COMBINING ADDITIVE MANUFACTURING AND CARBON FIBER PATCHED COMPOSITES FOR INDIVIDUALIZED AND SUSTAINABLE BIOMEDICAL APPLICATIONS

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Abstract
Combining additive manufacturing (AM) with carbon fiber reinforced polymer (CFRP) patched composites unlocks potentials in the design of individualized lightweight structures. This work investigates two arising design opportunities for biomedical applications. First is the geometrical individualization of a composite structure using AM cores. These cores consist of a thin shape-giving shell which is filled with removable filling material and thus able to withstand autoclave process conditions. Second is the load-bearing structure individualization employing the fiber patch placement method. Application of patches on a base layup is an efficient way of tailoring structures to individual load cases. Optimized patch reinforcements are found from numerical optimization. The design opportunities are demonstrated using the example of an exoskeleton hip structure. The approach of combining AM with fiber patched laminates is evaluated by assessing the mass and the number of parts for the demonstrator compared to a state-of-the-art aluminum hip component. Mass savings of 57 %, part count reduction by 77 % and a considerable decrease of fiber cutoff waste is achieved. This indicates that the approach is competitive for the manufacturing of complex, individualized lightweight structures.

1. Introduction

Powered lower limb exoskeletons are advancing as a promising technology to achieve independent walking for mobility-impaired individuals, such as those suffering from spinal cord injury. The available lower limb exoskeletons consist of a rigid frame that can support the weight of the patient, bilateral hip and knee joint actuators for locomotion and an ankle joint [1]. These devices either serve as a rehabilitation tool or as a personal mobility solution for impaired individuals [2]. However, present exoskeletons have low real-life performance. Primarily due to their limited walking speed, but also because of limitations in terms of traversing uneven terrain, and their common inability to climb stairs. A way to achieve greater capability is to improve the mechanical structure, where mass, cost and individualization are key factors.

Individualized components have high performance, however require a flexible, cost-efficient design and manufacturing route that can be applied to individual human bodies. Achieving a lightweight design reduces the required drive power and prevents excessive deformations, asymmetries and increased friction resistance during the gait. Functional integration offers the opportunity to reduce the part count and interfaces, thus increasing lightweight potential [3].

The combination of AM and CFRP is a promising option to resolve the conflicting requirements in the design of biomedical devices and paths the way to a substantial improvement of the performance and

cost-efficiency of individualized lightweight structures. Additive manufacturing and carbon fiber reinforced polymers are complementary technologies. AM allows for the direct production of complex load introduction elements as well as for the tools required to shape the CFRP, thus enabling geometrical complexity and individualizability. The principle of "complexity for free" devoted to AM also enables to integrate numerous functions into a single part without increasing manufacturing effort, while CFRPs excel at their outstanding stiffness- and strength-to-mass ratios. Due to their anisotropy and layer-wise build, carbon fiber reinforced composites are in addition well suited for tailoring load-bearing structures towards individual mechanical requirements. Load-tailoring can be very efficiently achieved using the fiber patch placement approach [4], which forms or reinforces a structure by applying small discrete fiber patches.
This paper aims to demonstrate the potential of combining additive manufacturing with carbon fiber patched laminates using the example of an individualized exoskeleton hip structure. The results are compared to a reference aluminum hip component which is introduced in Chap. 2. The overall design process for the individualized component is illustrated in Fig. 1. Starting point is an initial parametric CAD model of the structure. Secondly, the patient's geometry is captured using 3D scanning. The next step employs the patient's data to adapt a parametric CAD model to the individual body shape. Details are given in Chap. 3 and 4. The geometry model is then combined with the results of a multibody simulation for patient-specific load estimation in order to generate a finite element model of the structure. In the next step, numerical optimization is applied to determine optimized fiber reinforcements applied in addition to a fixed base laminate. The fiber reinforcement architecture from the optimization is then transformed to a patched laminate layup. Details are given in Chap. 5. The results of the design process for an AM-CFRP exoskeleton hip are discussed in Chap. 6. Chap. 7 concludes the paper.

