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MotorSkins—a bio-inspired design approach towards an interactive soft-robotic exosuit

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E-mail: facundo@motorskins.com and khashayar.Razghandi@mpikg.mpg.de**Keywords:** bio-inspired design, exosuit, assistive technology, fluid-driven, soft-robotics, soft-machines, designSupplementary material for this article is available [online](#)

Abstract

The work presents a bio-inspired design approach to a soft-robotic solution for assisting the knee-bending in users with reduced mobility in lower limbs. Exosuits and fluid-driven actuators are fabric-based devices that are gaining increasing relevance as alternatives assistive technologies that can provide simpler, more flexible solutions in comparison with the rigid exoskeletons. These devices, however, commonly require an external energy supply or a pressurized-fluid reservoir, which considerably constrain the autonomy of such solutions. In this work, we introduce an event-based energy cycle (EBEC) design concept, that can harvest, store, and release the required energy for assisting the knee-bending, in a synchronised interaction with the user and the environment, thus eliminating any need for external energy or control input. Ice-plant hydro-actuation system served as the source of inspiration to address the specific requirements of such interactive exosuit through a fluid-driven material system. Based on the EBEC design concepts and the abstracted bio-inspired principles, a series of (material and process driven) design experimentations helped to address the challenges of realising various functionalities of the harvest, storage, actuation and control instances within a closed hydraulic circuit. Sealing and defining various areas of water-tight seam made out of thermoplastic elastomers provided the base material system to program various chambers, channels, flow-check valves etc of such EBEC system. The resulting fluid-driven EBEC-skin served as a proof of concept for such active exosuit, that brings these functionalities into an integrated ‘sense-acting’ material system, realising an auto-synchronised energy and information cycles. The proposed design concept can serve as a model for development of similar fluid-driven EBEC soft-machines for further applications. On the more general scheme, the work presents an interdisciplinary design-science approach to bio-inspiration and showcases how biological material solutions can be looked at from a design/designer perspective to bridge the bottom-up and top-down approach to bio-inspiration.

1. Introduction

1.1. A brief intro to assistive technologies

Walking is arguably our main means of transportation, and motor disabilities can constrain a person’s activities in this regard. When talking about motor disabilities in lower limbs, we might refer to very different situations, such as spinal cord injuries, poliomyelitis or muscle weakness related to ageing. Even mild conditions such as age-related

musculoskeletal changes can have a great impact on the physical state of older adults and lead to psychological problems (Mace 1988).

Disability is, however, a socially constructed phenomenon; and understanding it as a situation that arises from the interdependence and interaction of a specific user with their environment (Cook and Polgar 2014 and Hamraie and Fritsch 2019), enables us to address this problematic relationship through assistive technologies such as exoskeletons.

1.1.1. Rigid and soft exoskeletons

Exoskeletons are among the most challenging assistive technologies. Projects such as the ‘Phoenix Suit’ or the ‘Rewalk’ (Palermo *et al* 2017) have proved success in helping people with severe motor disabilities to walk. Exoskeletons that consist of external, rigid frames that support the lower-body, and actuators that can power the limbs to perform movement have been the main focus of interest (Shimada *et al* 2008, Ikehara 2010 and Kong and Jeon 2006). Other research groups have provided meaningful insights on how to make such exoskeletons more efficient through lighter structures (Walsh *et al* 2006), and better sensing (Kim *et al* 2015 and Liu *et al* 2016) and control (Anam and Al-Jumaily 2012 and Beil *et al* 2015). The final systems in that line of work, however, can result - from a product perspective - in complex and expensive devices, inaccessible to many potential users. Furthermore, misalignment between the device joint (mono or bi-centric) and the anatomical reference (polycentric) can create discomfort or even injuries (Schiele 2009 and Cenciarini and Dollar 2011).

Exosuits, also called soft-exoskeletons, present a different strategy through a fabric-based construction. One possible actuation strategy for exosuit, is the implementation of cable-driven actuators for improving walking efficiency or assisting muscle weakness (Schmidt *et al* 2017, Awad *et al* 2017, Bae *et al* 2018, Quinlivan *et al* 2017, Jin *et al* 2016, Ding *et al* 2014, Asbeck *et al* 2014, Rus and Tolley 2015 and Böttger *et al* 2020). Parallel works have experimented with the development of soft sensors (Böttger *et al* 2020) that could enhance the benefits of such devices. Such soft structures can improve the synergistic interaction between the device and the human gait dynamics (Di Natali *et al* 2019), and at the same time results in lighter and potentially cheaper devices.

1.1.2. Soft robotics & fluid-driven actuators

Soft-robotics constructions (or soft-machines) generally consist of an elastomeric matrix embedded with flexible materials and are powered through fluid dynamics and interaction (Shepherd *et al* 2011). The current state of the research on these systems is geared towards actuators and end effectors with a wide range of potential applications such as object handling (Connolly *et al* 2015, Abd *et al* 2017 and Zhu *et al* 2016), packaging (Ou *et al* 2016), health applications (Payne *et al* 2017 and Yun *et al* 2017) or mobility (Bartlett *et al.* 2015 and Wehner *et al.* 2016). When paired with human motion, it can become a powerful tool for rehabilitation and assistance (Polygerinos *et al* 2015 and Payne *et al* 2018). An inflatable sheet approach to soft-robot production seems to be one of the keys to overcoming the limitations and the fairly low resistance that typical casted-rubber construction supposes (Ou *et al* 2016). Furthermore, soft-robots can incorporate different kinds of fabrics for tailoring its movement and mechanical properties (Cappello

et al 2018 and Elmoughni *et al* 2021). When applied to mobile devices such as exosuits, however, the supply of pressurized fluid for actuation becomes a challenge, since it can affect autonomy, as the maximum travelling range is limited to the storage capacity.

1.1.3. Semi-active and passively-actuated exoskeletons

While the main function of the active exoskeleton is to power the movement of a limb (Zeilig *et al* 2012), semi-active exoskeletons are another category of products that assist movement by improving control. These assistive technologies generally consist of frames and different braking systems that can help the user gain control during the walk (Kirsch *et al* 2014). Mechanisms that involve regulated blocking of specific movements to assist an activity require less external energy input and consequently, provide greater autonomy regarding its energy storage capacity. The underlying idea behind the concept of passively-actuated exoskeletons is to combine the functionality and efficiency of both systems, by bringing the activity not from an external energy source as an add-on to the system, but rather from the interaction of the system with its relevant environment. Passive dynamics is a well-known concept in the construction of walking robots (McGeer 1990), and when applied to the human gait, it can help reduce the metabolic rate of the user by harvesting potential and kinetic energy from the gait itself to assist limb movement (Collins 2008).

1.2. Passive hydro-actuation in plants: a relevant space for bio-inspiration

Nature in general, and plants in particular, are a great source of inspiration when it comes to such autonomous (passively) actuation mechanisms (Razghandi *et al* 2014, Burgert and Fratzl 2009, Fratzl and Barth 2009, Poppinga *et al* 2018, Knippers *et al* 2016, Poppinga *et al* 2010 and Estrin *et al* 2019). In such systems, different degrees of autonomy in regard to various aspects of the activity are implemented in the material system itself, moving away from centrally controlled reactions to autonomously regulated responses. Pinecone scales are a well-known example of such autonomous actuation systems; the scales are closed in the wet state—when the cone is still connected to the branch—protecting the seeds inside, and the scales will bend outward and release the seeds upon drying (Dawson *et al* 1997 and Razghandi *et al* 2014). Such hydro-responsive strategies can enable movement or deformation without active metabolic cost (e.g. in a dead tissue) and only through the differential response of the material to external stimuli. In response to environmental changes, the sophisticated material architecture of the system translates the water adsorption/desorption and the consequent volume changes in the micro scale into a deformation on the macro scale

(Gholami *et al* 2021, Razghandi *et al* 2014 and Burgert and Fratzl 2009).

This is the case for the reversible origami-like unfolding of the ice plant seeds' capsule through wetting and drying cycles, which ensures the protection and release of the seeds in response to the environmental conditions (Harrington *et al* 2011). The hygroscopic keels responsible for the unfolding of the seed-containing valves are made up of an array of elongated hexagonal cells arranged into a honeycomb (cellular) pattern and attached to a backing tissue. Each cell lumen is filled with a highly swellable cellulosic inner layer, and upon water absorption (e.g. exposure to rain) and swelling of this inner layer, the cells open along the shorter cross section of the cells. The collective swelling and opening of the cells results in unidirectional expansion of the cellular structure as a whole. As the cellular structure is attached to an inert, non-swelling backing tissue on one side, the compromise between the differential response of the two layers result in reversible bending of the 'bi-layer' structure upon water absorption/desorption, and the consequent unfolding/folding of the seed capsules (Harrington *et al* 2011 and Razghandi *et al* 2014a) (figure 1(b)).

