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An Approach to Transfer Biological Solutions Based on the Interaction of Mechanisms to Technical Products

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Abstract

Biological solutions are often used for developing technically innovative products in a biomimetic process. However, biological solutions do not always make it into a successful technical product, e.g. due to a lack of knowledge on the mechanisms of action. A new approach is presented for transferring biological solutions based on complex mechanisms of action. It is based on mathematical optimization methods and applied to the lightweight design of the musculoskeletal system. Finally, first technical implementations in the field of robotics, among others, will be presented.

Keywords: biomimicry (biomimetics), biologically inspired design, topological optimisation, lightweight design

1. Introduction

Biological solutions are often used to develop innovative technical products. There are various examples of technical products and processes whose concepts are based on biological solutions. In engineering design, for example, topology optimization methods are used, which follows the growth behavior of trees and bones (Mattheck, 1997; Witzel and Preuschoft, 2005). As a further example, hydrophobic surfaces can be manufactured in surface technology, using the lotus plant as inspiration, the so-called lotus effect (VDI 6220-1:2021). Other examples include flow-optimized surfaces oriented to the skin of sharks or aerodynamic improvements oriented on the flight of birds (Domel et al., 2018; VDI 6220-1:2021). The field that deals with the transfer of biological solutions to technology is biomimetics.

The benefits of transferring biological solutions to technical products can be saving resources and reducing weight as well as saving time and money during the development process of technical products. However, these advantages are often countered by the fact that many biological solutions discovered in nature do not make it into a technical product (Jacobs et al., 2014), even though they are well studied and understood on the biological side.

There are several different terms and approaches to describe the knowledge transfer from biology to technology (Cohen and Reich, 2016; VDI 6220-1:2021). Cohen and Reich (2016) introduce the term “The Biomimicry Zone” to include all approaches of this transfer. The biologically inspired design (*BID*), as used in this paper, refers to the biomimicry zone as introduced by Cohen and Reich (2016) unless stated differently. Innovation processes can utilize BID (Chirazi et al., 2019). Additionally, BID is a means for sustainable innovation (Cohen and Reich, 2016), which is proven by many studies (Graeff et al. 2019, Ahmed-Kristensen et al., 2014; Keshwani et al. 2017). Problem-driven BID (top-down approach) begins with a problem in technology and the search for a solution in biology (VDI 6220-

1:2021). Solution-driven BID (bottom-up approach) begins with a solution in biology and the search for an application in technology (VDI 6220-1:2021).

While many methods are already used to support technical-oriented developers in the top-down approach (McInerney et al., 2018), it is often challenging to transfer a discovered biological solution to a technical product in a bottom-up approach. One reason for the difficulties in technical-oriented development is that the biological solution must be understood in such a way that its transfer to a technical product in the BID process is obvious to perform.

In this paper, a new approach is presented with which a discovered biological solution can be made technically usable from the technical side without having to investigate the mechanisms of action in the biological system in detail.

2. Solution-driven biologically inspired design

Projects usually include BID to develop new products or improve an existing product. They start in academia, in industry or in collaboration of both academia and industry (Chirazi et al., 2019). As well as design processes, BID processes are interdisciplinary (Cohen and Reich, 2016) where biologists are usually part of the team and needed (Snell-Rood, 2016). However, Lenau et al. (2010) state from findings in one study that it is possible for designers to create biomimetic solutions without prior knowledge of biology. Besides interdisciplinary work, the transfer from biology to technology and progressing to commercialization are challenging aspects of including BID in a product development process.

Well-known methods for BID focus on the cooperation of biologists and technology stakeholders and on transferring knowledge from biology to technology and implementation for specific applications (e.g.: Speck and Erb, 2010; Nachtigall, 2010; Hashemi Farzaneh et al., 2016; Cohen and Reich, 2016; Graeff et al., 2019). These methods support the initial research and development phase in the overall process of using a biological solution for products on the market. For one of these BID projects to become a product or product improvement, it requires implementation from laboratory to market relevant applications and commercialization afterwards (Chirazi et al., 2019) as illustrated in Figure 1.