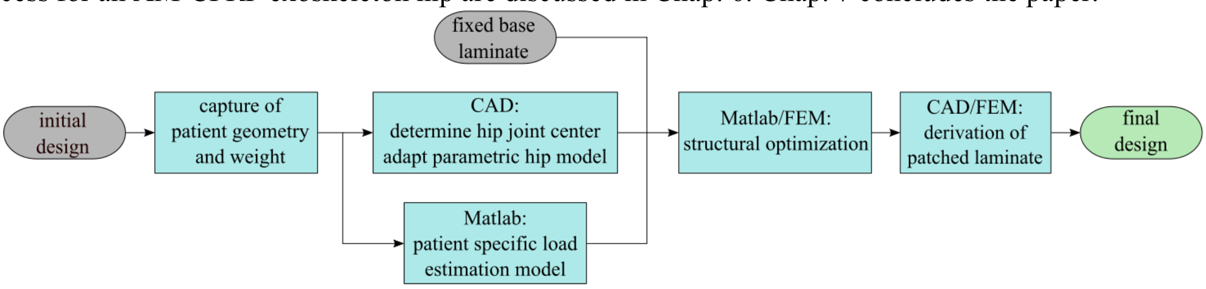

Figure 1: Design process for individualized AM-CFRP component

2. Reference exoskeleton structure

As reference exoskeleton serves the VariLeg 2. This exoskeleton is the result of a student focus project from different departments of ETH Zurich [2].

2.1. VariLeg 2 hip component

The exoskeleton hip structure has several functions: it connects the two motorized legs of the exoskeleton, provides the torso attachment for the patient, as well as serving as a mount for the electronic box. Furthermore, the hip structure is adjustable to fit different patients. The result is pictured in Fig. 2 as an aluminum tubular construction with milled clamps and corner elements.

2.2. Load assessment

In order to load-tailor the hip component, a load assessment model, providing individualized load cases, is required. Therefore, a multibody model of the exoskeleton and patient system is constructed. The model is parameterized, using the patients' masses and sizes to adapt the model. The walking motion of the exoskeleton is simulated and the load-time series for the hip component is computed, from which the critical loads are extracted. The multibody model is constructed using two subsystems to represent the system, an exoskeleton and a patient, as seen in Fig. 3. The patient is connected to the exoskeleton with three bushings, one on the hip and two on each thigh. To ambulate the exoskeleton, knee and hip angle time series are fed into the model which correspond to the motion trajectory used by VariLeg 2 [2]. The gait loads are computed and the total loading on the hip joints is extracted.

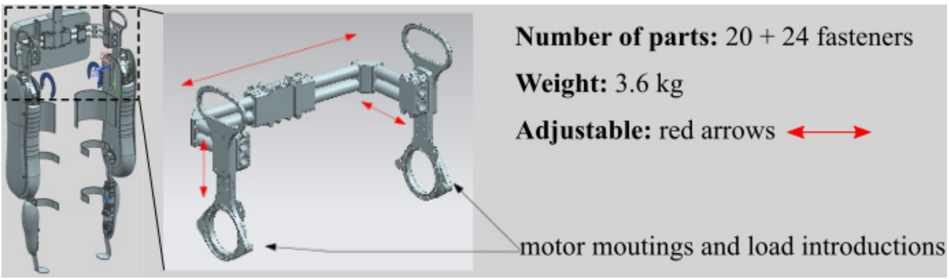

Figure 2: VariLeg 2 exoskeleton (left), reference hip component (right)

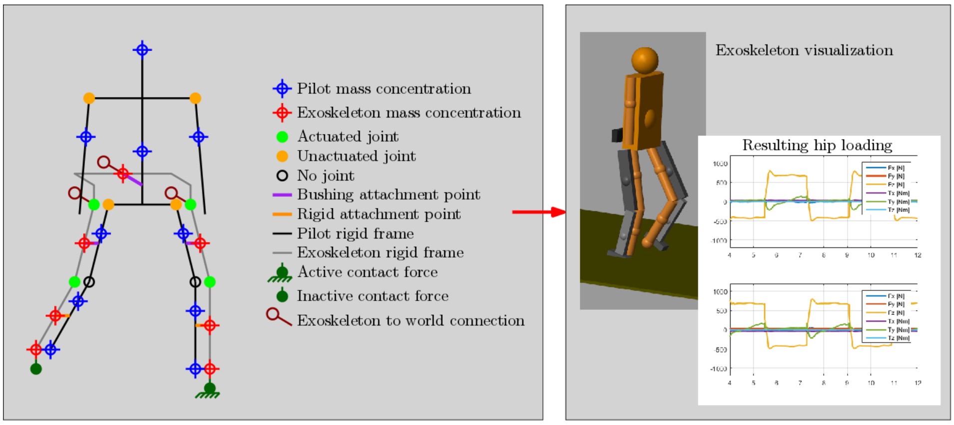

Figure 3: Multibody system consisting of exoskeleton and pilot (left), gait visualization and resulting load output on hip component (right)

Tuning and validation of the multibody model uses experimental data from in-situ load measurements with paraplegic patients. The load assessment used strain gauges applied to the loupe shaped motor mounts and a dedicated FE model to retrieve the moments acting on the hip. The computed hip loads from the final multibody model lie within a 5 % range to the experimental values.