Various research has taken the underlying principles behind the hydro-actuated movements in plants as a source of inspiration for the development of autonomously actuating systems (Erb *et al* 2013, Stoychev *et al* 2012, Guiducci *et al* 2016, Zhao *et al* 2014, Montero de Espinosa *et al* 2017, Stoychev *et al* 2013, Schleicher *et al* 2011, Knippers *et al* 2016, Poppinga *et al* 2010, Fratzl *et al* 2015, Burgert and Fratzl 2009 and Eder *et al* 2018, Rasmussen *et al* 2012).

In the context of this work, three characteristics of the ice-plant hydro-responsive system are particularly interesting from a bio-inspired design perspective:

- The cellular organization of the hydro-responsive honeycomb structure with elongated hexagonal cells that translates isotropic swelling into directional expansion on a larger scale (Guiducci *et al* 2016).
- The asymmetrical, differential response of the two layers attached to one another, which translate the unidirectional expansion of one into flexing of the overall structure (Polygerinos *et al* 2013, Polygerinos *et al* 2015, Cappello *et al* 2018 and Guiducci *et al* 2016).
- The concept of 'sense-action', where the acquiring and processing of relevant information and the regulation of a relevant functional response are integrated as one activity, embedded within various instances and scales of the structure of a material system and its interaction with the environment (Gholami *et al* 2021).

1.3. Objectives

While traditional exoskeletons generally consist of rigid frames with actuators to power the movement of the limbs (Cenciarini and Dollar 2011), exosuits are fabric-based devices gaining increasing attention as an alternative simpler and potentially cheaper solutions (Panizzolo *et al* 2016). Fluid-driven actuators, in this regard, are growing in relevance since they can enhance the flexibility of such soft robots (Park *et al* 2014). These devices, however, commonly need to be connected to a pressurized-fluid supply or a reservoir tank, constraining its autonomy in terms of maximum travelling range.

The objective of this work is to follow a bio-inspired design methodology as an alternative approach for envisioning a novel concept for autonomous assistive technologies. In the pursuit of a new paradigm, the work was founded on two research questions:

- How to reach a more energy-efficient and a more autonomous solution to the assistive exosuit paradigm with minimal compromise of the functional gain. More specifically, the work tackles the question of how to assist knee-bending in human gait with a passively-actuated device that can harvest potential energy from the walk, and encodes all the functions into its material arrangement dispensing of any motors, electronics or external energy sources such as batteries.
- How a design approach to bio-inspiration can bring out new insights to the aforementioned energy, autonomy, and material challenges of such assistive technologies. More specifically, and in a narrower context, exploring how one can get inspiration from plants' passive hydro-actuation strategies to propose a material system that translates local pressure changes to actuate complex movements on a macro scale.

The presented work goes through the process of the design exploration to tackle these questions. Although the common practice of separating the results from discussions can bring more clarity in the scientific writings, from a design perspective, we find it more constructive to follow a more fluid structure: the following chapter 'design processes: conception and exploration' dives into the process of developing and translating the design concept from bio-inspired principles, and follows the design exploration process through various materials and techniques. The subsequent 'final results and discussions' chapter expands on the final proof of concept, discusses the rationale behind the developed prototypes, and puts forward a more general reflection on the bio-inspired design methodology.

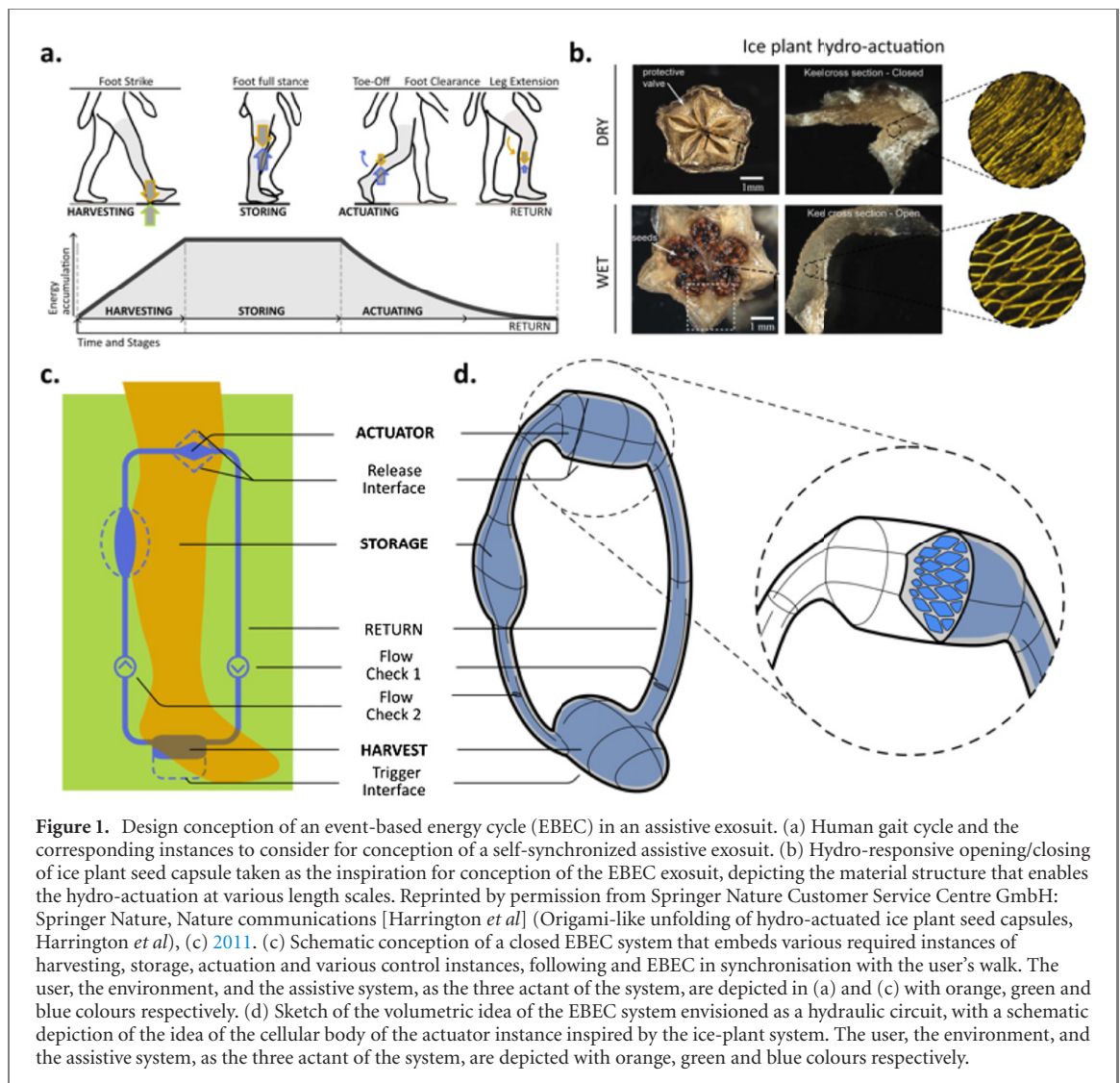


Figure 1. Design conception of an event-based energy cycle (EBEC) in an assistive exosuit. (a) Human gait cycle and the corresponding instances to consider for conception of a self-synchronized assistive exosuit. (b) Hydro-responsive opening/closing of ice plant seed capsule taken as the inspiration for conception of the EBEC exosuit, depicting the material structure that enables the hydro-actuation at various length scales. Reprinted by permission from Springer Nature Customer Service Centre GmbH: Springer Nature, Nature communications [Harrington *et al*] (Origami-like unfolding of hydro-actuated ice plant seed capsules, Harrington *et al*), (c) 2011. (c) Schematic conception of a closed EBEC system that embeds various required instances of harvesting, storage, actuation and various control instances, following and EBEC in synchronisation with the user's walk. The user, the environment, and the assistive system, as the three actant of the system, are depicted in (a) and (c) with orange, green and blue colours respectively. (d) Sketch of the volumetric idea of the EBEC system envisioned as a hydraulic circuit, with a schematic depiction of the idea of the cellular body of the actuator instance inspired by the ice-plant system. The user, the environment, and the assistive system, as the three actant of the system, are depicted with orange, green and blue colours respectively.

2. Design processes: conception and exploration

2.1. Design conception and translation

The complex scenario and multiple variables mentioned above are first put together as a design concept that fulfills the requirements of the particular problem at hand (assisting the bending of the knee), in the specific context (level ground walking) while translating and adapting the abstracted bio-inspired principles into the new application scenario.

2.1.1. Conception of an autonomously actuated system

The basic principle of passive actuation is to harvest energy from the users' walk and use it in the later stages of the gait for assisting the bending of the knee. To this end, we propose an energy cycle that harvests, stores, and releases energy in a closed loop, where different stages of this cycle follow the different phases of the user's walk (Vaughan *et al* 1999), performing an EBEC (figures 1(a) and (c)).

In this conception, the complete system is composed of the user, the environment, and the assistive

system—depicted in figure 1, with orange, green and blue colour respectively.

The main instances of this EBEC in auto-synchrony with the user gait (as depicted in figures 1(a) and (c)), can be described as the following:

Harvesting. First instance. Deals with the harvesting of the potential energy from the body weight during the foot strike. The user invests energy on balancing his body forward during the swing phase, and as the heel strikes the floor, the force generated from the weight of the user on the substrate can potentially be harvested in a material system.

