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ENGINEERING DESIGN OF AN ADAPTIVE LEG PROSTHESIS USING BIOLOGICAL PRINCIPLES

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*Keywords: biomimetics, biological principles, idea generation,
engineering design, biological literature, shape adaption*

1. Introduction

Engineering design using biological principles is also referred to as biomimetic design. From a design point of view nature represents an interesting opportunity with its wealth of well-proven solutions that has been developed, refined and proven through 3.8 billion years. Finding and using the right inspiration in nature makes it more likely that the designer can generate improved products. However biomimetic design also represents at least four challenges: Formulation of the design problem, finding biological analogies, understanding the biological phenomena and the abstraction of the functional principles. The first and the last of these are traditional design challenges while the other two are new to designers. This paper explores the biomimetic design process through a design case: An adaptive leg prosthesis. In particular, the aim is to investigate which methods, tools and knowledge sources that are available and if the biomimetic design process can be carried out with a minimum of biological knowledge and without using advanced design methods. In the design case biomimetic design was successfully carried out resulting in 14 biological analogies for the design problem 'shape adaption'. It is proposed that search results are handled using special cards describing the biological phenomena and the functional principles.

2. Biomimetic design

2.1 Bottom-up and top-down

Learning from nature has taken place since the early days of mankind, but the systematic use of biological principles in engineering design is a very young discipline. The term biomimetic is constructed from Greek "bios" meaning life and "mimesis" meaning to imitate [Benyus 1997]. Generally speaking it deals with the transfer of nature`s profound knowledge into human needs. In particular biomimetic design could grant access for technical problem solving with the help of already solved problems in nature if one knows how to use it the right way [Lindemann 2004]. Most of the biomimetic design work has until now been focused on what could be called a bottom-up approach, where an interesting biological phenomenon is analysed and transferred into a technical solution. Many of the well known examples on biomimetic design like the Velcro fastener and the Lotus flower self-cleaning surfaces belong to this category. Our interest is the opposite – one could call it a top-down approach, where an engineering problem is the starting point and used to search the biological domain for relevant analogies.

Biological systems with one billion try-out cycles in structure, function and organization offer examples of many kinds [Benyus 1997]. In some cases solutions are directly found in nature like the cockleburs/Velcro which remind of copying. However the amount of inspiration available in nature is much larger than the amount of direct analogies. Many of the underlying principles that explain the functionality in animals and plants are not immediately recognizable and a more advanced study is required to find and understand them. Biomimetic design as a scientific discipline needs to formulate theories that will explain the relations between nature and technology and develop methodologies that will facilitate the design process.

2.2 Procedural models

The top-down approach to biomimetic design has been pursued by a number of researchers using different techniques. Hill describes a five step procedure including analysis and abstraction of functional attributes, transfer into the biological world using a catalogue with biological phenomena, comparison of functions and biological equivalents, selection and finally creative transfer of principle structures [Hill 1993]. The critical point is the availability of a suitable catalogue with biological phenomena, but it is not mentioned whether the catalogue has been created.

The München group describe a four step procedural model involving the steps 1) formulate the intention / the target, 2) correlate biological systems, 3) analyse the correlated systems and 4) realise the technical solution [Lindemann 2004]. Like any procedural model for design it is iterative. The correlation with biological systems is proposed done using a transfer checklist between technical functions and terms in biology. The checklist is straight forward to use, but is limited to the functions and biology terms that exist in the list.

Vincent also describes the transfer of knowledge from nature into humankind‘s technology [Vincent 2002]. The idea is to use the TRIZ-method to search for biological equivalents with similar functional properties. TRIZ includes a formal framework for describing functional requirements that can be used for searching a comprehensive database with patents. Vincents idea is that a similar database can be made for biological phenomena. This approach represent two challenges: Designers need to be trained in using the TRIZ-method, which is not a trivial task and a large database needs to be made and maintained.