3. Design-assisted manufacturing approach

The novel exoskeleton hip is fabricated using additive manufacturing and autoclave carbon fiber prepregs. The complexity-for-free principle of AM and the excellent mass-specific properties of CFRP allow for the creation of a highly integrated lightweight structure. The hip is mainly subjected to bending and torsional loads. It is thus designed as a closed shell structure as seen in Fig. 4, which allows for the part to sustain the bending loads predominately through membrane stresses in the thin CFRP skin. The following two sections give details on the AM core and manufacturing route.

3.1. AM core design

The principle idea for the manufacturing of an individualized CFRP hip component relies on a core as seen in Fig. 4, that is additively manufactured for each specific pilot. In general, such a core may remain inside the final part or may be removed after manufacturing. This work uses an AM core that consists of a thin hull, which serve as a shape-giving male tooling element for the prepreg layup. Selective Laser Sintering (SLS) is employed to fabricate the hull from PA12 with a thickness of 1.6 mm. As the AM core is very thin, it would not be able to withstand autoclave process conditions. Hence, prior to processing, the core is filled with common salt (sodium chloride NaCl) through an opening on its top. Common salt is a suitable choice, because it has a high melting point and compressive modulus. Furthermore, its granular structure provides mechanical interlocking and thus shape stability. After filling, the opening is closed with a threaded plug. The core can be re-opened after curing to remove the salt. In order to simplify manufacturing, the core is also able to hold and position the required metal load introduction elements and inserts through integrated form fits until the co-cured interface with the CFRP is established. To remove accessible sections of the core after processing, the core features a set of breaking lines with a reduced thickness of 0.8 mm. That way, the core can be broken into small fragments and removed after the curing process. Support leashes are printed on the inside of the AM core surface. These support leashes can be accessed via the opening on the top side of the hip. They allow generating the mechanical force required to rupture the core along the breaking lines. After the core is divided into small pieces, it can be removed through the top hole. Thus, the lightweight potential of the structure is increased. The final hip and its components are shown in Fig. 5.

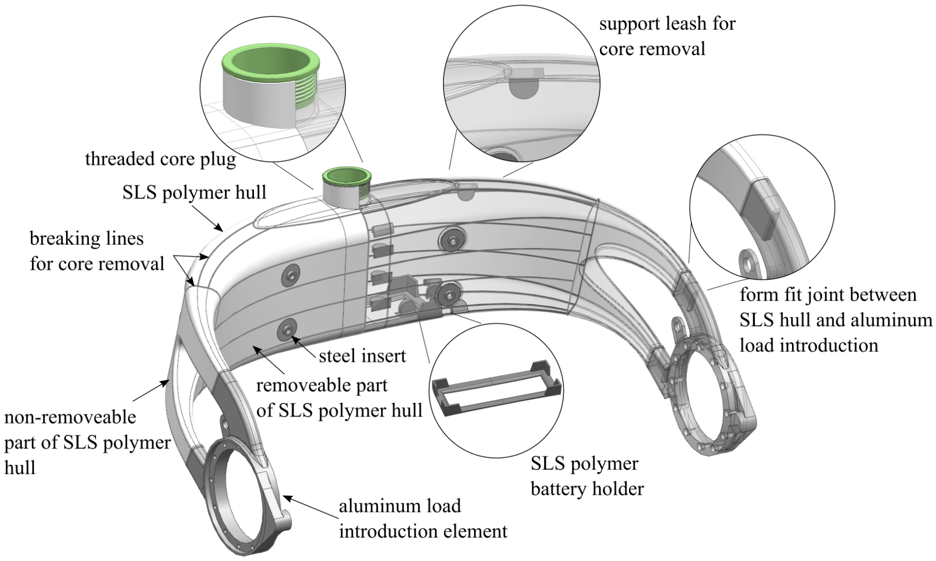

Figure 4: Concept of core design. The right half side of the hip is shown transparent.

