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COMPENSATION OF BENDING MOMENTS AS A NATURE-INSPIRED DESIGN PRINCIPLE?

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1. Introduction

There are numerous advantages of transferring biological phenomena into engineering environments. Besides the optimization of existing products with regard to their weight or lifecycle robustness, nature-inspired design leads to radical new and innovative solutions in the field of technical applications [Otto and Speck 2011]. Therefore biomimetic design is a well attended subject of research in the last decades. The focus in engineering design is about understanding the structured and efficient process of the transfer between the engineering and biological domains in terms of how to overcome interdisciplinary barriers. In general there are two different approaches for biomimetic engineering. On one hand, there is the top-down process (technology pull), that begins with a formulated problem within existing products. In this case biological analogies help to overcome technical challenges not solved to date. On the other hand the bottom-up process (biological push) has its origin within basic biology-research that induces results potentially promising for the implementation in engineering domain. Milwich et al. propose a bottom-up-process-model derived from several conducted research and development projects [Milwich 2006]. Herein he integrates the biological and the engineering view within a five step approach starting with experimental analysis of biomechanics and functional morphologies of biological systems (1). Further quantitative analysis generates a deep principle understanding of shape, structure and functionality of biological archetype (2). The subsequent steps enable the passover to the field of engineering by abstracting the found principles from the concrete biological domain (3) as well as the prototypical realization (4) and evolution towards market maturity (5).

There are several successful applications and examples adopted by biomimetic design like the well-known lotus effect as well as the fin ray effect [Speck and Erb 2011]. Biological materials are multifunctional and self adaptive. Due to their hierarchical structure they have a high tolerance against damage, they continuously renew their material and they are able to regenerate from injuries. Thus biological materials have an extreme long life-cycle. Moreover, they are recyclable and no high temperatures are needed for processing. Therefore biological models were used as examples for effective materials, structures, tools, mechanisms, processes and algorithms in multiple disciplines [Bar-Cohen 2006]. Furthermore there are several methods of structural optimization to be mentioned in this context. The methods CAO (Computer Aided Optimization), SKO (Soft Kill Option) utilize the general rules of biological adaptation to optimize structures under given boundary conditions [Zhao 2010]. CAO is a FE (finite elemente)-based shape optimisation that simulate biological growth strategies. The biological counterpart for the CAO is the design of branch forks of trees in which notch stress is reduced. In contrast, the SKO optimizes the topology of components, that means that holes can be generated within a component. The biological equivalent is the sponge-like structure inside of bones.

Following the presented bottom-up-process model this paper describes a phenomenon examined by anatomists and biologists offering promising results for the transfer into the engineering domain. As illustrated in Figure 1 within the biomimetic design process the necessity to prove and evaluate emerging potential for technical applications arises. To be able to assess the suitability of the approach the biological phenomenon is abstracted and analysed by FE simulations.

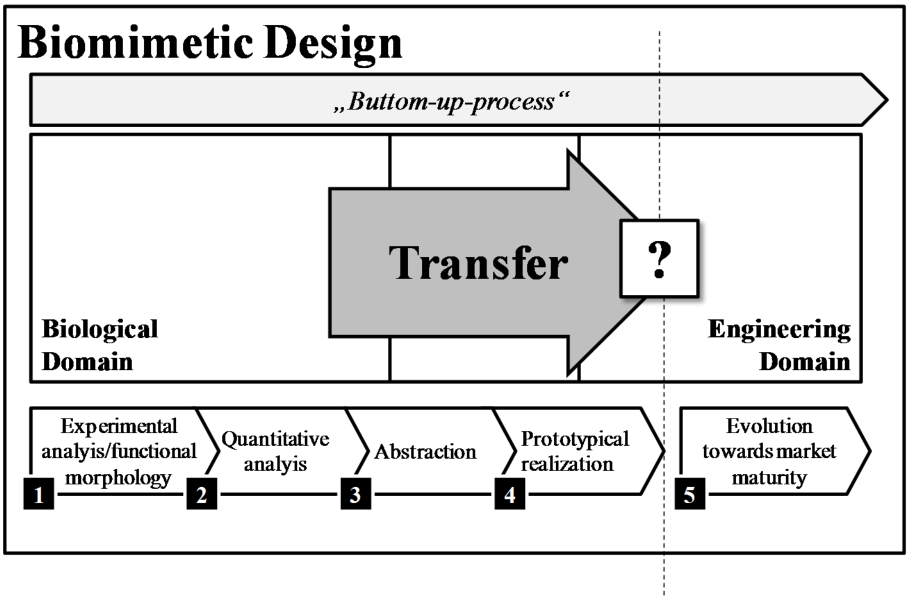

Figure 1. Bottom-up-process in biomimetic design (modified after [Speck and Erb 2011])