The Toronto group highlight the problems in natural language processing which among other things include the different terminology within the engineering and the biology domain. They manage the access to biological knowledge by using an online version of a standard biology textbook [Shu 2006]. Especially the search for biologically meaningful keywords corresponding to engineering keywords marks a difficulty [Cheong 2008]. They suggest finding keywords in the functional basis [Stone 2000] and use WordNet [wordnet] to generate synonyms, troponyms (more specific meaning) and hypernyms (more general meaning). The functional basis is a vocabulary describing many of the known functions in products. In order to translate these functional terms into biological equivalents they propose a procedure that includes identification of nouns often used close to the functional keywords in a biological text [Cheong 2008]. Often are other bridge-verbs in the same sense used in other sentences or paragraphs and it is likely that these verbs belong to the biology domain. The biological relevance of these bridge-verbs could be validated by checking them in a biology dictionary.

Previously a four step procedure for biomimetic design has been presented [Lenau 2009]. The four steps are (a) problem formulation and search for relevant analogies, (b) proper analysis of the biological solutions, (c) interpretation and identification of design principles and (d) design of the desired artefact. It is not a linear procedure but involves many iterations. The procedure was used in six student projects involving problems like energy saving, navigation and protection. The projects resulted in good solutions, but illustrated the difficulties in carrying out the search phase involving problem formulation, generating keywords and the biological search itself.

2.3 A refined procedural model and the challenges

One of the experiences from the adaptive prosthesis case (described later) were that the search and the analysis phase in figure 1 was by far the most difficult and each of them involved several steps. A refined and expanded model is therefore proposed, see figure 1. In the refined model the former search phase has been split into a problem definition phase and a new search phase, that focus on keyword formulation and the search itself. Each of the five overall phases have one or two more detailed stages like formulation of the specific and the general problem. The stages are bound together by activities that are indicated in figure 2 as rounded arrows going from left to right. Angular arrows going right to left in the figure represent the backward oriented activities in iterative work.

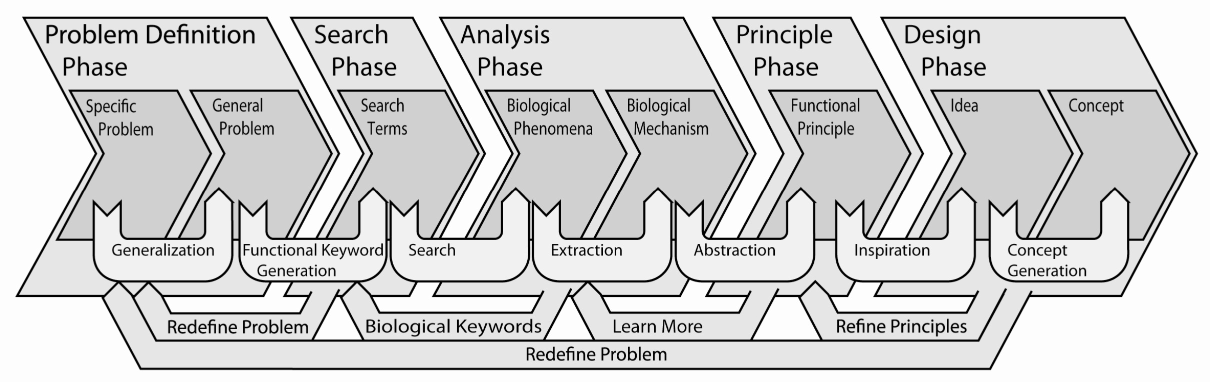


Figure 1. The second refined procedural model for biomimetic design

The model starts with the problem definition phase where focus is on what the key problem is. This is often difficult for designers due to a multitude of competing problem areas and several stakeholders. The problem is first formulated in terms of the specific design case and then generalized in order to better allow findings of biological analogies. The degree of the generalization depends on the problem itself and the goal of the design project.