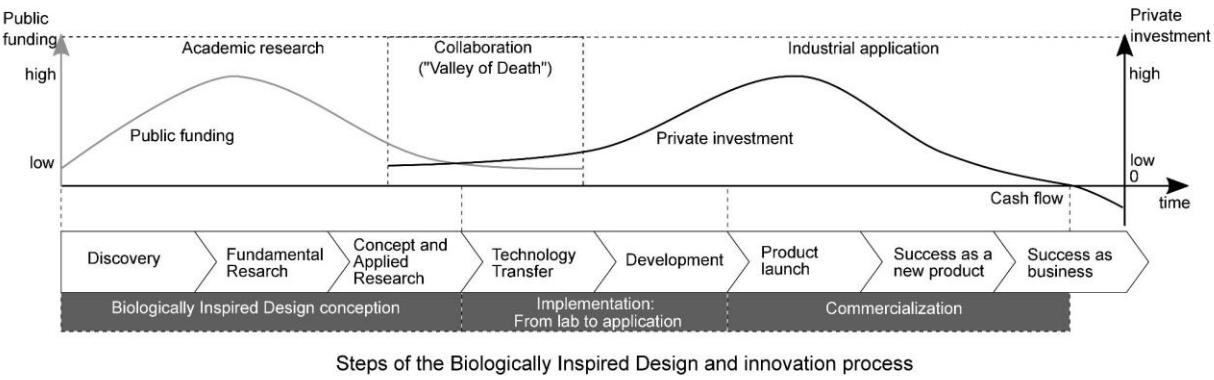

Figure 1. The biologically inspired design and innovation process. Adapted from (Chirazi et al., 2019) with permission.

Implementation and commercialization in a BID process depend on private investment (Chirazi et al., 2019). Due to the gap between academic research and industry (Bhushan, 2015) and general challenges of innovation processes (Chirazi et al., 2019), projects often fail to make it to the market. The gap between academic research and industry) is the gap between a discovery in laboratory and the willingness of the market to commercialize the discovery (Bhushan, 2015). In other words, a large gap between academic research results and industry needs at the end of public funding might prohibit private investments and the continuation of the BID process. Chirazi et al. use the term "valley of death" for this period of the overall BID and innovation process, as processes tend to end at this stage (Chirazi et al., 2019).

Solution-driven BID (bottom-up approach) starts with a solution in biology (Nachtigall, 2010; Speck and Erb, 2010; VDI 6220-1:2021; Hashemi Farzaneh et al., 2016; Cohen and Reich, 2016). One challenge of solution-driven BID is application search, i.e., identifying technical applications that benefit from the biological solution (Lenau, 2019). There are several approaches to support application search, e.g. (Lenau, 2019; Hashemi Farzaneh et al., 2016;). Lenau (2019) emphasizes the feedback of stakeholders, and involving stakeholders coincides with the recommendation of Chirazi et al. (2019).

At the end of publicly funded research in BID, it needs to provide solutions that are mature enough to attract private investment. Literature suggests a market analysis to identify the potential of the solution early in the process (Hashemi Farzaneh et al., 2016; Chirazi et al., 2019). Additionally, Chirazi et al. (2019) suggest to identify an application early in the process and to involve customers and developers from those target application areas during the publicly funded research process as well as developing a business and financial framework. In solution-driven BID, these suggestions are sometimes difficult to follow, as suitable technological applications may be unknown.

3. An approach to support the solution-driven transfer of biological solutions that are based on the interaction of mechanisms

Most of the solution-driven BID processes in the literature involve biological solutions where the biological solutions are well understood at the beginning or during the process (Lenau, 2019; Hashemi Farzaneh et al., 2016;). Biological systems usually contain several solutions for the same problem that beneficially interact with each other, where the solutions are based on the interaction of different mechanisms. Therefore, extracting single solutions and their mechanisms without considering their interactions can lead to a loss of potential for technical implementations (Nachtigall, 2010). However, these interactions are more difficult to investigate and understand. Therefore, in solution-driven BID processes, problems can arise when researchers and engineers attempt to transfer biological solutions that are based on the interaction of mechanisms.