2. Biological optimization

Evolution is the engine of the biodiversity and therefore the creator of many remarkable solutions for living in a permanent changing environment. In the following, the focus is put on the adaptations in the musculoskeletal system of vertebrates. One of the most important tasks of the skeleton is to resist and transfer loads. Therefore it is not surprising that the muscle-skeletal system is well adapted to that purpose. In general there are two strategies that adapt the systems the their purpose: the evolution and the functional adaptation, whereas the functional adaptation is a result of evolution. Due to the mechanisms of evolution multiple different skeletons have emerged. Many of them are examined and understood, but there are still numerous exotic features in some skeletons that pose a riddle to modern scientists. Nevertheless, different design principles and objectives can be derived. A major role plays the reduction of weight. The second strategy of adaptation of organisms to their environment is to adjust features to external influences during their lifespan. This is described as functional adaptation or the phenotypic plasticity of organism. An organism is indeed determined by its genes, but genes only determine a "developmental space". Features of an animal can change, as result of interactions with their environment, for example the adaptation of bones to their loading regime [Wolff 1882], [Carter et al. 1996], [Curry 2012]. Stress values in bones can practically be considered to be constant under physiological conditions [Frost 2003]. A permanent change in the loading regime for example as a result of an injury lead to changes in bone mass and density. Due to mass and density adaptation stresses under the modified loading regime fall back to the previous stress values. In case of increasing bone mass this phenomenon is known as hypertrophy. Whereas the effect of decreasing bone mass is described as atrophy. Thus weight and morphology of bony structures are coupled to their use.

Stresses in bones can be substantially diminished as a consequence of compensated bending moments [Pauwels 1965]. Therefore bending moments on bony structures are reduced due to the appropriate muscle arrangement and activation patterns. Bones act as rods and muscles and ligaments represent tension resisting elements. A result of locomotion are changing forces and moments in the skeleton. Thus muscles are used to generate moments as well as compensating counteracting moments. That means that active forces are used to ensure minimal bone stress and minimal bone weight [Minhu

1992]. This principle is largely unnoticed in biology research, so it's potential importance for technical applications is yet unknown.

To illustrate the biological compensation of bending, the example of the loading regime of the upper part of the femur is shown in Figure 1. Bending moments are induced into the shaft of the femur as result of the joint reaction force in the hip joint (Figure 2A). To prevent the defection of the femur, forces are generated by the abductor muscles and the iliotibial tract. Therefore high stress in the peripheral parts of the shaft are diminished and the structure is loaded in compression (Figure 2B) ([Taylor 1996], [Sverdlova and Witzel 2010]).