Storing. The harvested energy would then be transferred and stored as potential energy in a material system. This instance would occur between the foot strike and the foot clearance stage, while the full weight of the user is still laid on the leg.

Actuating. Actuation occurs when the user has the intention of taking the next step. Then, the device would release and translate the stored energy for assisting knee flexion and foot clearance.

Return. Finally, while the energy is consumed during actuation, the weight of the leg on the swing stage

is bigger than the remaining actuation force of the device, and the leg can freely extend again, restarting the whole cycle.

Control. In this conception, *event-based* refers to the self-synchronization of the aforementioned instances with the gait's stages, through the user's intentions and interactions with the assistive system and the environment. To ensure the sequential and temporal aspects of this EBEC, the system incorporates the following control instances:

Trigger interface: this control instance mediates the interactions between the heel during foot strike (user) and the ground (environment). In doing so, it simultaneously senses the impact and starts the harvesting of energy.

Release interface: this interface synchronizes the release of the stored energy with the stage of the walk previous to the swing phase (toe-off) for actuation. It follows a lock/release logic. It should lock the energy flow during the stance stage and enable it (release) when the leg is ready for the swing stage.

Sequential flow-check controls: the system as such is a cycle with a sequence. These 'flow'-check controls ensure the directionality of the EBEC.

2.1.2. Translation of the EBEC design concept and the bio-inspired principle

The path to translating the aforementioned EBEC conceptual system (figure 1(c)) into a material proof of concept using bio-inspired principles is not linear. Its materialization presents several challenges regarding the development of a smart material system that encodes the proper responses in its architecture to assist the human walk.

The EBEC design concept can be envisioned within various modes of carrying out energy transfer through a closed circuit (for instance through electrical sensors and actuator circuitry). Abstraction of the underlying principles behind the ice plant actuation system (figure 1(b)), inspired the design of a hydro-actuated, cellular body where the different instances of the EBEC design concept can be understood as chambers of a closed hydraulic circuit (figures 1(c) and (d)).

The main design transfer challenges in this sense relate to the sequential event-based response within such a hydraulic circuit, and the nature of both the stimuli and the materially embedded mechanism that trigger the angular movement for assisting the knee bending.

While the ice plant's hydro-actuation relies on swelling of an inner cellulosic layer to induce the volume change of the cells, here, the functional inflation/deflation of the envisioned chamber system can be achieved through flow and constraining of an incompressible fluid (e.g. water). These regulations can be triggered as a response to the varying forces at the interfaces of the user, device and the environment, the three actants of the system (figure 1). Various

stances of harvest, storage, actuation and controls can all be realized within this hydraulic circuit logic.

Moreover, the ice plant hydro-actuated deformation mechanism was envisioned particularly in the design of the actuation instance. The abstracted geometrical principles of the cellular pattern and the bi-layer arrangement from the underlying structure-function relation in the ice plant (figure 1(c)), allows to translate the fluid volume transfer of the chambers into a bending movement. Conceptually, similar asymmetric constraints can be embedded in the structure of the actuation chambers, where constraining the inflating cell on one side and leaving it free to swell on the other, can result in an overall angular movement (figure 1(d)). This provides an alternative to the common articulated lever systems that transform linear into angular actuation. The regular arrangement of such inflating cells into a quasi-cellular organization can amplify the asymmetry of the system and consequently enhance the overall angular movement of the cellular body (figure 1(d)).

2.2. Design explorations

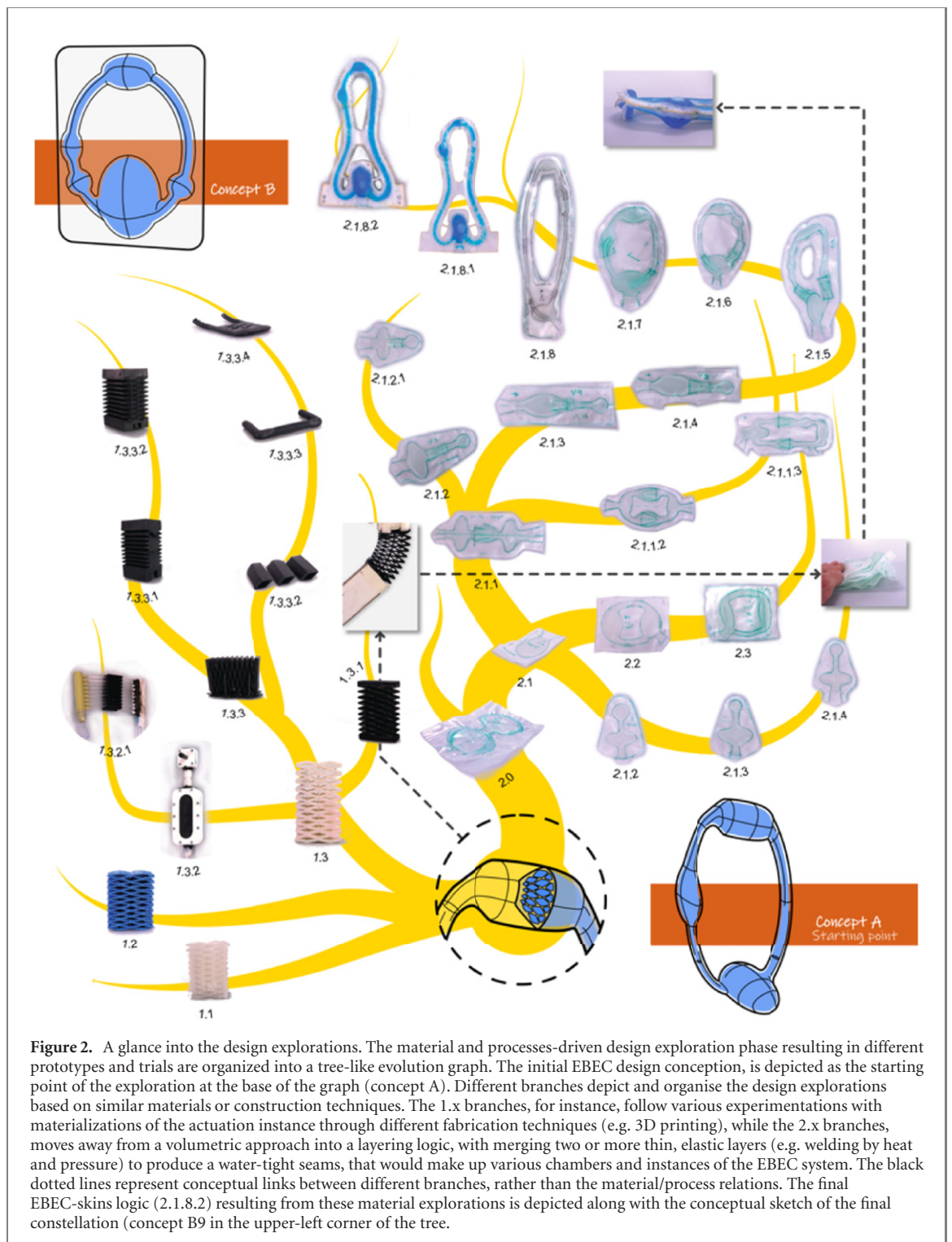
The conceptual sketch that results from the above described translation and conceptual system definition is the starting point for the more extensive and rich design exploration.

2.2.1. Design experimentation; an evolutionary inquiry

The development of the design concept was followed by a series of hands-on material- and process-driven design explorations to materialise the envisioned system. The rationale, processes and results of the design exploration are briefly presented here, and the detailed description of the materials and methods is covered in the next chapter.

Figure 2 organizes and makes sense of the different experimentation paths and prototypes that were developed during the design exploration. The figure organization resembles an evolutionary tree where different possible solutions appear, develop, and often die. The branches of such tree group solutions share the same materials and construction processes, and these generally grow in complexity (chronologically) as they go further from the trunk of the tree. The links between branches, on the other hand, represent a conceptual connection between the prototypes in spite of the different material, shape or construction (for more details of these design iterations see supplementary material 1 (<https://stacks.iop.org/BB/16/066013/mmedia>)).

The very base of the trunk of the tree is the conceptual sketch of the design translation and synthesis stage. The first branch (1.x) explores materializations of the cellular body of the actuation instance of the EBEC system, as proposed in the sketch. Branches 1.1 and 1.2 attempt to produce flexibility through a



compliant design, while 1.3 rely on flexible materials. Experiments in branch 1.3.1 were taken as a proof-of-concept for bending actuation by attaching a non-stretching layer in the inner part, transforming the general linear movement of the actuator into bending (asymmetric constraint). While most of the experimentation was carried out by using water (pressure) as the medium for transferring the forces for actuation, branch 1.3.2 explores air as the fluid for powering actuation. The 1.3.3 branch explores a different 3D printing method that enables better resolution

and water-tight walls. 1.3.3.1 is a logical development that increases the complexity by having all the actuating cells and the inner channelling integrated in a single part design. Although all of these design experiments resulted in different variations of the desired cellular body, they failed to give the system the desired robustness: one single leak at any given place of the part led to the failure of the actuator, as the cells were interconnected. 1.3.3.2 is an attempt to recover that robustness by having fully independent cells that assemble together for macro

movement. Though conceptually better, it presents new challenges regarding the integration of the system, as the approach required a more mechanistic assembly strategy, rather than the desired integrated metamaterial-like system.