Concerning these solutions, the transfer of a general solution that is applicable for several technical applications, as Hashemi Farzaneh et al., (2016) suggest, is difficult. One reason for this is, that technical applications have differing requirements. If a general solution utilizes the interaction of mechanisms, its effect on a technical application can be positive or negative depending on the requirements. Another reason is, that finding general solutions for several technical applications or requirements is time consuming. Additionally, the solution space resulting from general solutions can be large for solution based on the interaction of mechanisms, as several new parameters are introduced with the general solution in comparison to a prior or competitive design (Bartz et al., 2019).

So far, no approaches can be found that fit the needs for the transfer of a solution which is based on the interaction of mechanisms to technology. However, there are several useful approaches that serve specific needs during the transfer process. In this paper, a new approach is obtained by combining approaches from literature and extending them with new aspects if necessary. The new approach is derived from the author's research approach on the transfer of a biological solution which is based on the interaction of different mechanisms. This means that the chosen research method is a combination of literature-based and explorative approach. In its general representation in this section, the approach might also support other biological solutions. Additionally, the approach might help to provide academic solutions that are more likely to attract private investment by industry stakeholders. It is possible to make BID available to researchers and developers without a background in biology, as Lenau et al. (2010) show and is worked on e.g. by Fayemi et al. (2017). This paper presents the approach to use BID as a research group of engineers without a background in biology for solutions based on the interaction of mechanisms.

Development and validation of the approach bases on the transfer of system lightweight design solutions (Henning and Moeller, 2020) from the human body. The human body is an example of a system with biological solutions based on the interaction of mechanisms in terms of system lightweight design (see section 4 and Uttich et al., 2019). Figure 2 presents a general overview of the new approach.

The new approach promotes an iterative research process with several iteration steps, like Lenau (2019), which is represented by the spiral on the left part of Figure 2. One iteration sequence consists of the phases discover, abstract and apply, as presented by Nachtigall (2010). The sequence is not fixed, i.e., during a process it is possible to, e.g., work on abstract and apply in parallel, jump from apply to discover or from discover to apply. The sequential presentation in Figure 2 is used to simplify the presentation of the process and knowledge acquisition during the process. Every iteration step leads to new insights, represented by the term *gain of knowledge* used on both sides of the Figure.

