and SNG were involved in supervision; AK and HR were involved in investigation; AK and HR were involved in data curation; AK was involved in formal analysis; HR, SNG and AK were involved in funding acquisition; HR and AK were involved in methodology; HR was involved in project administration; SNG was involved in resources; AK was involved in validation; HR and AK were involved in visualization; AK was involved in writing—original draft preparation; AK, HR and SNG were involved in writing—review and editing.

Funding Open Access funding enabled and organized by Projekt DEAL. This study was financially supported by "Federal State Funding at Kiel University" Grant to AK.

Data availability All supporting data are available in the article and on: https://doi.org/10.6084/m9.figshare.13013456.

Compliance with ethical standards

Conflict of interest AK, SG and HR are inventors on a German Patent application 4009.10 submitted by Kiel University.

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