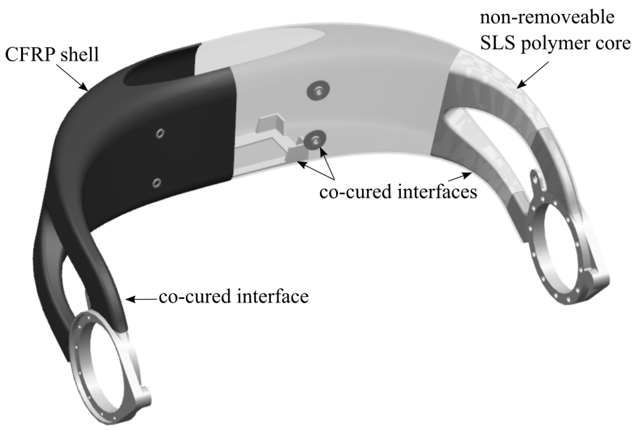

Figure 5: Final exoskeleton hip component. The SLS core is partially removed in order to

3.2 Process route: AM co-cured with autoclave prepregs

The employed manufacturing technique is a co-curing autoclave process. Load carrying elements are inserted into the shape-giving hull, which also serves as an inner layup tool. This combination allows the manufacturing of a complex, integral part. The general process steps are shown in Fig. 6 and described: (a) Preparation: In order to resist autoclave conditions, the hull is filled with salt. For partial core removal, release agent is selectively applied. The hull and the load introduction elements are connected through form-fits. (b) Layup: The prepreg is draped on the core. Fiber patches are placed between continuous base laminate layers for local reinforcement purposes. (c) Bagging and Curing: The part is covered in outer tooling molds made from silicone. Vacuum bagging is conducted. The composite is co-cured and consolidated at 80°C and 3 bars pressure. Excessive resin in the prepreg is used for creation of the interfaces between CFRP and AM and metal parts. (d) Demolding and Postprocessing: The bagging and outer tools are removed. The AM hull is opened and the salt filling is removed. The hull is divided and partially removed from the CFRP shell.

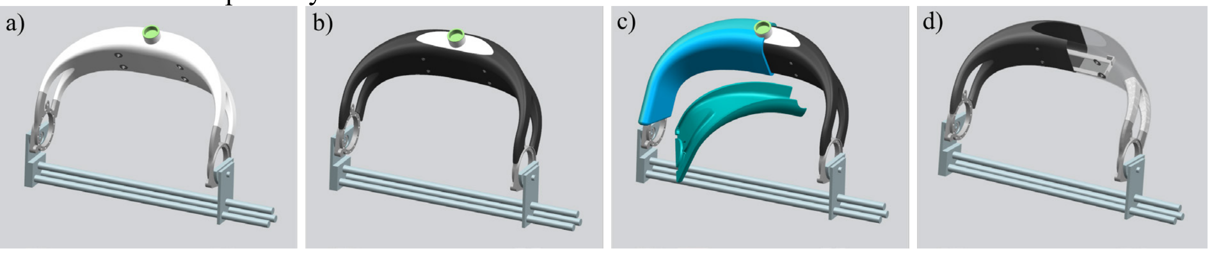

Figure 6: Process steps: a) assembly of AM core and load introductions; salt filling, b) draping of fibers, c) bagging into silicone molds and vacuum bag; autoclave curing, d) partial removal of core

4. Geometrical individualization

Geometrical individualization of a lightweight CFRP structure is a valuable design opportunity arising from the combination with additive manufacturing. The two required steps for individualization, namely geometry acquisition and automated model adaptation, are outlined in the following.

4.1. Capture of patient's geometry

First step for the individualization of the structure is carried out by capturing the patient's geometry. Devices such as a Microsoft Kinect Sensor are employed to capture a body surface with a precision in the 1 mm range, which is sufficient for individualizing the exoskeleton hip. As illustrated in Fig. 7a), paraplegic patients are scanned hanging in an upright position using a standing vest. Prior to scanning, marker points are attached to the patient on three anatomical landmarks: the left and right anterior superior iliac spine on the sides of the human hip as well as the posterior superior iliac spine on the back side of the human hip. Fig. 7b) shows two body scans with attached marker points.