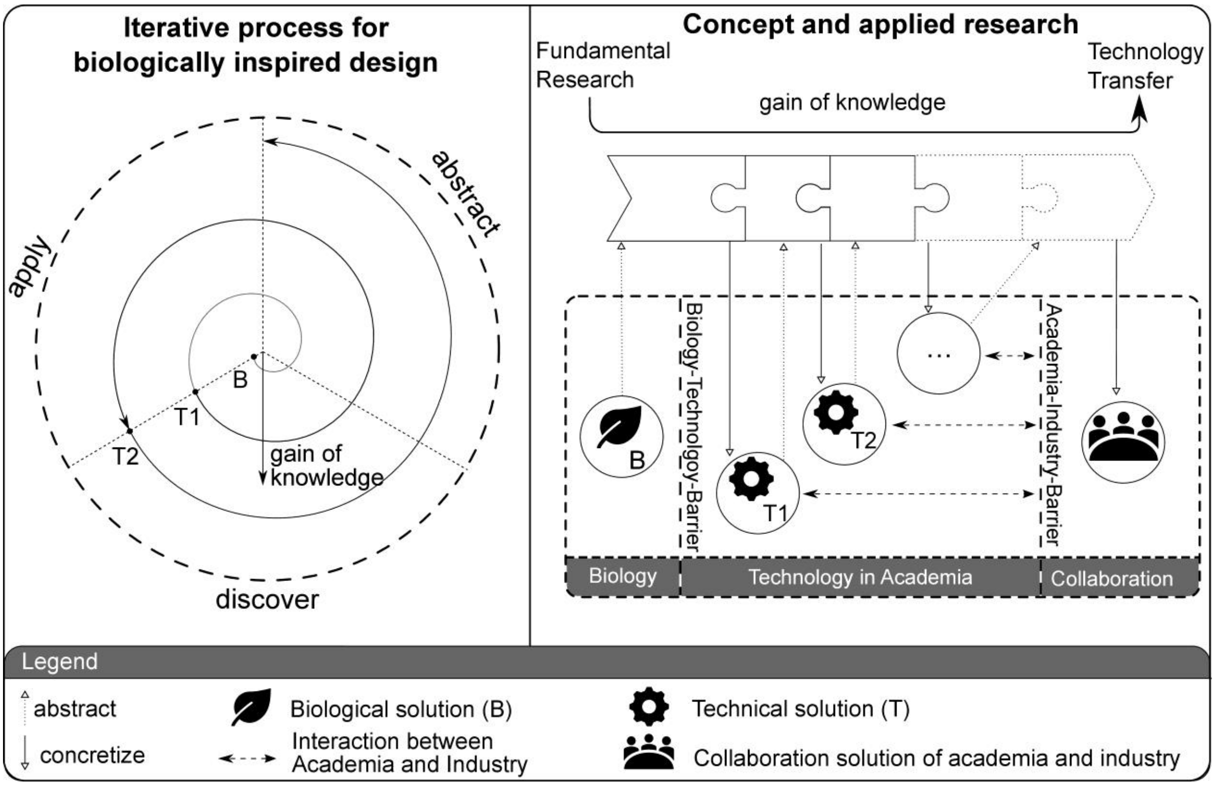

Figure 2. Visualization of the new approach for the solution-driven research and transfer of biological solutions that are based on the interaction of mechanisms.

To put the approach into context, the new approach uses the parallels of BID and innovation processes as shown by Chirazi et al. (2019), who also propose and stress the necessity to connect both processes. The new approach focusses on the concept and applied research phase of the BID innovation process as presented on the right part of Figure 2. The starting point for the process for biologically inspired design is a biological solution identified in nature (B). To investigate the biological potential for technology, an iterative process is followed, indicated by the spiral shape on the left of Figure 2, or the arrows up (abstract) and down (concretize). Every research project is represented as a puzzle piece and contributes to the overall progress as it adds knowledge on the solution. With each iteration loop the gain of knowledge grows.

Two barriers are introduced in the new approach, see Figure 2. The Biology-Technology-Barrier represents the challenges to overcome when first transferring a solution from biology to technology, while the Academia-Industry-Barrier represents the gap between academic research and industrial application. A BID process starts with information on the solution from literature or biologists. In terms of identifying the potential and possible applications of the solution, biologists, engineers or both in parallel could investigate the solution in their respective domains. In case of a team without biologists, the new approach proposes to overcome the Biology-Technology-Barrier by attempting to develop a technical solution (T1) that recreates the observed and described effects in the biological system. That means: The solution is investigated on the technical side, rather than investigating the solution in the biological system according to technological needs. Section 4 contains a detailed description and explanation of the direct transfer to technology using the example of the musculoskeletal lightweight design of the human body.

Based on the first technical solution (T1), subsequent developments (T2, T3, etc.) aim at a better understanding of the solution and its cause-effect relationship in technology. Concerning this aim, the basic hypothesis is that an increased understanding of a solution and its technical application increases the chances to attract private investment of industry partners. Discovering aspects that are relevant for industry and application in industry is a key aspect of research in subsequent developments. To support the discovery of relevant aspects and inspired by Lenau (2019), solutions (T1, T2, …) are presented to

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possible stakeholders of suitable applications and request feedback on them. Additionally, analyzing suitable applications in terms of their requirements and anticipating possible challenges of using a solution for these applications supports the discovery of relevant aspects. Working towards collaboration and commitment in academia as well as in cooperative academia-industry projects is required to overcome the valley of death. Though the new approach is intended to improve the transfer of solutions to technology, communication with possible stakeholders may also reveal reasons to stop research on the solution and shift to other important projects earlier.