After deciding the level of generalization an idea generation session marks the beginning of the search phase. Functional keywords related to the general problem are generated with the help of a brainstorm. The keywords are used to find biological phenomena in different search engines available on the internet as well as online sources at the library. The keywords can with advantage be formulated as verbs describing the desired functionality. However in some situations also nouns can be used together with verbs, like in ‘change shape’. These initial keywords rely primarily on the personal association of the participants and their prior knowledge. The initial functional keywords normally only give a limited amount of useful search results and biological keywords should therefore be identified; biologists use a different vocabulary to describe biological phenomena. It can therefore be useful to consult biological expertise that can help generate new keywords. A second search using the new keywords could expand the amount of relevant search results.

In the analysis phase interesting biological phenomena related to the problem are investigated in order to extract the biological mechanism. The biological mechanism describes the underlying biological process in the phenomena. To understand the phenomena scientific literature in books and journals is used. In addition biological expertise can be consulted here to understand the phenomena. The analysis can also generate new keywords. The description of the biological mechanism is formulated in terms close to the biology domain, and an abstraction into the functional principle is therefore beneficial for the further design work. This is done in the principle phase where the central aspects are isolated and unnecessary details removed and the principle presented in a language natural to the designers. The functional principles are often best illustrated with a simplified sketch.

In the design phase the identified functional principles are used to generate ideas for partial soulutions and concepts for complete solutions. The method is iterative where one returns to previous stages and phases in order to refine the work.

3. Case: Adaptive leg prosthesis

3.1 Prosthesis

The procedure is illustrated with insights from a case study: The development of an adaptive leg prosthesis. Figure 2 shows two examples of existing prothetic legs. The goal of the case-project is to develop an adaptive leg prosthesis with the help of nature`s inspiration for an innovative solution.

The project deals with residual limb volume fluctuation, which is a problem that most lower limb amputees experience. The fluctuations vary both in amount and frequency, and can be due to a number of reasons, such as sichness, physical activity, fluid balance and body growth, as can be seen in figure 3. Most users (amputees) experience a volume fluctuation of up to 5 %, which could be compensated for with adjustments of up to a few mm’s . Several products are on the market that are based on an interface consisting of a hard socket over a soft “liner”, which is worn directly on the residual limb. The liner provides support for the residual limb and comfort for the amputee.

Figure 2. (left) A fifteen year old prosthesis user having her prosthesis adjusted due to body growth. (right) Many prosthesis users at all ages want to be physically active. Picture used with kind permission of Ossur

However, when the residual limb shrinks, the fit deteriorates which decreases comfort for the user. Current solutions are socks worn over the liner. By wearing socks an even volume is added to the residual limb, but since volume changes occur in soft tissues, not bones, they are not equal in the front and the back. The overall goal of the project is that the user should be able to use his prosthesis from morning to evening, comfortably, without needing to take it off for adjustment; a simple to use, care-free interface between the hard socket and the residual limb, which adjusts to the natural volume changes of the residual limb. To get a new perspective on potential solutions, it was decided to seek inspiration in nature through the biomimetic design method.

3.2 Problem definition phase

The starting point is to formulate the specific problem. For the adaptive leg prosthesis it can be formulated in the following way: *A residual limb changes its size and shape during the day and will therefore only fit tightly into the hard prosthesis shell part of the time.*

This statement can be generalized into broader and more general problem statement: *An object of variable size and shape does not fit tightly into a hard cavity.* This can be re-formulated even more generally as a question: *“How to adapt to changing shape?”*. Creativity can be restricted by a too detailed formulation of the problem. It leads to a more narrow search and the analogies further away will not be considered. A broader and less specific problem definition makes the search wider but also more complex and hard to manage. A high degree of generalisation was chosen in order to widen the possible solution space, since one of the ambitions was to challenge predispositions on the function of the residual limb – prosthesis interface. This may have caused difficulties in finding relevant phenomena in sources which mainly describe specific phenomena.