Branch 2 moves away from a volumetric, 3D printing approach into a layering logic. In the biological reference, the cell walls are relatively thin resulting in a more efficient swelling/growth. 3D printing in this given scale results in either relatively thick walls or thin but prone-to-failing ones. The main idea here instead is to merge two or more thin, flexible layers of polymer by applying heat and pressure to produce a water-tight seam. The sealed perimeter defines an inner, closed area of detached layers that will house various instances of the hydraulic circuit.

Sample 2.0 represents the first attempt in this direction, which could successfully produce two interconnected watertight chambers. The material (LDPE) used for this first attempt, however, did not provide the elastic deformation desired for energy storage. Branch 2.1, follows the same construction logic and technique, but with sheets of thermoplastic elastomer (TPE), which could provide the desired elastic deformation and energy storage upon inflation.

Sub-branches 2.1.2 to 2.1.4 explore different chambers' area ratio, to find a functional elastic deformation of the small chamber to be used as energy storage. Branch 2.2 plays with the connection of the (minimum) two chambers but in a circular cycle rather than in a linear one. Branches 2.1.1 and 2.1.2 show the first attempts at developing a simple, layer-based non-return valve and integrating it into the hydraulic circuit.

The non-return valve developed for this project unfolds from the layer-merging construction logic. It consists of an inner channel that is connected to the main channel in the inlet while loose in the outlet side. Through various iterations, the form of these inner channels have evolved from a cone (2.1.1), to a pocket (2.1.2), to a hose (2.1.6), and, finally to a curved hose (2.1.7) aiming for an efficient non-return effect while keeping the flow in the desired direction with low resistance (see also figure 3(b) and the supplementary figure 2(b)). The rationale behind these design features are addressed in the final results and discussion section.

All the main features for the harvest, storage, actuation and flow-controls were developed separately.

Various hands-on experiments led to the merger of the test 2.1.1.3 with the branch 2.1.5, and followed by further tailoring of various features and their connections towards the layout of the complete hydraulic circuit within the skin unit.

A significant layout change can be observed between 2.1.8 and 2.1.8.1. This change corresponds to a change in the testing setup conditions. Up to 2.1.8, all the samples were tested in the plane. When moving into a 3D distribution of the skin layers (3D leg

setup) the position in the space produced several spots where the channels were throttled. The 2D layout of 2.1.8.1 reduces these issues when positioned in the 3D setup. 2.1.8.2 merges several skin units for enhancing actuation anisotropy through a multi-unit approach.

Finally, the 2D layout of 2.1.8.1 was taken as the suitable candidate material system for development of the proof of concept (supplementary figure 2).

2.2.2. Materials and production techniques

The materials and techniques used in production of the various aforementioned prototypes and branches of the design exploration tree are briefly highlighted in the following:

3D printers: I3-Berlin for fused deposition modelling (FDM) and FORM1 (FormLabs) for stereolithography (SLA).

Branch 1.1: FDM with acrylonitrile butadiene styrene filament.

Branch 1.2: FDM with polylactic acid filament.

Sample 1.3 and sub-branches 1.3.1 and 1.3.2: FDM with flexible thermoplastic polyurethane filament (Ninjaflex[®]).

Branch 1.3.3: SLA with flexible resin (Formlabs FLFLGR02).

Branch 2.0: sealing layers of low-density polyethylene (LDPE) 0.25 mm thickness with adapted iron welder at 345 °C. The iron welder was adapted to have a tip with a bigger and smoother area (metal tip, flat disc \varnothing 5 mm).

Branch 2.1: sealing layers of styrene-ethylene/butylene-styrene TPE foils of 0.25 mm thickness (Vreeberg) with adapted iron welder at 345 °C.

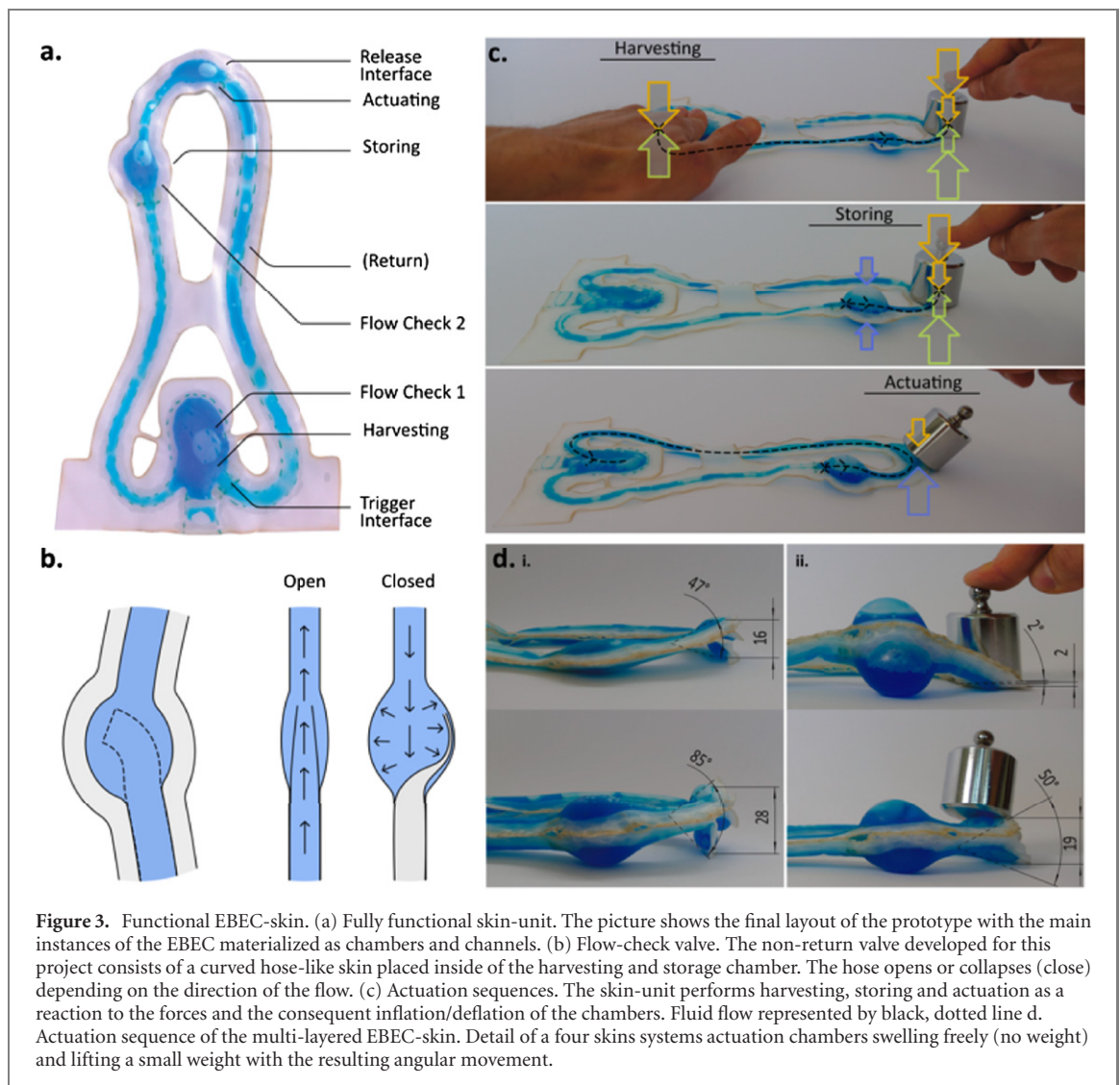
Softwares: all the aforementioned 3D models for 3D printing and 2D layouts for laser cutting were produced with Rhinoceros 5.0 software. Ultimaker Cura 3.0 software was used for slicing the models for 3D printing.

Design pipeline for the candidate material system: The double-layer logic within branch 2 was picked as the most suitable material system for exploring various design features and implementing the EBEC design concept. A design pipeline for production of this material system can be summarized as the following:

Design of the layout. Definition of the functions and features the system must perform, as well as the general dimension, to design the layout. The 2D design is aided by vector-based software (i.e. Rhinoceros).

Cutting. The layers are cut by a laser cutter (epilog laser mini printed through adobe illustrator[®]).

Sealing. The two TPE sheets are welded together in a watertight way. If the system has non-return valves, the hoses of the valves are first individually sealed, and then welded to the main two layers before the general outer perimeter is sealed. After testing the quality of the seal, the system is filled in with water, and the



inlet is closed. For this proof of concept, water was coloured with blue ink for better contrast.

Merging. Merging of the several subunits that compose the final skins-system together. The merging conditions affect, and can be used to tailor, the final movement (e.g. bending instead of linear growth by asymmetric merging).