To handle the large solution space of general solutions for solution synergies, an approach inspired by Hashemi Farzaneh et al. (2016) is used in the new approach. It promotes to transfer the solution to technical applications on increasing levels of detail with predefined requirements. E.g., in Figure 2, T2 respects more detailed requirements than T1. A practical example is presented in section 4. Academic research begins with low levels of detail to identify the general potential of the solution for technical applications. The level of detail is increased, if necessary, to solve critical aspects that are discovered during discussions with industry stakeholders. High levels of detail are achieved during collaboration of industry and academia.

To provide a better understanding of the new approach and to take the first steps towards verification, the application of the new approach using the example of the transfer of the human musculoskeletal lightweight design is presented in the following section.

4. Application of the new approach on the lightweight design of the musculoskeletal system

The new approach presented in the last section to open up the potential of biological systems in a solution-based BID process is to be used in particular for solutions that are based on the interaction of different mechanisms. A biological system that exhibits a high degree of different interacting mechanisms and which is often used as inspiration for technical lightweight design is the human musculoskeletal system. Some lightweight design solutions of the human musculoskeletal system are already applied in technology, e.g. the simulation of functional remodeling processes of bones in the context of topology optimization of structure components (DIN ISO 18459:2015), while other lightweight design solutions are not yet implemented.

The lightweight design of the human musculoskeletal system is based on several lightweight design solutions and mechanisms and their synergetic interaction. The synergetic interaction can also be considered as an own lightweight design solution (Bartz, 2019). So far, neither have all lightweight design solutions been technically implemented, nor has their interaction. Therefore, there is still a large lightweight design potential of solutions in the musculoskeletal system that have not yet been utilized.

In addition to a hierarchical structure of bone material, lightweight design of the musculoskeletal system is based on an interaction of these causes (e. g. Pauwels, 1965; Frost, 2003):

- A functional remodeling of bone mass adapted to the mechanical stress (structural adaption)
- and a coordinated interplay of redundant muscle forces to avoid active bending moments (redundant motion generation).

The aforementioned causes lead to a bending-minimized structure, in the shape of bone structures adapted to the load, which affects lightweight structures with barely any bending stresses. This allows the human body to save resources and increase the load-bearing capacity of the skeleton.

In the context of a classical biomimetic process (solution-based), the biomimetic process would start with the analysis and abstraction of the mentioned lightweight solutions of the biological system in detail, which includes all levels of scale. This should help to understand the mechanisms of action in the biological system and to establish clear cause-effect relationships (Nagel et al., 2011). The aim is to use this understanding to enable application to technical systems.

In the musculoskeletal system, as in many other complex systems that are based on the interaction of mechanisms, a precise assignment of cause-effect relationships effect is challenging due to a high degree of multicausality. In addition, the analysis of the interaction of the lightweight solutions of the musculoskeletal system on a biological level is more difficult because muscle forces cannot be

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measured, but only their activity can be determined. This is the point at which the new approach described in section 3 comes into play.
The hypothesis of the new approach is that for a successful use of a biological solution, the interaction of mechanisms of action and solutions do not need to be understood at a detailed level in biology. Only the causes and effects need to be known separately, but the interaction of causes that leads to an effect does not need to be precisely understood biologically. The assumption is that on the technical side the desired effect has to be tried to be reproduced and it is therefore sufficient to investigate the interaction directly on the technical side to find causes that can lead to this effect. However, biology as a science should not be completely excluded, as otherwise errors can occur (Fish and Beneski, 2014). Such an application of the new approach is explained in more detail in Figure 3.