Table 1. List of the identified biological examples

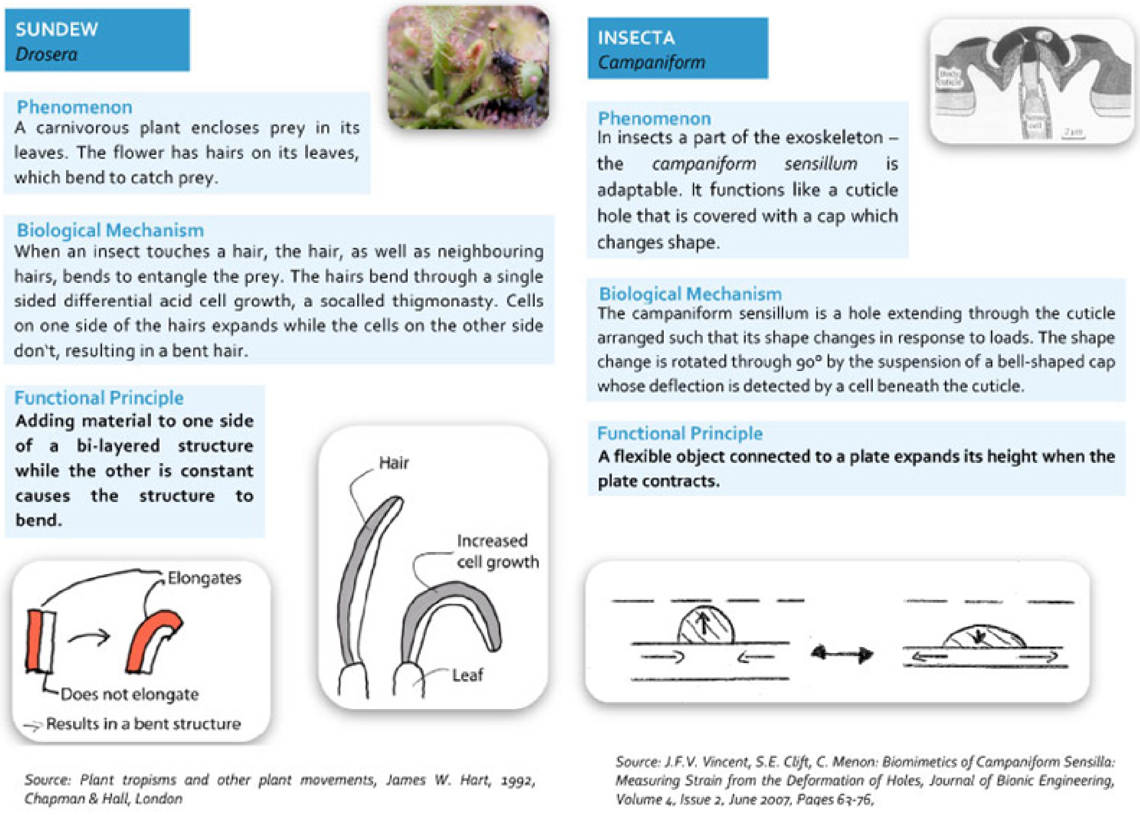
No.	Keyword	Source	Phenomena (trivial)	Phenomena (latin)
1	Change	Asknature	Sundew	*Drosera*
2	Change	Asknature	Insecta	*Campaniform sensillum*
3	Expand	Asknature	Clark`s nutcracker	*Nucifraga columbiana*
4	Swell	Asknature	Fungi	*Arthrobotrys*
	Swell	Life		
5	Humidity	Asknature	Pine cone	*Pinus silvestris*
6	change AND volume	Asknature	See anemone	*Cnidaria*
	change AND volume	Library search		
	decrase AND shape	Google Books		
7	volume AND change	Asknature	Ribbon worms	*Amphiporus lactifloreus*
8	pressure AND support	Asknature	Blackback crab	*Gecarcinus lateralis*
9	size AND change	Asknature	Crabs	*Crustacean*
	(volume OR shape OR length) AND (regulation OR regulate OR change)	Google books		
10	Extend	Asknature	Dragonfly	*Odonata*
	(volume OR shape OR length) AND (regulation OR regulate OR change)	Google books		
11	Constant	Asknature	Earth worms	*Annelids*
	regulation AND volume	Google books		
	change AND volume	Library search		
	Flex	Life		
12	regulation AND volume	Library search	Osmosis	*Osmosis*
	regulation AND volume	Google Books		
	regulate / shrink / volume	Life		
13	regulation AND volume	Technical literature	Amoeba	*Amoeba proteus*
14		specialist	Blowfish	*Tetrodontidae*