4.2. Adaption of CAD model

A parametric CAD model is set up to reduce the effort for deriving an individual hip component as a recurring design task. For a given pilot the 3D-scanned body geometry is imported and orientated to a global coordinate frame. As Fig. 7c) shows, the scanned marker points at the hip spines are used to estimate the hip joint centers through a predictive method [5]. Their connection defines the axis of rotation of the hip drive motors and thus of the position of the hip component. The contour of the exoskeleton hip follows the outer body surface with a specified offset. To automatically adapt the structure to a certain 3D scan, support points are utilized. These points are created by intersecting the scanned body with predefined set of lines originating from the center of the exoskeleton hip. The support points that result from a specific scan are used to update the CAD design in a parametric manner including high-level features such as splines and loft functions defining the exoskeleton hip geometry.

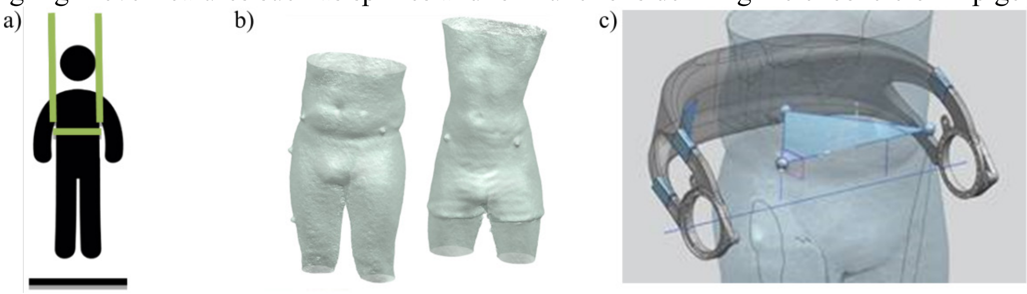

Figure 7: a) Setup for patient scanning, b) 3D-scanned body surfaces with marker points, c) estimation of hip joint center using marker points

5. Load-bearing structure individualization

Individualization of the load-carrying structure is the second promising design opportunity. It arises from the utilization of the so-called fiber patch placement method. The approach for obtaining optimal fiber patch reinforcements is detailed in the following.

5.1. Model setup and material

An FE stress analysis of the individualized component is carried out to ensure structural integrity during operation. The geometry for the FE model is supplied by the parametric CAD model, whereas the loads are obtained from the multibody simulation. The load-bearing hip shell consists of a CFRP twill weave for the base laminate. Local reinforcements are placed using unidirectional (UD) fiber patches. The material properties are given Tab. 1. To assess failure of the laminate, a maximum strain criterion is used.

Table 1: Material properties and allowables

Material	E_1 (GPa)	E_2 (GPa)	G_{12} (GPa)	G_{23} (GPa)	ν_{12} (-)	t_{layer} (mm)	ρ (kg/m^3)	$\varepsilon_{11,max}$ (%)	$\varepsilon_{22,max}$ (%)	$\varepsilon_{12,max}$ (%)
CFRP weave	60.0	60.0	5.0	5.0	0.1	0.190	1600	0.4	0.4	0.6
CFRP UD	107.4	6.8	3.3	3.3	0.36	0.252	1600	0.4	0.4	0.6

5.2. Determination of base laminate

The load-bearing shell consists of a quasi-isotropic (QI) base laminate from CFRP weave, which is then reinforced by locally applied UD carbon fiber patches. The task of the continuous fiber reinforced base laminate is to ensure continuity of the layup throughout the structure. Additionally, it guarantees basic load-bearing capabilities of the structure regardless the load direction and thus serves as a safety function against unpredictable loadings.

The base laminate is designed to withstand the loads created by a 5th percentile female patient [6]. This user has a mass of 47.2 kg and a height of 1.52 m, resulting in a torsional and bending moment on the hip of M_x = 136 Nm and M_z = 91 Nm, respectively. In order to sustain this load case, a constant thickness QI layup $(45_f/0_f)_5$ with ten layers is required. Therewith, a maximum failure index of 0.951 is obtained. The total base laminate thickness is 1.9 mm.