The technical drawing (shape, size, corresponding volume etc) of the candidate material system of branch 2.1.8.1 is presented in the supplementary figure 2.

3. Final results and discussions

To recap, the core idea of the work is the conception and the bio-inspired translation of an EBEC that could be used for further development of fluid-driven devices that can assist the bending of the knee in accordance with the user's walk (figure 1). These first steps provided a basis upon which we could explore various materials and techniques to tackle the challenges of realizing various instances of harvest, storage, actuation and controls of the proposed hydraulic circuit (figure 2).

The final result and discussion unfolds in three sections: the EBEC-skin proof of concept, addresses the challenges and solutions regarding such integrated smart material system that would function in a synchronised interaction with the user and the environment; the design methodologies addresses the values and challenges of such exploratory bio-inspired design approach.

3.1. Proof of concept: EBEC-skin

3.1.1. Smart material system: programming features, embedding controls

3.1.1.1. A fluid-driven skin system The potential candidate to serve as the basic functional unit of the system is composed of two sheets of TPE sealed so that it embeds a watertight hydraulic circuit (figure 2, branch 2.1). As described in figure 3, the sealing perimeter defines functional areas for fluid flow and confinements resulting in chambers and channels. The tailored transfer of an incompressible fluid (here water) through the subsequent functional areas, can realize the instance of harvesting and storing of energy for powering the actuation.

This double-layered fluid-filled material system - from here on referred to as skin-would serve as the base material system for addressing various features and functionalities within the proposed interactive exosuit.

3.1.1.2. Defining areas, programing functional features

The abstract instances of the EBEC can thus be embedded within the proposed material system as various chambers and features of the hydraulic circuit. Variations on the design of its perimeter define functional areas and affect the way these areas would react to the transfer of a specific volume, with varying degrees of swelling and elastic inflation. Understanding this relationship between the sealed edge and the resulting behaviour enables tackling these circuits as 2D designs. In this regard, two variables can be tailored:

- The shape of the functional areas
- The relative size of the functional areas

The shape of the functional areas refers mainly to how the form-factor will define the behaviour upon inflation. In this regard, in the 2D design we distinguish the 'thin areas' (with smaller distance between the sealing edges) from the 'wide areas' (larger distance between the sealing edges), which in the flooded state will roughly assume the shape of a cylinder and a sphere respectively. In the proposed layout design (figure 3 and the supplementary figure 2), the 'thin areas' have smaller cross section than the 'wide areas' (with a diameter ratio of about 1:3 in the flooded state). Given the same material, wall thickness and inner pressure, this difference in the cross-section (and the corresponding skin surface area) results in a larger force acting on the spheres in comparison to the cylinders (force = pressure \times surface area). Consequently the skin of the wider areas have an earlier onset of elastic deformation and inflation compared to the thin ones (e.g. for the same reason it is harder to inflate long balloons).

From the design point of view, the more spherical shape would behave as chambers, inflating and accommodating a larger volume of the fluid that can be used for harvesting, storing, and actuating. While the more cylinder-like sealed areas (smaller distance between the sealing edges) present significantly less inflation, and would act as channels that can connect and transfer the fluid between the chambers (figures 5 and 6).

In terms of harvesting and storage, if we consider volume as the 'energy currency' of the system, the relative size of the functional areas, provides a means to tailor the behaviour of interconnected chambers. The transfer of the fluid volume between two chambers with similar material and surface areas results in a symmetric inflation/deflation behaviour. Assuming the ideal case with no energy dissipation, the work that is put into the system would translate into similar fluid pressure and tensile stress inside and on

the skin of the second chamber respectively, which would allow a symmetric energy cycle. Alternatively, the flow between chambers with significantly different initial skin surface area, would result in an asymmetrical behaviour. Upon the deflation of the larger chamber, the smaller chamber would undergo a larger elastic deformation and inflate to assimilate the extra transferred volume. As such, the chambers' size ratio provides a design parameter to enhance and tailor the elastic energy storage in the storage chamber (figures 5 and 6).

3.1.1.3. Embedding self-synchronisation control The shape and sizes of the functional areas can serve as useful design parameters to define the relative functions and instances. However, these functionalities and instances need to be considered and embedded within an integrated larger system of body-device-environment as a whole, and as such, be paired with the stages of the gait to achieve an autonomous EBEC (sense-action).

Here, we defined two types of controls embedded in the material system to ensure the self-synchronization between the main instances (harvesting, storing, and actuating) and the users' intentions during the walk:

- User-interface (active) controls
- Flow-check (passive) controls

User-interface (active) controls are surfaces that mediate the user-environment and user-device interactions. These functionalities are defined mainly in relation to their position within the cycle of the EBEC system, and how they transfer the external forces to affect the flow through the system.

The trigger interface is located between the heel of the user and the substrate environment (i.e. floor). When the foot strikes the floor, the weight of the user gradually compresses the harvesting chamber. This triggers the transferring of fluid volume to the storage chamber, while keeping the harvest chamber closed.

The release interface is located in the upper part of the device, mediating the user and device interaction at knee level. The main function of this interface is to 'sense' the stage of the walk and control the flow through the actuation chamber accordingly. When the user applies their full weight to the leg (stance stage), the interface is compressed and closed. When the lower limb starts to lift and the weight is transferred to the opposite leg, it can open and allow a volume transfer from the storage to the actuation chamber, releasing the stored energy to assist the bending of the knee.

These control interfaces can thus be realised as areas that can sense relative pressure over the system and, according to their design, allow, block, or regulate the flow between the different instances.

Next step in the design of the hydraulic circuit is to ensure the sequences of harvest, store, actuate, and return within the cycle. Flow-checks (passive) controls are valves that define and ensure the directionality of the flow.

The first flow-check of the system is needed between the harvesting chamber and the return channel, to ensure that upon compression of the harvest chamber the volume is transferred to the storage chamber and not back to the return channel (figures 1(c) and 3(a)). The second flow-check is located between the harvest and storage chambers, to block the back-flow, keep the storage chamber inflated and ensure the energy storage. Once the fluid is transferred to and has inflated the storage chamber, the storage can be achieved through the combined action of the flow-check 2 and the release interface blocking the flow through the actuation chamber. These flow-checks are hose-like, non-return valves that are realized from the sheet-based building logic.

The hoses of the check-valve 1 and 2 are fixed to the external layers of the storage and the harvesting chambers at its inlet while remaining loose in the exit (figure 3(b), supplementary figure 2(b)). The design logic behind locating the hose inside the chambers and not in the channels is that the hose-like valve needs a space wider than the regular channel, and making the channel wider at any point would result in a new 'chamber-like' area, making it more convenient to locate them inside of pre-existing chambers areas.

Moreover, the hoses are curved, presenting different angles in respect to the main axis of the channel (figure 3(b), supplementary figure 2(b)). The design logic behind this is that introducing a slight curvature to the tip of the hose located inside of the chamber will enhance the non-return functionality of the valve. The inflowing fluid pressure would ensure the entry of the fluid into the chamber without any restriction, while as the inflow pressures from the harvest chamber stops upon lifting of the foot, the pressure within the storage chamber would collapse the slightly angled loose end of the hose inside the chamber, and obstruct the backflow of the fluid..

3.1.2. Integrated prototype

3.1.2.1. From EBEC-skin unit to a multi-layered system The developed fluid-driven skin system provides a unit that realizes the primary functions of harvesting, storing, and actuating within a closed circuit skin, hence realizing the envisioned EBEC design concept (figures 3(a)–(c)). The scaling up of these skin-units into an integrated multi-layered system (figure 3(d)), provides the means to realize the abstracted bio-inspired principles:

Enhanced anisotropy. The swelling of a chamber presents an expansion that is bigger in one of its axes as a consequence of the diamond-like cross-section

when inflated. Such anisotropy is enhanced by a cellular design that piles up the functional chambers in the desired expansion direction.

Transformation of linear growth into angular movement. The resulting linear expansion over one main axis can be turned into an angular movement (flexing) by applying an asymmetric constraint that forces an uneven swelling of the inner region and outer regions (figure 3(d)).

Robustness. Since the basic units are functioning as independent hydraulic circuits, the multi-layered system is more robust as if one or several of the basic units fail, the overall behaviour prevails.

3.1.2.2. Testing the event-based energy cycle The first setup is in outspread 2D configuration. In the test, the hands represent the user's full weight (red arrow) over the device (figure 3(c)). Pressure over the harvesting chamber triggers the harvest as the transfer of fluid to the storage chamber starts. The flow-check controls guarantee the right direction of the flow. After the fluid has been fully transferred, the potential energy is stored in the elastic response of the inflated storage chamber. The flow-check 2 prevents the fluid from going back (even when the force has been removed from the harvesting chamber), while the force over the actuating cell blocks the flow into and through the actuation instance. When the force of the user over the actuating chamber is removed (right hand), the stored elastic energy is released for actuation, pushing the fluid that swells the actuating chamber and lifts the small weight over the actuation chamber that represents the weight of the lower part of the leg. As the fluid goes through, it continues the way to the harvesting chamber, closing the cycle.