3.3 Search phase

A brainstorming session was conducted, where the participants came up with keywords which could be used for searching online resources, based on the general problem and the participants' prior knowledge. The keywords generated in the first session were *vary, change, adapt, extend, increase, decrease, flexibility, suit, adjust, cover, grow* and *transform*. These keywords were used for the initial search in a biomimetic based website AskNature [asknature 2009] which contains a summary of biological phenomena collected by the website staff. More keywords were generated to try to get more results, and keyword combinations such as *shape AND adaption* were generated. To help generate more keywords, some aspects of the problem were simplified, like changing the three-dimensional variability into a one-dimensional change of length, which resulted in the keyword combination *change AND length*. Keywords used in biological literature, such as *metamorphosis, swell* and *shrink*, were continuously added to the list of keywords. To add further to the list of keywords, a thesaurus function in Google documents, which is based on Britannica Online, was used to generate synonyms for the keywords in the list. As the search phase progressed, more complex search strings, using Boolean operators such as *(volume OR shape OR length) AND (regulation OR regulate OR change)* were tried as well. Late in the search phase the Zoological Record Search Guide was found, which provides a thesaurus of controlled biological terms used within the database itself. Unfortunately, it was found too late in the project to be properly put to use, however, this is probably a good place to start looking for biological keywords, as it is a reputable source within biology. During the search phase, 30 potentially relevant biological phenomena were found, the most promising fourteen of which can be seen in table 1.

An underlying goal for the search, was to find phenomena within both zoology and botany, ranging from the micro (cells, organs) to the macro level (whole organisms). For this purpose, journal papers and articles were searched in bibliographic databases such as Biosis Previews, Zoological Record, Google Scholar, Jstor and ISI web of knowledge. Books were searched using classical library search methods and by searching in Google Books. Furthermore an electronic version of a basic biology book, Life: The science of Biology [Purves 2003], which is used for teaching in introductory courses in biology was used for the search. Additionally AskNature was searched in the start. The first ten hits were considered, except when searching in Life, where this would have limited all searches to the first two chapters. Combination searches could be used in most cases exept pdf-files like Life that only allow simple text-string search.

The majority (11) of the identified phenomena were found through the search in AskNature. Most of these were also found in other sources in later searches, as can be seen in table 1. AskNature proved to be useful but it has a number of limitations. It provides summaries of biological phenomena which have been deemed interesting by the AskNature staff. The content is therefore highly relevant, but at the same time limited, in terms of the quantity of available content, in comparison with other online resources, particularly given that the website is still in progress. Another limitation is that it only covers the macro level, i.e. animals and plants but not the micro level like cell biology. It is time efficient to search a biomimetic database like AskNature, but it will most likely limit the solution space if other sources are not searched as well.



SUNDEW
Drosera

Phenomenon
A carnivorous plant encloses prey in its leaves. The flower has hairs on its leaves, which bend to catch prey.

Biological Mechanism
When an insect touches a hair, the hair, as well as neighbouring hairs, bends to entangle the prey. The hairs bend through a single sided differential acid cell growth, a socalled thigmonasty. Cells on one side of the hairs expands while the cells on the other side don't, resulting in a bent hair.