5.3. Numerical optimization

The targeted patient for this study is a 85 kg heavy male with a required exoskeleton hip width of 498 mm. The moments on the hip are found to M_x = 245 Nm and M_z = 150 Nm. Compared to the 5th percentile female case, the loads are increased by 65 to 80 %. Hence, the base laminate will not be able to sustain the significantly higher load of the targeted patient. Therefore, an efficient optimization algorithm for stiffness and strength of composite structures is applied in order to determine fiber reinforcements [7]. The initial optimization model consists of the base laminate. Additional eight layers of UD CFRP with the fiber orientations (0/22.5/-22.5/45/-45/67.5/67.5/90) are specified with initial zero thicknesses. The optimization routine selectively switches the initial zero thicknesses to multitudes of the single ply thickness value using sensitivity information. The optimization result indicates that optimal reinforcements are placed with seven layers in 0° and one layer in 90° direction. As Fig. 8a) shows, major reinforcement areas are covering almost the complete top surface. At the bottom hip surface mainly the rearwards region is reinforced.

5.4. Derivation and analysis of patched laminate layup

In order to derive a patched laminate layup, the optimization solution is post-processed. This includes enforcing left/right symmetry of the reinforcements, smoothing of their boundaries and the definition of the reinforcement plies staggering. Finally, draping simulation is applied in order to obtain flat patterns of the reinforcements. The resulting flat patterns are used to define the patch reinforcement solu-

tion. The fiber patches have rectangular shape. The width of the patches is fixed to 20 mm, however their lengths can be varied in discrete steps to 20, 40 and 60 mm.
For the derivation, the fiber patches are placed in a way that matches the intended reinforcement contours and fiber angles as closely as possible as can be seen in Fig. 8b). In order to patch-reinforce the individualized hip, 196 patches of length 60 mm, 36 patches of 40 mm length and 20 patches of 20 mm length are required. Alternatively, the hip could be reinforced by 32 continuous plies. Every layer of UD patch reinforcement is placed between the continuous base laminate layers. Thus, load transfer from two adjacent upper and lower continuous plies into the patched layers is guaranteed.
Patched laminates suffer a loss of stiffness compared to continuous laminates. Horn et al. [4] report a loss of Young's modulus of 8.88 % for a patched laminate with a comparable single ply thickness and a suitable overlapping pattern. Hence, the modulus of the patched laminate layers as given in Tab. 1 is reduced to 97.9 GPa in the FE model. Therewith, a maximum failure index of 0.998 is found for the final patch-reinforced hip model.

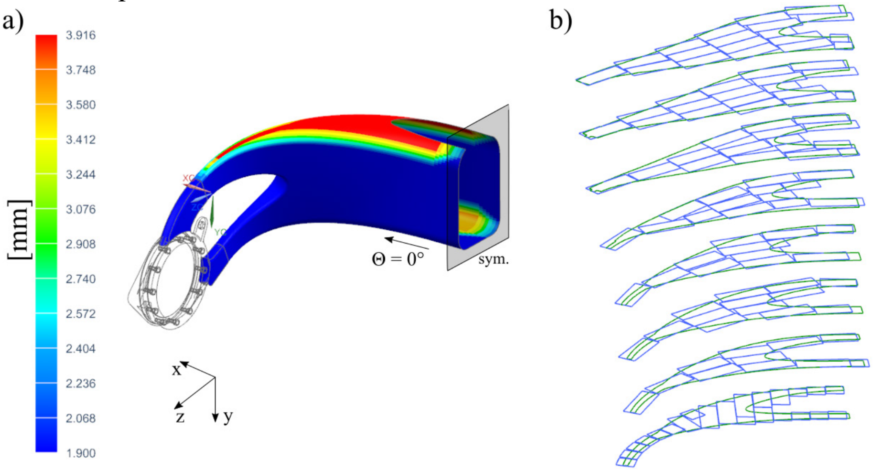

Figure 8: a) Total laminate thickness, b) eight layers of upper hip patch reinforcements: optimal reinforcement contours are colored in green, physical rectangular fiber patched are shown in blue color.