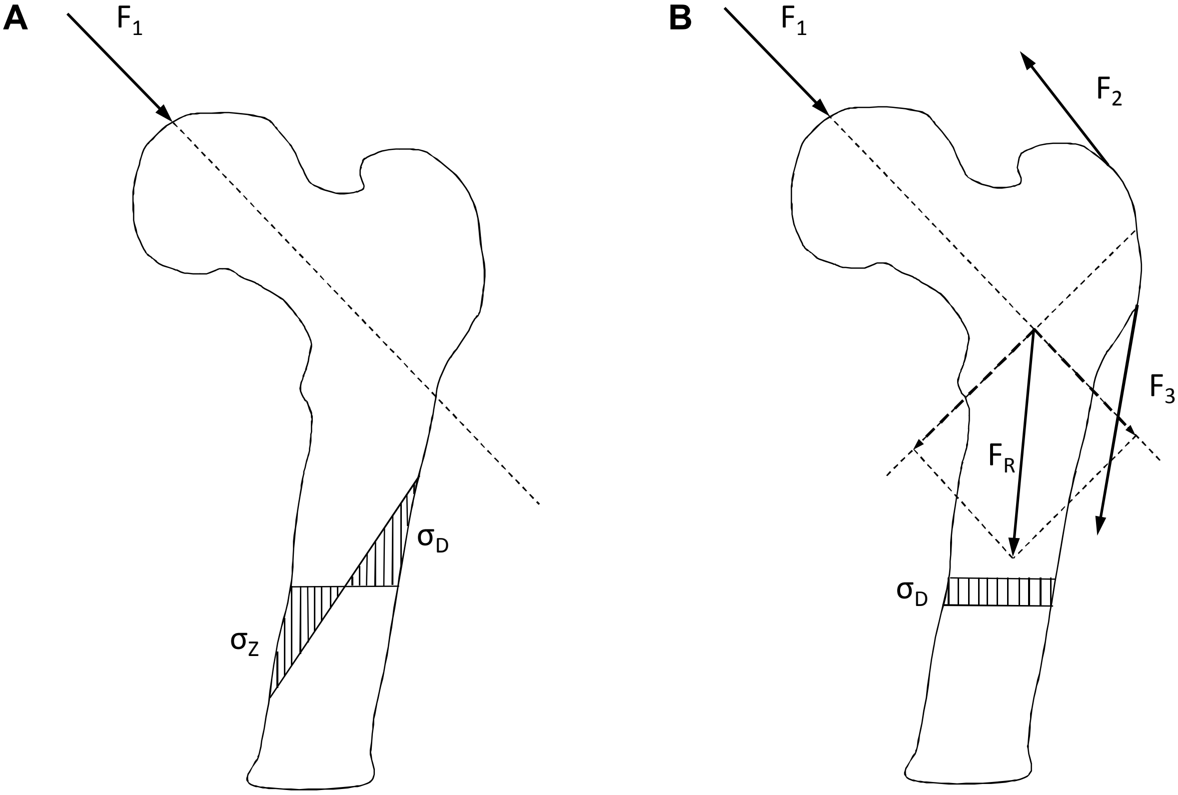

Figure 2. Loading of the proximal femur. F_1 hip joint force, F_2 abductor muscles, F_3 iliotibial tract produce F_R resultant force (modified after [Taylor 1996])

Biological systems are highly complex, so research is a major challenge and the results are not always clear. The biomechanic research and the evaluation of design principles in the musculoskeletal system is interfered by unknown key measures. Muscular forces are not measurable in vivo. Therefore, the simulation technology becomes more and more popular in biological research. The implementation of the biological rules of adaptation into FE-Software leads to different applications. Beside the technical use, it was applied to evaluate biological design principles. The FESS (Finite Element Structure Synthesis) is used to synthesis biological structures, for example skulls of various animals [Witzel and Preuschoft 2005]. The method allowed for the first time to prove the absence of bending in bony structures under physiological loading. As a result of the virtual generated bony structure the forces that determine shapes could be identified. Figure 3 shows the modelling of the skull of a Diplodocus applying the FESS method. The method starts with the analysis of the biological model (Figure 3A) and the creation of a FE design space (Figure 3B). After the application of force vectors (Figure 3C), which are determined by analysing the biological model and a following optimization of force equilibrium for minimizing bending moments a topology and shape optimizations are conducted (Figure 3D). Last step of the FESS is the verification of the applied boundary conditions by comparing the biological model with the generated virtual model (Figure 3E). Hereby FESS proves a further biological optimization strategy: the active compensation of bending moments as a result of muscular activity patterns. The design and organization of the muscular skeletal system certainly play a major role in this system. There is a separation of partial functions in the skeletons of vertebrates. Bones are loaded in compression and ligaments and muscles provide tensile restraint elements [Sverdlova and Witzel 2011]. This separation into partial functions in combination with the anisotropic biological materials are the basis for the little-noticed strategy of light weight constructions in the musculoskeletal system.