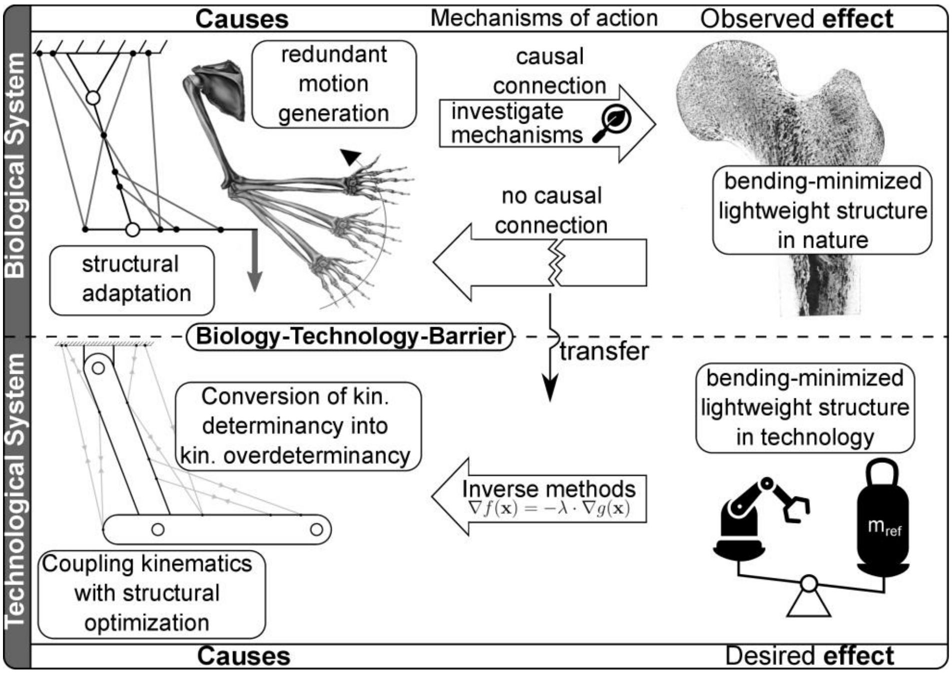

Figure 3. Applying the new approach for the technical implementation of the cause-effect relationships in musculoskeletal lightweight design.

The upper half of Figure 3 shows the cause-effect relationship in the biological system (musculoskeletal system) and the lower half shows a suggested implementation in technology, based on the application of the new approach from section 3. As shown above, the causes that lead to a bending-minimized structure as an observed effect in the musculoskeletal system are an interaction of redundant motion generation and structural adaptation. In classical determinism, only causes can be inferred from effects and not vice versa (represented by the arrow from left to right (causal connection) and the broken arrow from right to left (no causal connection) in the figure).
In a classical biomimetic process, the mechanisms of action, i.e. the interaction of the causes that lead to the effect, would now have to be investigated at the biological level (marked by the arrow with the magnifier). In the context of the new approach, this interaction is not being investigated at the biological level, but directly at the technical level. For this purpose, the biological causes and effects are taken as given and an attempt to reproduce the desired effect is made at a technical level, i.e., to generate a bending-minimized lightweight structure, with technical causes. This is shown in the lower part of figure 3, starting on the right-hand side at the desired effect. This directly transfers the biology-technology barrier shown in figure 3.
In contrast to the biological system, in which the relationship between causes and effects follows a clear direction due to determinism, mathematical optimization methods (inverse methods) can be used in technology to find causes for the interaction of several causes that lead to a desired effect (Tarantola, 2005). This is one of the main aspects of the new approach in this paper, which uses optimization methods (inverse methods) to predict effects and causes in technology without having to conduct further

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investigations at the biological level. On the one hand, this is an advantage because it allows engineers to be directly involved in a BID process, and on the other hand, it should minimize the risk of bridging the valley of death described in section 2.