When a system composed of four units is tested in similar conditions, it proves a maximum angular actuation of 85° when actuating freely and 50° when lifting 200 g (figure 3(d), Supplementary figures 3 and 4 and the supplementary videos 4–6 3–6).

3.1.2.3. Integration of the EBEC-skins as an exosuit proof of concept Once verified the performance of the EBEC, the following setup tests the prototype in conditions closer to the real use (figure 4). The proof-of-concept prototype was not designed or constructed as a final product for user trials but as a demonstrator that could perform the intended instances of EBEC in a sequence that simulates a human step. For doing this, a 3D-printed leg-like structure with a main joint was used. The leg-like structure is moved from the top, simulating the user's body and weight. A two-part press, fixed to the lower and upper segments of the leg structure, performs the function of closing and releasing the swelling of the actuating chambers. When the leg is extended with full weight on top, the press is closed, when the weight is removed, it can be open.

Harvesting starts when the leg-structure impacts the ground with its sole and fluid transfer from the

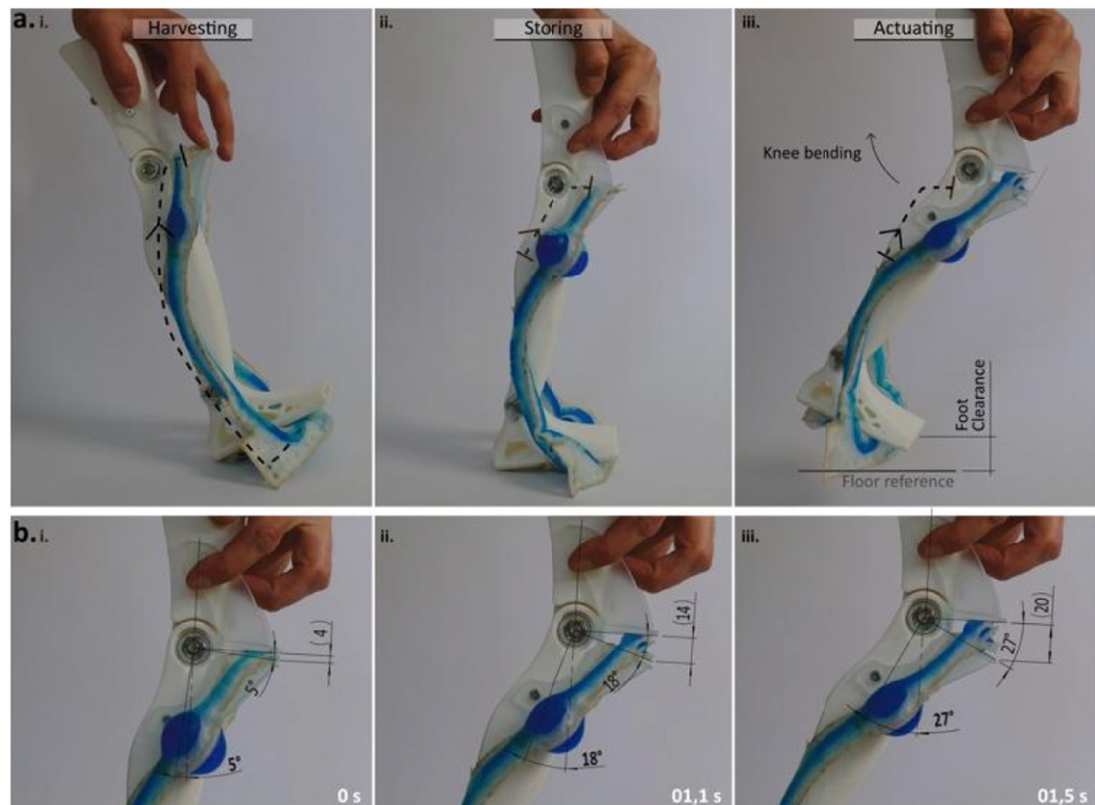


Figure 4. EBEC multi-skin system tested within a leg-like setup. (a) The three main instances of the EBEC and the fluid displacement and chambers inflation. (i) Harvesting, the lower chamber is compressed and displaces the fluid to the storage chambers. (ii) While the 'foot' is on the ground, the fluid cannot return (non-return valve 2) nor go further (knee press) hence it is stored upon elastic deformation of the storage chamber. (iii) Once the foot is in the air, the storage chamber pushes the fluid through the actuating chamber. The swelling of the actuating chambers push (open) the press resulting in the bending of the knee of the model fluid flow represented by black, dotted lines. (b) Image sequence depicting the fluid transfer from the storage to and through the actuating chamber, and the resulting actuation and the angular movement of the knee joint.

harvesting to the storage chamber starts. The force from the top (representing the potential energy of the user's weight) keeps the knee press closed and the storage chambers are inflated. When the pressure from the top is removed, and the leg slightly lifted, the fluid is pushed through the actuating chambers that swell and push the interface surfaces of the press, transforming the swelling into a bending of the leg. As depicted in figure 4(b)(iii), a multi-layered system of four units applied to the leg configuration can achieve a maximum angular movement of 27° .

3.1.3. Design space for fluid-driven EBEC-skins; a practical tool

Table of figure 5 depicts the five main variables to consider when designing and producing the basic unit of the skins. The top row in figure 5 presents, schematically, the basics of the sealing perimeter, while the bottom row depicts the dynamic behaviour of these units upon pressure changes. The described variables can be summarised as the following:

- Shape of the sealed area, and how it will configure chambers or channels.
- The relative size of two interconnected chambers and the resulting behaviour.

- The different control instances that can be embedded for triggering, releasing or controlling the flow direction.
- How to integrate many functional layers to enhance anisotropic behaviour and program linear or angular growth.

The second table shown in figure 6, can be considered as a tool that links the design variables with various features and functions that can be desirable for similar fluid-driven EBEC systems. It is aimed as a choosing aid tool for the design variables library presented above. The basic features are: to channel (connect), sense, harvest, store, actuate.

3.2. Bio-inspired design strategy

In conjunction with the discussions of the former section around the design of the proof of concept, the following section would reflect on the involved processes and approaches from a design methodology perspective.

3.2.1. Bio-inspiration beyond mimicry; a designer perspective

The design process summarised in figure 7, depicts an entangled process that contains various stages of

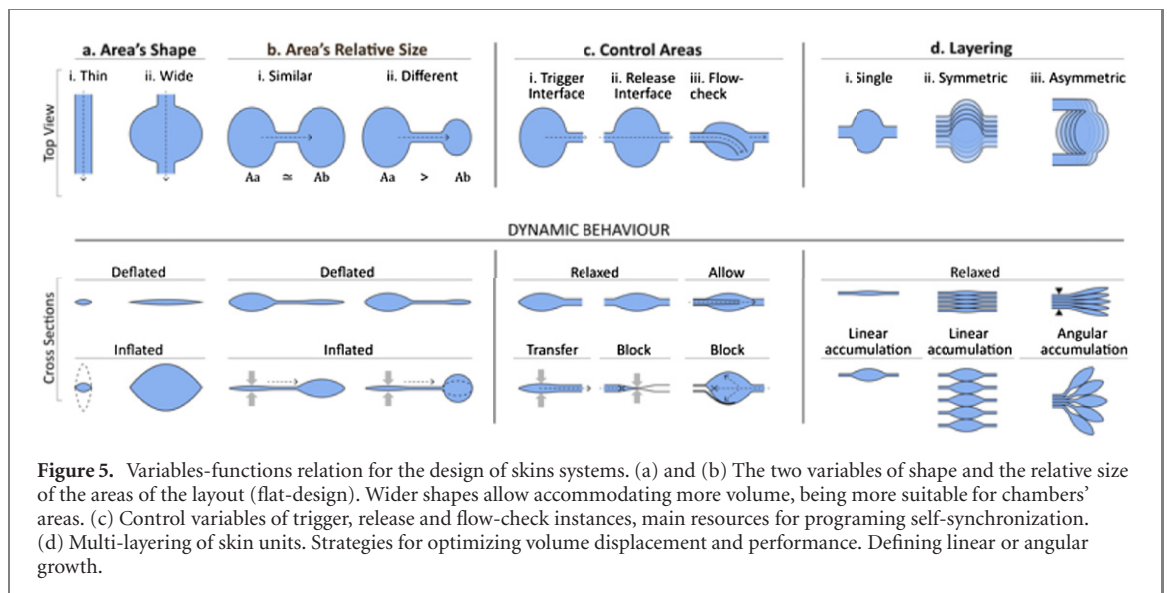


Figure 5. Variables-functions relation for the design of skins systems. (a) and (b) The two variables of shape and the relative size of the areas of the layout (flat-design). Wider shapes allow accommodating more volume, being more suitable for chambers' dynamics. (c) Control variables of trigger, release and flow-check instances, main resources for programming self-synchronization. (d) Multi-layering of skin units. Strategies for optimizing volume displacement and performance. Defining linear or angular growth.