6. Results

Fig. 9a) compares the mass of the aluminum reference with the AM-CFRP hip. The major mass drivers in the aluminum version are the tubes and milled connector elements, whereas the fasteners only add a small portion to the total mass. In the novel hip design, the significant mass reduction is mainly due to the load-tailored CFRP shell and a redesign of the load introduction elements. A total mass saving of 57 % or 2048 g is obtained. Fig. 9b) compares the number of parts of the differentially designed aluminum hip to the novel concept. The highly integral AM-CFRP design comprises of 10 parts, yielding a reduction of 77 %.
The switch of the patient from a 5th percentile female to a 85 kg heavy male results in an increased torsional moment by +80.1 % and an increased bending moment by +64.8 %. Optimization results indicate that this load increase can be compensated by an additional +20.5 % laminate mass as Fig. 10a) shows. Fig. 10b) shows the result of a nesting optimization, yielding a cutoff waste of 42.5 % for a continuous fiber reinforcement while for the patched solution only 7.9 % are cutoff waste material.

7. Conclusions

In this paper a digital process chain for the efficient design of individualized and highly optimized lightweight structures is developed. As example serves an exoskeleton hip made from additive manufacturing and carbon fibers which is compared to an aluminum reference solution. Individualization is carried out on the one hand in terms of geometry using a 3D scanning approach. On the other hand, individualization is subject to the load-bearing CFRP shell. It is shown that reinforcing a thin base laminate with unidirectional fiber patches is a highly efficient way of load-tailoring. Moreover, sustainability is increased due to a significant cutoff waste reduction. These findings demonstrate the potentials that arise from combining additive manufacturing with patched laminates and suggest that the herein proposed approach might be competitive for the manufacturing of individualized light-weight structures.

The need for more fundamental research can be identified in two areas. First is the design of the removable AM cores. The utilized approach using breaking lines is suitable in well accessible regions, but lacks robustness if access space is limited. Second, further research is required for the analysis of the patched laminates. A submodeling routine must be developed which allows for a detailed analysis of the effects of discontinuities in patched laminates.

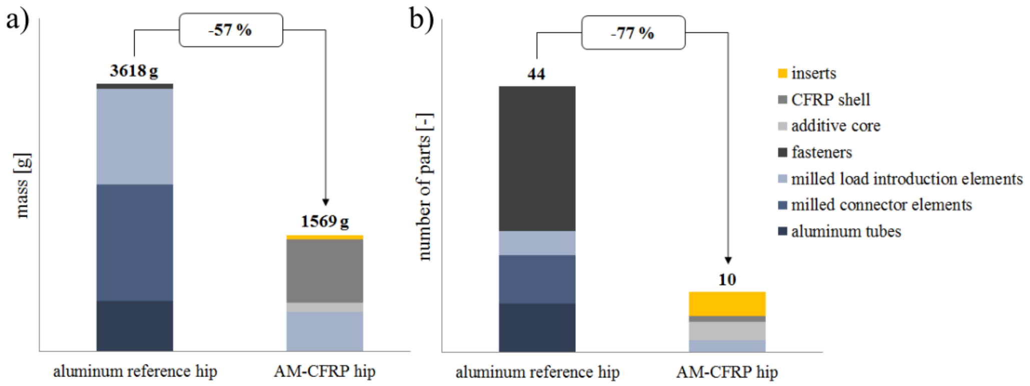

Figure 9: a) Comparison of mass and b) number of parts for reference and AM-CFRP hip

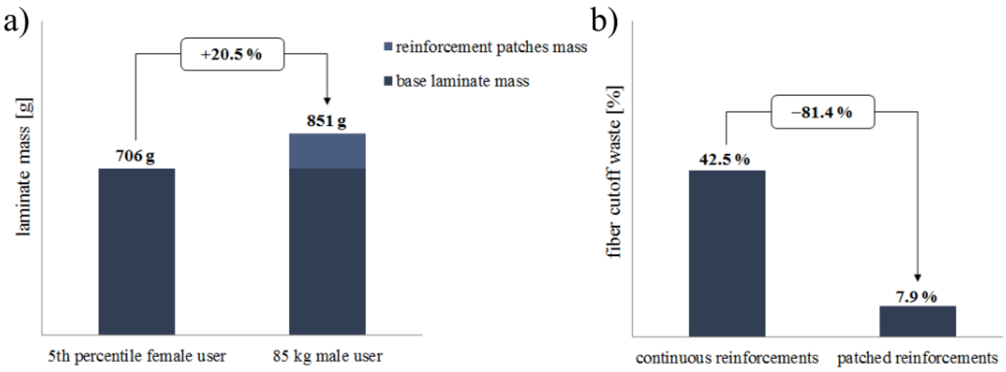

Figure 10: a) Comparison of laminate mass increase for 5th percentile female and 85 kg male user and b) comparison of cutoff waste

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