Functional Principle
Adding material to one side of a bi-layered structure while the other is constant causes the structure to bend.

Source: Plant tropisms and other plant movements, James W. Hart, 1992, Chapman & Hall, London

INSECTA
Campaniform

Phenomenon
In insects a part of the exoskeleton – the *campaniform sensillum* is adaptable. It functions like a cuticle hole that is covered with a cap which changes shape.

Biological Mechanism
The campaniform sensillum is a hole extending through the cuticle arranged such that its shape changes in response to loads. The shape change is rotated through 90° by the suspension of a bell-shaped cap whose deflection is detected by a cell beneath the cuticle.

Functional Principle
A flexible object connected to a plate expands its height when the plate contracts.

Source: J.F.V. Vincent, S.E. Clift, C. Menon: Biomimetics of Campaniform Sensilla: Measuring Strain from the Deformation of Holes, Journal of Bionic Engineering, Volume 4, Issue 2, June 2007, Pages 63-76,

Figure 3. Two cards that describe the biological phenomenon, the biological mechanism and the functional principle for a sundew plant (left) and the insecta (right)

Three of the phenomena were identified within the search in Google books. This source provides a full text search that has the advantage that it provides direct access to the text block containing the search terms, which helps the evaluation of the results in terms of relevant biological phenomena. While access to older books can generally be obtained through Google books, online access to newer books is often limited. Several phenomena were identified through the search within Life. The main advantage was that it was possible to get directly familiar with the text block containing the search term, but it was very time consuming to inspect every incident where the single search words appears.

Two examples show that going through the online database of the local library and searching for technical literature can provide results with books of all ages, with unlimited viewing inside the library. The limitation of a classical library search engine is that it is usually only possible to search within the title and a short description, which makes it is necessary to point the search in a specific field and combine the keywords with a specific area like plants or insects. Expertise from a librarian with a biological background was consulted. Her advice lead to technical literature that lead to another two new phenomena. The librarian also led directly to one biological phenomenon, the blowfish.

It was difficult to find biological phenomena in the article databases because they are limited to searches in fields such as titles, abstracts and keywords, and lack the direct access to a relevant text block in the results. Moreover, the majority of online article databases are limited in their access to articles of newer date, which may lead to the omission of older biological discoveries, which are only represented in older articles and books. Nevertheless, subject specific databases, such as Biosis Previews and Zoologic Records, save the researcher for being faced with results that fall outside of the field of biology as well as being the primary source for newly discovered phenomena.

3.4 Analysis phase and principle phase

As desired the spectrum of identified phenomena spans from the micro level (osmosis), to animals and plants. To get an overview, the biological phenomena are arranged on cards with the four fields: Title, phenomena, biological mechanism, functional principle and a simple sketch to illustrate the principle. The sundew and the Insecta phenomena, marked with grey in table 1, illustrates the structure of the cards in figure 3. The title refers to the name of the organism, which can be used in discussions when referring to the card. The Latin name (e.g. *Campaniform sensillum*) is used to limit the results during the research and for further literature search. The second field describes the phenomenon – in case of the sundew the bending of hairs on the carnivourous plant's leaves that is used to catch prey. The biological mechanism field explains the performance of the phenomena. For the sundew the mechanism behind the hair bending is a single sided differential acid cell growth, a socalled thigmonasty. The abstraction into functional principle formulation of the biological mechanism presents the last field. The functional principle of the sundew is the bending of a by-layered structure when material is added to the one layer while the other is constant.

3.5 Design phase

In the design phase the cards act as inspiration tools for idea generation. Since the functional principles on the cards can be quite simple, it was decided to discriminate between ideas and concepts, where it is not necessary for ideas to cover the whole product or even to be technically sound. In the project a lower limit on the number of ideas was set at one idea per card to ensure that the identified solution space was being covered. When a sufficient number of ideas has been generated, more holistic concepts are generated on the basis of the ideas, where user needs and technical feasibility play a larger role.