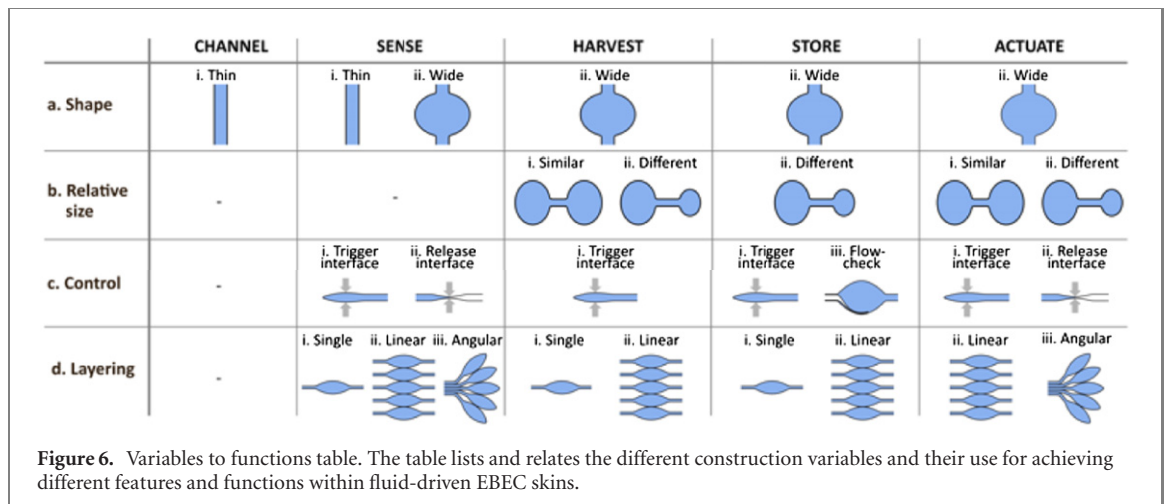


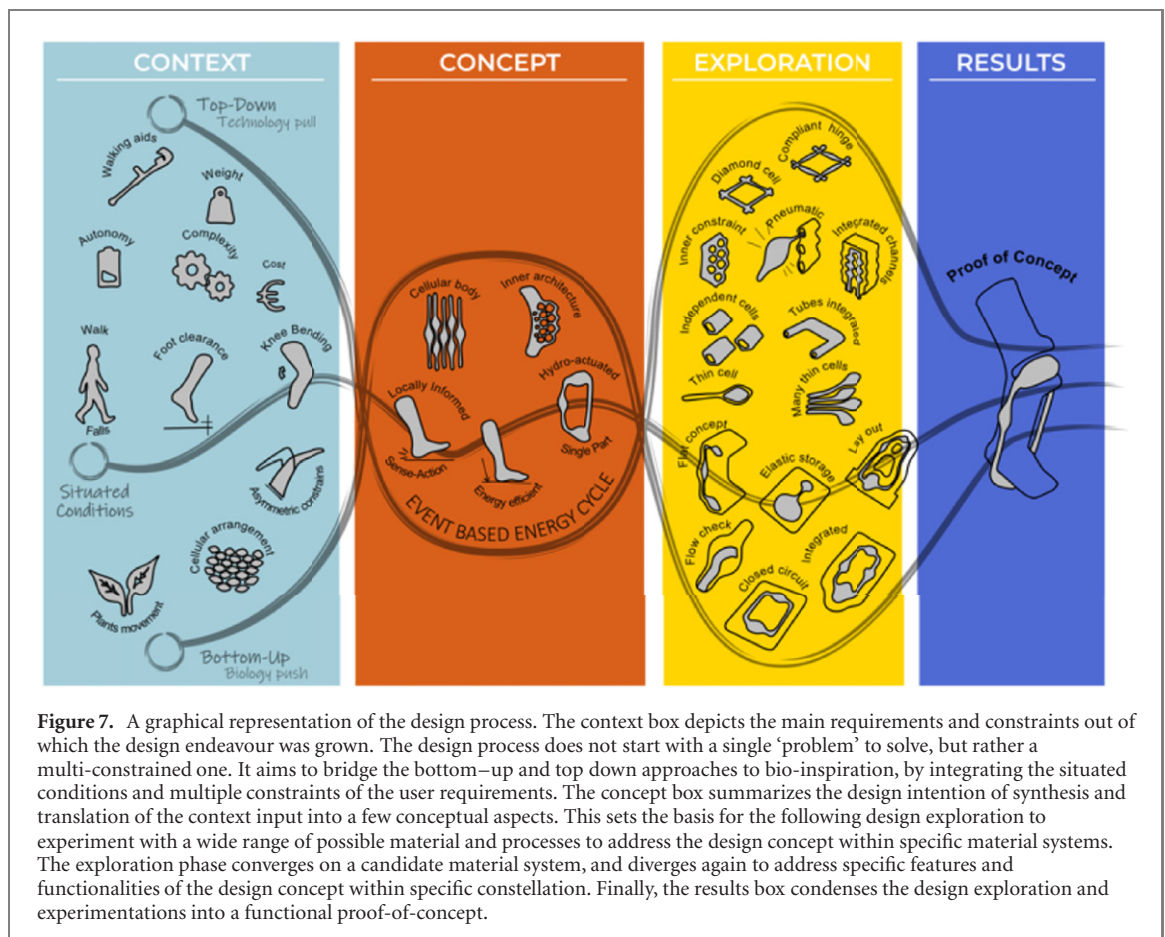
Figure 6. Variables to functions table. The table lists and relates the different construction variables and their use for achieving different features and functions within fluid-driven EBEC skins.

exploration (divergences) and concretisation (convergences) that track the process through the initial context, the design conception, the design exploration and the final result as a prototypical proof of concept (the four boxes depicted in figure 7).

In this work, bio-inspiration is presented as a design method that, on the one hand, is based on a set of abstracted models and principles from a biological model system, and on the other hand, considers the functional and contextual requirements, the interrelations and the boundary conditions of the envisioned system (figure 7 context box). Here, the starting point is not a single and detached problem but rather a complex set of requirements and constraints, which, we argue, provides a more comprehensive ground and mind-set for a bio-inspired process. The initial set of design conceptions, and the main abstracted bio-inspired principles, were followed by a set of general design strategic decisions such as reducing the number of components and different materials in the system; using no electronics, no

external energy input (e.g. batteries); basing the EBEC on a hydraulic circuit, and basing the hydraulic circuit on water and so on.

This way of taking bio-inspiration as a design strategy helps to bridge the bottom-up and top-down approach to bio-inspiration (Goel *et al* 2014 and Speck *et al* 2008). Considering the multitude of boundary conditions and constraints from both sides (depicted in figure 7 context). It is only through these initial convergences that the design conception can grow to fulfill the requirement of the desired functionalities (e.g. ECEB system, depicted in figure 7 concept). Ultimately, these better informed design conceptions could serve as the playground upon which the design exploration can follow (figures 2 and 7). The tree-like design explorations depicted in figure 2 complement this picture by highlighting the non-linearity and the back-and-forth paths within the exploration and concretisation stages of the design process.



3.2.2. Bio-inspired design strategy; a designer guideline

In Benyus’ biomimicry guild, life’s principles are presented as a table, or checklist of features to be considered when addressing a problem. It contains features such as being locally attuned, resource efficient, adapting to conditions amongst others (Peters 2011). Similarly, we want to put forward a way of understanding bio-inspiration beyond the specific solutions that can be learned from specific biological model systems, and put it forward as a design strategy.

Biological material solutions are constrained through various boundary conditions: their evolutionary history; the entanglements with other actants in their immediate environment and broader ecologies, the availability of material compositions; the available energy resources, and so on. These constraints or boundary conditions result in some general characteristics of biological solutions that, from a design/designer perspective, can be abstracted as bio-inspired design guidelines:

3.2.2.1. Material affordance; few elements, diverse functionalities Unlike the modern design and engineering which make use of diverse materials, biological materials solutions are limited and based on few basic components such as sugars, minerals, proteins etc which mainly consist of a few basic elements (C, N, O, H, Ca, P, S, Si etc) (Eder *et al* 2018, King

2019 and Fratzl 2007). The material efficiency in this regard and its diverse properties and functionalities are mainly achieved through diverse material architectures, where a few basic elements—materials and design components—are embedded through various scales of the structures and forms of the material systems to achieve multiple features and functionalities (Eder *et al* 2018 and Fratzl 2007).

In this regard, the proposed EBEC-skin concept has only two main components: the elastic skin and the pressurised fluid inside. They together build the structure and various features and functional areas: channels, harvest, storage, and actuation, valves and control instances. Multiple complex functionalities are achieved through a few basic elements, and through the architecture of the material system.

Moreover, this makes the mono-material system more efficient from a sustainability perspective, where fewer elements and components in a device are preferred for the recyclability of the system (Coulter *et al* 1998).

3.2.2.2. Energy affordance; embedded intra-activity Biology does not have the luxury of energy that human manufacturing has been running on. The long history of entangled co-evolutions have resulted in more energy efficient solutions to afford the energy requirement for making and maintaining specific functions. The case of hydro-responsive actuation of

ice plant seed capsules is an example of this, where the required energy and information for the proper response (seed dispersal) is embedded through the material architecture and its interaction with the environment (Harrington *et al* 2011, Gholami *et al* 2021 and Razghandi *et al* 2014a).