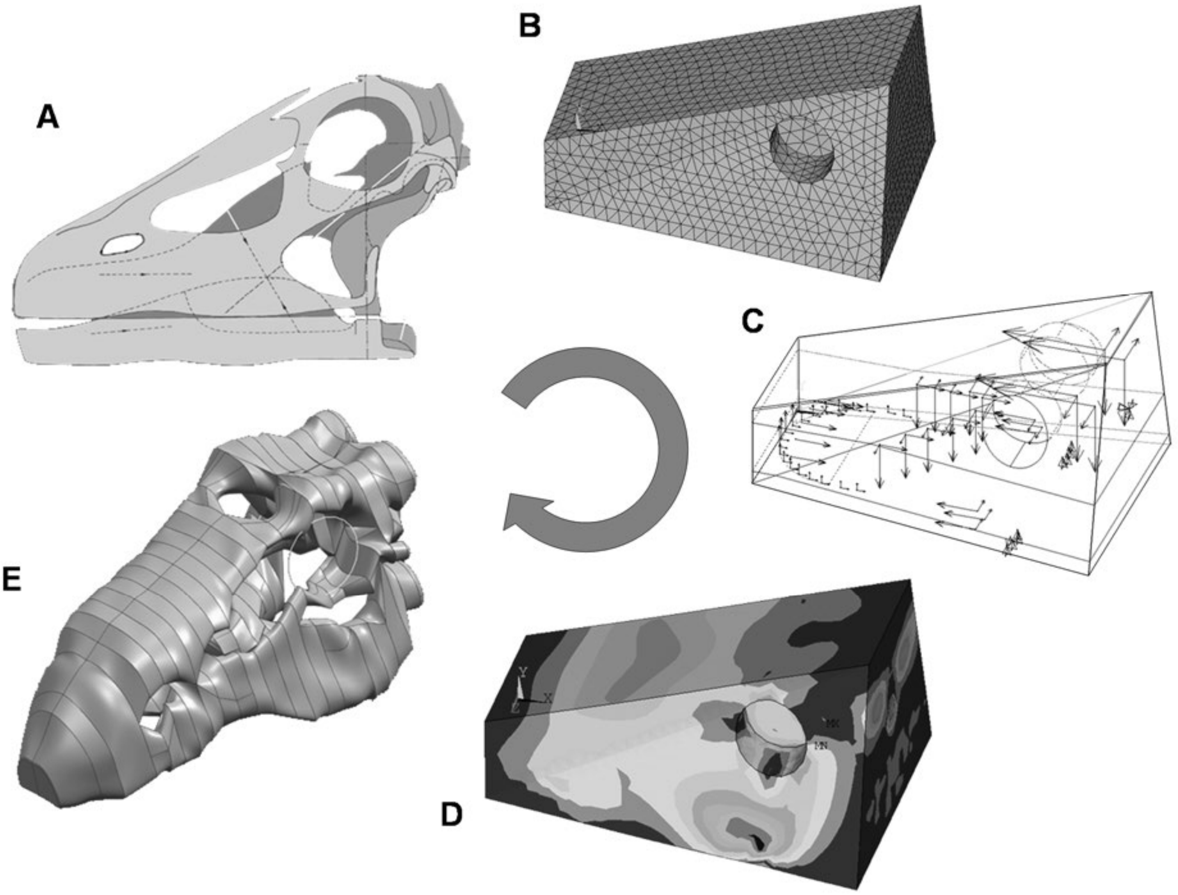

Figure 3. Method of the FESS; A analysis of the biological model; B design space; C boundary conditions of the calculation; D compressive stresses; E virtual generated model (modified after [Witzel and Preuschoft 2005])

3. A new approach for nature-inspired innovations?

Vertebrates have developed various mechanisms to save weight, resourcess and energy. Particularly in the musculoskeletal system principles exist that might be interesting for technical applications. To save weight, the musculoskeletal system adapts to mechanical stimuli. In case of hard physical training, muscles and bones increase their mass. Furthermore this effect can adjust forms up to pathological deformations in the skeleton. Decreasing physiological loading e.g. as result of injuries and/or immobilization lead to a decrease of muscle and bone mass [Rittweger 2005], [Amin 2010].

Therefore the skeleton represents the current lifestyle of an individual. Another principle of saving weight in the skeleton lies in the structure of bones. The inner structures are constructed as frameworks of thin bony rods. This architecture was a guidance for several biomimetic constructions. Furthermore a topology optimization was implemented (SKO) to generate biomimetic frameworks for product components. However, there is a further principle within the musculoskeletal system. The loading regime of each bone is optimized to reduce bending moments. In consequence stress in bones is minimized. Due to the relation between bone mass and bone loading, elements can be built of less material due to reduced loading [Minhu 1992]. In other words the load-carrying capacity increases when the resultant force within the bone is directed in line with the long axis of the bone [Kim 2007].

There is no similar approach in product development. It is well known that bending should be avoided in supporting structures to reduce material. In cases were bending cannot be avoided, there are several opportunities to design rigid structures [Pahl and Beitz 2005]. One option for biomimetic designing is the application of SKO. This paper reveals the biological principle of counteracting moments to show basic options for innovation in product development.