The idea generation was performed as brainwriting sessions for each card, where each participant carefully studied the card. The card reminded the participants about the phenomenon and the principle at work, thus facilitating an idea generating session focused on the particular phenomenon. Ten minutes were spent drawing or writing ideas on a piece of paper. After the ten minutes the generated ideas were discussed, with only positive comments allowed, and ways of improving or combining the ideas. Another ten minutes were used with pen and paper, to generate new ideas based on inspiration from the others or from the discussion, or to further develop or combine the ideas that were already on the table. The result of the brainwriting sessions was a total of sixty-five different ideas including forty-eight ideas that specifically addressed the design (specific) problem: “How to adapt to changing shape”. The remaining ideas addressed supplementary functions or sub-solutions to the design problem. Two examples of ideas generated are shown in figure 4.

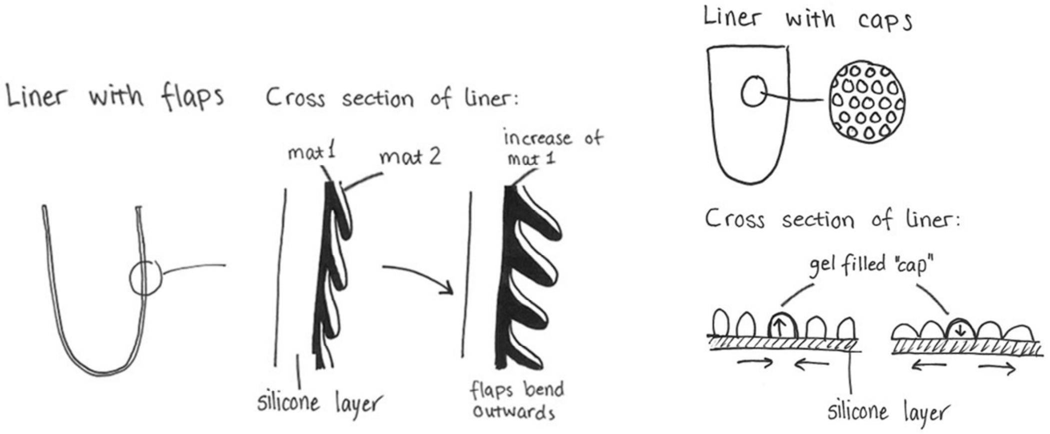


Figure 4. Example of ideas generated in the brainwriting sessions. Ideas based on the sundew card (left) and the insecta card (right)

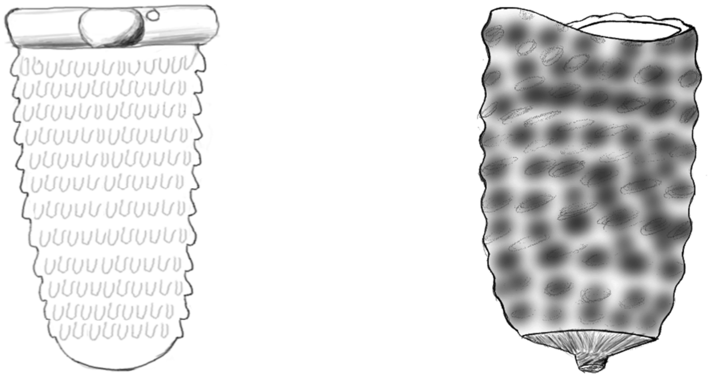


Figure 5. Examples of concepts, at an early stage, developed in the design phase. Concepts developed on the basis of the sundew (left) and insecta (right)

In order to manage the vast number of ideas and to facilitate their use in the concept development it was decided to group the concept ideas by similarities of function, with the intention to manage the ideas while sustaining the diversity of the ideas. The result was twelve groups from where twelve different holistic concepts were developed, by combining the ideas and integrating existing functionality of current products where relevant. The concepts need to fulfil the user demands beyond adapting to volume and to be, at least potentially, technically feasible within the near future. Examples of concepts are shown in figure 5. The number of concepts was then reduced through the use of screening and scoring matrixes to facilitate the decision of a final concept.