The proposed EBEC-skin units are energy efficient, in the sense that the energy cycle is embedded in the organisation of the material system and its event-based interaction with the user and the environment. User intentions and actions, the assistive exosuit and the substrate work together in an integrated system that responds and makes use of these intra-activities to assist the function, without the need for a centralised or additional information processing or energy reservoir (sense-action).

Energy harvesting through interaction and EBECs are at the core of the proposal, allowing a smart use of the available energy in the system (user-environment) rather than just powering it with external sources.

3.2.2.3. *Adaptive design; accommodating changes*

The multiple constraints acting as boundary conditions of the biological material systems, dictates solutions that would be flexible enough to adapt to the changing conditions. Locally attuned properties, responsiveness, robustness and so on have been highlighted as such adaptive features in various biological systems (Peters 2011, Fratzl *et al* 2015 and Eder *et al* 2018). What from a design perspective we can call adaptive design, in this sense, is the necessary design condition of biology as situated and entangled within a specific history and ecology.

The adaptive design of the EBEC is not only a sense-acting system, but the presence of multiple skins, each contributing to the final functionality of the system (inspired by the cellularity of the ice plant hydro-responsive keel) brings a degree of robustness to the system (defined here as tolerance of failure). Failure in one of the functional units (e.g. leakage of a skin-units) affects the functionality of the system but does not lead to failure of the system as a whole.

This cellularity also makes it possible to adapt the actuation force of the system to specific conditions. For instance, adding more EBEC-skin units to the multiple skin system to adjust and tailor the actuation force for a specific user case. Besides, the flexible production system of fabric layers merging, instead of complex multi-part assembly, enables to tailor and adapt the technology to specific users and needs as it dispenses any kind of tooling, moulds, or standardisation.

3.2.2.4. *Morphogenesis; emergence of form*

Biological solutions are not subordinate to a preconceived shape, but are the result of a complex multi-constrained generation process. Morphogenesis highlights a contrast with the way design is conventionally addressed where form leads the idea-generation process, and the materialization of such ideas is merely understood

as an issue of material and manufacturing technology selection (Oxman 2010). Form generation and description through geometries are deeply rooted in design disciplines, and conditions and limits the paths to viable solutions.

For the EBEC-skins the material selection and choice of production process are prior to the final shape. The choice of TPE for the construction of the prototype is based on the desired elastic properties of the layers that would allow the harvesting, storage and actuation instance of the EBEC hydraulic circuit. Heat-pressure melting was chosen as the main production process mainly because of its availability and the ease of the process (resonating with bio-inspired affordance).

This 'good-enough' material and production process provide a proper playground and setting within which and through various trials, iterations, and selections, the final shape emerges. The final form of the skin system results, not from a foreseen geometry to which a material has been subordinated, but from the interactions between materials properties, production process, and the actors involved. The multi-function and multi-constraint defined conditions gradually shape the design through various design iterations (figures 2 and 7). The final arrangement does no longer follow old form/function, material/structure dichotomies; instead, everything is entangled and embedded in the material architecture of the layered-based skin.

3.2.2.5. *Contextually 'good enough'*

The common understanding of nature's solutions as perfectly efficient can be misleading in the bio-inspiration discourse. Biological material solutions are not 'perfect', yet they are contextually 'smart': biology is situated and entangled within a specific history and ecology, and this is reflected in 'affordance' and 'good enough' principles, as in a balance between what works and what is possible within the context (history and ecology). The same material, or functional zone within an organism, has to cope with several constraints and functionalities at the same time (Oxman 2010 and Eder *et al* 2018). Similarly, human made products (design, engineering) are also required to fulfill not only functional needs, but also various other constraints related for instance to material selection, fabrication methods, cost, desirability, sustainability, etc, and as such, are also multi-constrained. In the process of exploring for novel design solutions, we tried to address this multi-constrained aspect, by abstaining as much as possible from limiting the exploration to specific legacies.

The bridging of the bottom-up and top-down approach to bio-inspiration in this work is achieved through various design strategies that are neither in pursuit of a one-to-one mimicry of the bio-inspired principles, nor are oriented in search of a perfect solution. The aim was to explore diverse and good

enough viable paths that would address various constraints and represent alternative novel solutions and improvements in the specific context.

4. Conclusion

The presented design endeavour helped explore various design spaces to address the two research questions brought up in the introduction: first, how to envision a more energy efficient and autonomous solution to the assistive exosuits paradigm; following a potential application context for assisting knee bending in human gait. Second, how a design approach to bio-inspiration can bring out new insights to this challenge; specifically, exploring inspirations from plants' passive hydro-actuation strategies.

The significance of the bio-inspired design project can be summarised as the following.

- The proposal and development of an EBEC design concept, that can harvest, store, and release energy for actuation, while self-synchronizing with the contexts and usage conditions
- Development of a proof-of-concept prototype that materializes the EBEC concept as a hydraulic circuit; articulation of a design pipeline for such multi-layered, fluid-driven soft-machine.
- A showcase for how a design strategy can serve as a path bridging the bottom-up and the top-down approach to bio-inspiration; abstract and translate biological material solutions into and in accordance with a specific real world challenge and its particular requirements and boundary conditions.

In comparison with other strategies commonly found in assistive technologies devices, the presented EBEC-skin approach have few intrinsic drawbacks. In comparison, devices with rigid structural frames (such as traditional exoskeletons) present in general a more efficient transfer of energy (from the actuator to the desired body segment to move). Moreover, the energy that can potentially be harvested with the proposed fluid-driven EBEC can only be low to mild. In this regard, it cannot match the actuating power of systems with external power supply (e.g. batteries for electric motors or pumps for pneumatic actuators). Finally, the smart-features that can be embedded in the material arrangement (e.g. controls, self-synchronization etc in section 3.1.1) are significantly limited in comparison with the possibilities of electronic sensing-processing-actuating systems.

In spite of these shortcomings, the proposed approach can serve as a proof of concept for a novel approach to design of fluid-driven interactive soft-robotic exosuits. Not requiring an external power source makes the proposed EBEC-skin system an

ideal candidate for moving applications where being lightweight and low profile is crucial for the user. Moreover, the fabric-based construction and the simplicity and low cost of fabrication, would make such products scalable and affordable, making these soft-machines good candidates for assisting simple, daily life activities.

One area of application that can benefit from the novelty of the EBEC-skins, are assistive technologies such as lower limbs exosuit that assist dorsiflexion and/or knee bending for reducing the chances of falling for: post-stroke, elderly, incomplete spinal cord injury amongst others (Awad *et al* 2017 and Bae *et al* 2018). The proposed system can also provide/boost plantar flexion, aiming to reduce the metabolic cost of walking in as a performance garment for outdoor activities such as hiking (Quinlivan *et al* 2017, Witte *et al* 2020 and Yandell *et al* 2019).

The analog nature of the EBEC-skins—allowing the transfer of energy and information through (fluid) mechanics rather than electronics—is presented as a crucial advantage of the proposed system. However, we see the fast development of soft, textile sensors and flexible electronics (Islam *et al* 2020 and Wang *et al* 2020), as a potential source of improvement of the system, for integration of such sensors can help to get a better, real-time understanding of the gait pattern of specific users.

Moreover, pairing the EBEC-skins system with low profile electro-valves can potentially enable one to program a greater range of possible reactions or modes that dynamically adapt to the user's movement. This can be an advantageous add on, as such micro-tunings can be achieved, with lower energy consumption compared to active pumping, without increasing the construction complexity of the skin system itself.

The prototype at its presented stage is not a product or a functional prototype, but rather a proof of concept of the feasibility for materializing the proposed fluid-driven EBEC-skin design concept, and as such, the performance analyses of the presented proof of concept were concentrated on the feasibility of materialising this initial design concept, and further quantitative performance analysis were out of the scope of this first exploratory stage.

Currently, the project is moving forward as a startup⁴ (Gutierrez *et al* 2021) developing textiles with embedded fluidics for dynamic garments with potential applications in various fields. The current project aims to bring this early stage proof of concept closer to a wearable exosuit that could provide mild-power assistance to the gait, support daily activities, or help the rehabilitation through activation and massage of

⁴ MotorSkins UG is a company that develops shape-changing textiles for human-machine interaction, with strong focus on hydrodynamic apparels for sports and medical applications.

certain areas of the leg and so on, with a comfortable, affordable and sustainable interface material system.

The presented interdisciplinary work can be taken as a case study for bio-inspired design strategy. The presented science-design collaborative methodology angle, can help to see the biological phenomena at hand from a design stance, which compared to science or engineering stances, we argue, can allow a broader take and abstraction of the underlying principles, resulting in a more open detachment from the biological phenomena that considers the conditions and constraints of the biomimetic transfer target.

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Data availability statement

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Conflict of interest and other ethics statements

The authors declare no conflicts of interest.

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