3.1 Abstraction and analyzation by FE simulations

To demonstrate the research objective, two FE-simulations were conducted. The basic model is a simple upright 2D beam with dimensions of 80mm x 20mm. The model resembles a design space in which elements adapt their material properties in an iterative process. The model is constrained against vertical displacements at the lower edge. A further constraint in the lower left corner fixes the model in the horizontal axis. A load vector in the upper right corner forces the model diagonal downwards to the left (Figure 4A). The first structural topology optimization is realized using the Ansys Topology Optimization Tool. The program calculates the energy density in the model. Based on the results the Young's modulus distribution in the model changes. While elements with higher energy density get a high modulus of elasticity of 210000MPa (bright areas in Fig 4B), elements with lower energy density values assigning a modulus of 1MPa (grey areas in Figure 4B). Due to the modified material distribution there is a change in the structural behavior of the model. Elements having a Young's modulus of 1 MPa have no supporting function. The procedure of calculation and changing material distribution leads to an optimized design, whereas the optimum is defined by maximum structural efficiency by using minimal resources. In order to demonstrate the effect of the novel biomimetic light weight principle a second structural topology optimization was conducted. In addition to the first model a second force was applied in the line of action of the first force vector near the upper left corner (Fig 5A). The second force is directed diagonally downwards to the right to generate a counteracting moment.

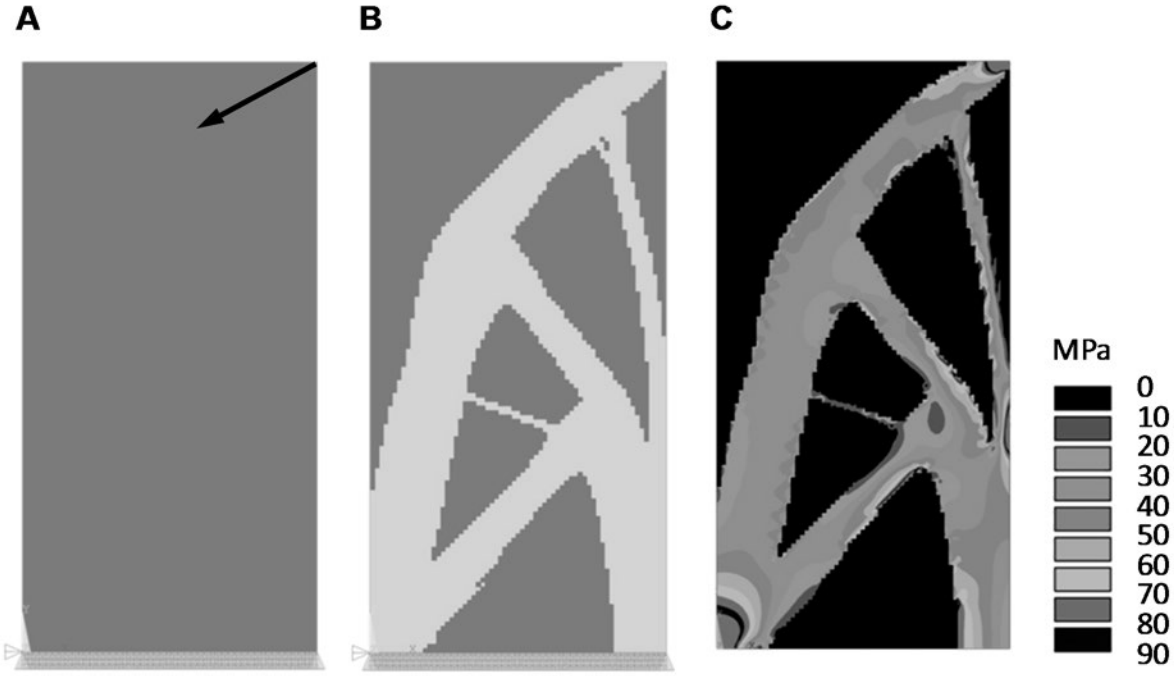

Figure 4. Topology optimization. A design space, B optimized structure, C von Mises stress