The concept developed from the sundew is a liner with a matrix of flaps that lift up to add volume when filled with fluid from a finger pump placed on top of the liner. The concept developed from the insecta principle is a liner with multiple knobs that extend and flatten when the liner stretches, and contracts and rises when the liner contracts with the volume fluctuations of the residual limb.

4. Discussion

One of the goals of our study was to investigate how easy it was for designers without prior knowledge of biology to carry out biomimetic search and design. Table 2 shows an estimation of the time spent on each phase. The duration takes into account the iterations of the phases and the learning time. The time spent was not always very productive, which is especially true in the search phase, which tended to be very time consuming in the start because the selection of keywords was not critical enough. As more knowledge was acquired on how to perform the search, the time spent became more productive. This included the use of thesauruses, terms from biological literature and the filtering functions available in the search engines. An alternative to this approach could be to use the Toronto method for identifying relevant biological search words. We have not made a comparison, but both methods seems to have a learning curve for first time users.

The search phase produced phenomena from different levels and types of biological organisms, that is cells, organs, whole organisms, animals and plants. This was in part to provide a wider solution space, but also influenced by the wish to make a better basis for discussing the potential of the method.

In the analysis phase, the work was more productive when books were used to identify the mechanism than when article databases were used. In some cases, however, articles on highly specific subjects like the viscoelastic properties of the mesoglea in sea anemones were the only source of information on the mechanism. The lack of biological knowledge certainly hampered the search for new phenomena, as the team had limited prior knowledge of biological phenomena. In terms of understanding the biological literature however, it did not seem to have a noticable negative effect. When sources were found that contained the information needed on the phenomena, the team could usually extract the information without too much trouble.

Table 2. An estimate of the total amount of time spent on the phases, including later iterations

Phase	Time spent
Problem definition	A few days
Search	Two weeks
Analysis	One week
Principle	One week
Design	One week

The overall experience of using the biomimetic method was that it provided inspiration and helped looking outside the box in search for new ideas. Having the different phenomena portrayed on the cards also helped the team to be thorough in the design phase, in terms of covering a broader solution space.

5. Conclusion

The study showed that it is possible for designers without prior knowledge of biology to perform biomimetic design. For the design of an adaptable prosthesis 14 good ideas were generated. Total time consumption was about a month, which included learning time, the examination of a variety of data sources and reflections on improving the search procedure.

For the adaptive leg prosthesis the most apparent challenge was in the search phase, where the lack of prior knowledge made it hard to get quick results. It is important to anticipate periods with no relevant search results and to plan alternative ways to find keywords. The amount of time used for generating and managing keywords is time well spent. Collaboration with biologists can be very useful for identifying new phenomena and biological keywords, but further research on how to generate, identify and manage keywords systematically and efficiently is needed. Furthermore, a study of how to apply keywords in different search engines is beneficial.

It is certainly more difficult to find interesting phenomena in biology literature, than in a biomimetic example database such as AskNature, as the sheer vastness of information available on biology can seem overwhelming. However, to limit the search to such a database would limit the potential solution space, and potentially the degree of innovation in the final product. We recommend spending time on reflecting on where to direct the search; there are numerous sources that can be used for identifying new phenomena each having their respective advantages and limitations. In that perspective the help of a librarian can be very useful, at least for the first searches.

Using biomimetics as a design method is challenging. Those that use the method for the first time can expect to use time to get familiar with it, especially the search phase where different search methods is tried. The learning curve is steep in the start, but it does not take much time to get enough grip on the method to provide results. The adaptive leg prosthesis case suggests that its successful completion provides access to a broad solution space, which so often is the key to innovation. Natures inspiration proved valuable in pointing out unconventional ways of solving the problem, thus providing alternatives to the team, which is often a key component in design methods.

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