In the example of the lightweight structure of the musculoskeletal system in Figure 3, technical causes are found for the desired effect (to generate a bending-minimized lightweight structure) by means of inverse dynamic methods (Shabana, 2016) based on multicriteria optimization (marked by the lower arrow in the Figure). The precondition for the application of this approach is to create similar causes in the technical system as in the biological system: The possibility of redundant motion generation as well as a coupling with structural optimization (shown in the lower left corner of Figure 3).

With the help of the new approach, it is possible to examine an optimal interaction of redundant motion generation and structural adaptation directly on a technical level, without having to analyze this complex interaction on a biological level. For a more detailed description of the chosen optimization methods and the inverse dynamic procedures, as well as a detailed description of the process, the reader is referred to the work of Bartz et al. (2019) among others, as well as to the cited works in Figure 4.

Figure 4 shows the iterations performed so far to open up the lightweight design potential of the musculoskeletal system, carried out with the new approach within the framework in this work.

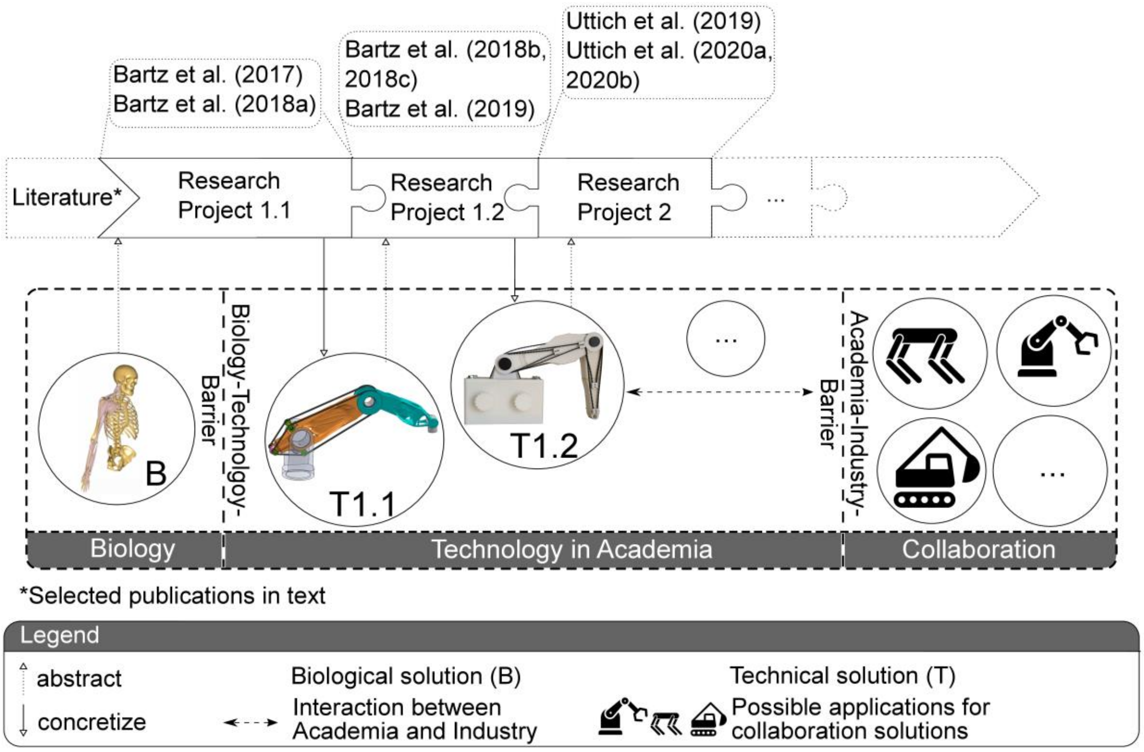

Figure 4. The research and development process to open up the musculoskeletal lightweight design for technology with the new approach.