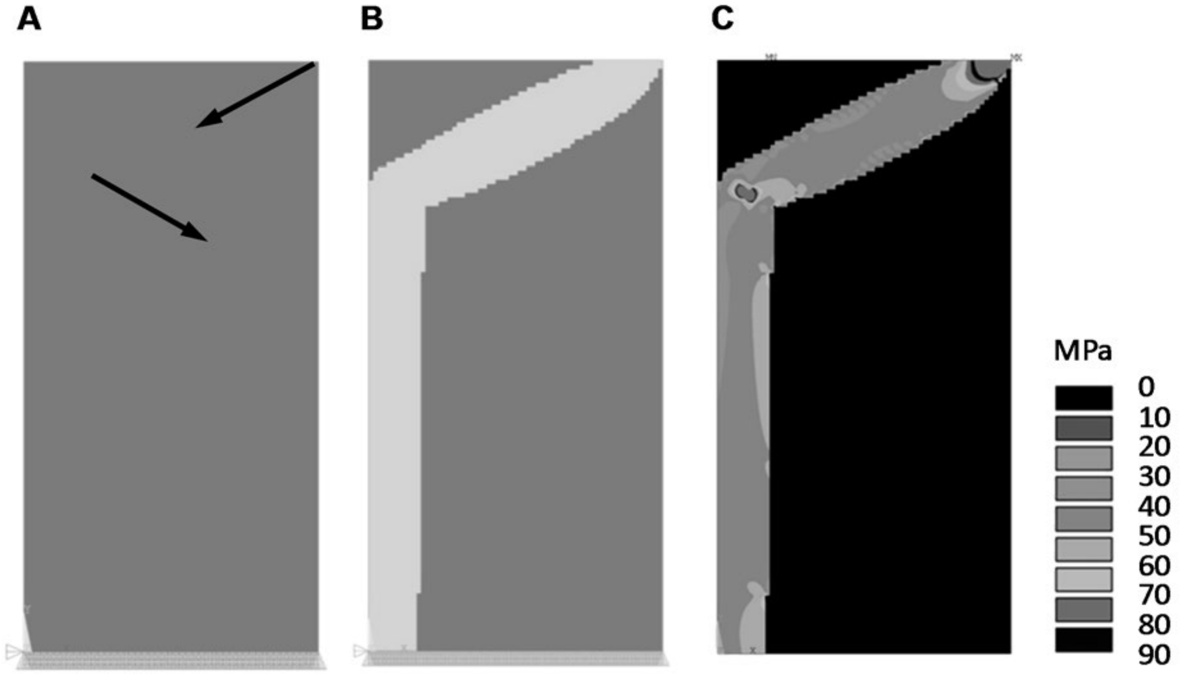

Figure 5. Topology optimization under the absence of bending. A design space, B optimized structure, C von Mises stress

3.2 Results

The result of the first topology optimization in Figure 4B shows that the area of the design space was reduced about 50 %. The synthesized structure resembles a framework whereas von Mises Stress in Figure 4C show an almost homogeneous distribution, with exception of the areas in the lower corners, where stresses rise above factor two. The second simulation, in which bending moments were counteracted by an additional force, the generated component in Figure 5B looks like a bended rod. The design space is reduced about 75%. Von Mises stress distribution in Figure 5C is nearly homogeneous and in comparison with the previous model the mean stress magnitudes are reduced about 30 %. The FE-simulations show that the modification of the boundary conditions have a major influence on the design of the resultant component.

3.3 Discussion

The presented FE-simulations demonstrate that the topology optimization generates considerably deviant designs when bending moments are minimized. Furthermore this approach changes the type of loading, the result in Figure 5C is loaded with compression only. Therefore the stress in the component is lower compared to the results in Figure 4C. This resembles the biological principle of separating partial functions in the musculoskeletal system. Bending stresses are divided into compression and tension, whereas bony structures are loaded in compression and muscles and ligaments are forced in tension. To guide force to minimize stress of load-bearing components is a general principle in the design process of technical components [Pahl and Beitz 2005]. Nevertheless the biological model ensures a minimized loading of bony structures by producing additional forces and counteracting moments.

This coherence is highly complex and the examination within the musculoskeletal system is very challenging. Muscle forces compensate dynamic loading and altering mechanical demands that occur as consequence of movement of the body. Therefore a precise interaction of several muscles and short reaction times are necessary to achieve the effect as demonstrated.

4. Summary and future work

According to the biomimetic bottom up process in Figure 1 this paper introduces and abstracts a biological phenomenon, whereby the proof of the described effect is based on simulations and literature. Nevertheless the presented 2D FE simulations demonstrate that an active minimization of bending moments can have beneficial effects on the design of loadbearing structures.

The consequent separation of compression and tension lead to diminished masses, stresses and joint forces within bony structures. Therefore it is promising to adopt the described principle for technical applications. To evaluate the potential for improvements, it will be necessary to find technical applications. The questions how additional forces can be applied to compensate for bending moments and how they can be controlled in technical components are challenging requests. Maybe further investigations of the musculoskeletal system can provide indications for solutions. The musculoskeletal system is a highly integrated system, in which all components have several functions. The example of the loading regime in Figure 2 shows that muscles for the abduction of the leg are used for the compensation of bending moments during standing or walking. The considerations of more than an individual component for an optimization could also be a useful approach to find solutions.

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