In a first phase (Research Project 1.1), selected studies on the topic of lightweight design of the musculoskeletal system with redundant motion generation were reviewed and own investigations were performed, shown with the Literature* arrow at the left of Figure 4 (e.g. Wolff, 1892; Roux, 1895; Pauwels, 1965; Frost, 2003; Kummer, 2005; Sverdlova et al., 2010; Fratzl-Zelman et al., 2011; Schünke, 2013; Gößling et al., 2014; Lutz, 2016; Uttich et al., 2017; Uttich et al., 2018). Based on the conclusion that the lightweight design of the musculoskeletal system has not been fully investigated and understood on a biological level due to its high complexity, the knowledge gained in the first phase (Research Project 1.1) was transferred directly to a technical system, even without knowledge of the exact mechanisms of action (Bartz et al., 2017; Bartz et al., 2018a). During the process, a direct transfer of the biological causes of lightweight design, i.e. redundant motion generation with structural adaptation (as described in Figure 3), was carried out using an articulated arm robot as an example. This enabled the biology-technology barrier to be crossed directly.

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In the second phase (Research Project 1.2), further research could then be carried out directly at a technical level and requirements of technical systems could be directly considered (Bartz et al., 2018b; Bartz et al., 2018c; Bartz et al., 2019). This proves to be an advantage because the biology-technology barrier has already been crossed. In this way, it is possible to evaluate from the academic field directly with real technical applications from industry whether the solution developed in the BID process has already been developed sufficiently to overcome the academic-industry barrier or whether further investigations still need to be carried out at the academic level.

The aim of Research Project 2 is to acquire additional knowledge on specific aspects of the investigated solutions in the previous research projects. To find relevant aspects that need further investigation, suitable applications were identified, e.g., excavators, robot arms for human-machine-collaboration or mobile robotics (Uttich et al., 2019), or quadruped legs. Afterwards, interaction was initiated with possible stakeholders, e.g. in the mining industry and representatives from the robotics industry. The stakeholder feedback led to the decision to focus research on the lightweight design effect of redundant motion generation as in the human musculoskeletal system. Consecutive research is concerned with applying this solution under different boundary conditions and requirements. Currently, Research Project 2 is ongoing (Uttich et al., 2020a; Uttich et al., 2020b).

5. Conclusion and outlook

In this paper, a new approach is presented to successfully transfer biological solutions into technical applications. The aim of the new approach is to help engineers and companies, that do not have a detailed knowledge of biology, to transfer a biological solution into a technical product. The approach was developed in particular for biological solutions with a high degree of interaction between the mechanisms of action. The new approach is intended to enable a successful transfer to technology, even in the case of biological solutions where the mechanisms of actions are difficult or even impossible to investigate.

The new approach was developed using the example of the lightweight design of the musculoskeletal system. As shown in section 4, the first application of the new approach is well advanced and is the subject of current work. The finalization of this process is to be carried out using an example of, e.g., an excavator manufacturer and an articulated arm robot manufacturer. If a successful market launch is possible with these manufacturers, the new approach can be considered suitable in a first instance using the example of lightweight design of the musculoskeletal system.

Of course, applying the new approach to further biological solutions and for other technical applications is a prerequisite for a final verification as a long-distance goal. For this purpose, individual biological solutions that have already been implemented in technical products can be used in further work and transferred again, taking into account all interactions of mechanisms. On the other hand, the new approach can be directly applied to newly discovered biological solutions in order to start a biomimetic or BID process.

Finally, it can be stated that there is a need for methods and approaches, especially from a technical point of view, to provide support in the product development process of bioinspired products. For this reason, a new guideline (VDI 6220-2) was developed between 2019 and 2021 as part of a committee of the Association of German Engineers (VDI). This guideline was developed by an interdisciplinary team of biologists and engineers from research and industry. Many of the results of this paper have been incorporated into the development of the VDI guideline, especially elements of the spiral for the iterative process in biologically inspired design shown in Figure 2. The new guideline VDI 6220-2 with the working title "Bionic development methodology - Products and processes " is expected to be published in summer 2022.

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