2025 IEEE/SICE International Symposium on System Integration (SII)
January 21-24, 2025, Munich, Germany

Preliminary assessment of an open-source leg prosthesis based upon the OSL 2.0

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Abstract— **In this paper, we introduce an academic-level, highly modular leg prosthesis based upon the Open Source Leg (OSL) 2.0, targeting improved manufacturability, cost-effectiveness, and functionality in prosthetic technology. The OSL's structure has been amended by implementing a modular design and more standard components to support flexible configurations for both left and right leg amputations. With respect to the OSL 2.0, our results demonstrate a 40-70% reduction in manufacturing time and costs while maintaining high standards of safety and functionality as confirmed by Finite Element Analysis (FEA), which showed an enhanced safety factor of 1.107 under static loads. The new prosthetic leg achieves a significant cost reduction and facilitates greater accessibility and adaptability, promoting further adoption.**

I. INTRODUCTION

Research in lower limb prosthetics critically depends, among other things, on the availability of dexterous, modular, accessible prosthetic hardware. One such successful attempt is the Open Source Leg (OSL), now at version 2.0, see [1]–[5]), an open-source two-motor modular prosthesis which can be used for both trans-humeral and trans-tibial amputations, as well as as a test-bench on non-amputated subjects. While the OSL 2.0 is a remarkable resource for the whole Community, its adoption can be hindered by relatively high procurement costs and complex manufacturing processes, particularly impacting smaller institutions. The commercially available version of the OSL, although simplified, does not adequately reflect the open-source designs [6]–[8], presenting significant barriers in cost and practical usability [9].

In this paper, we present a series of modifications to the OSL 2.0 aimed at reducing complexity and cost, thus enhancing its accessibility and functional adaptability. We describe the redesign of the device to align production methods with open-source principles while adhering to requirements for manufacturability, material selection, and design optimization (see Table I) [10].

II. METHODOLOGY

We redesigned the OSL 2.0 to improve manufacturability, reduce costs, and maintain essential functionalities. These requirements, outlined in Table I, form the basis for the planned modifications.

To achieve a *more modular* and versatile design,the*core functionality* must be maintained while introducing elements that allow for flexible configurations. This will ensure that the OSL can be adjusted as both a left and right leg and support dual transtibial applications, increasing adaptability and usability in various prosthetic setups (Tab I, Functionality). *Simplifying manufacturing* and *optimizing fabrication* applies Design for Manufacturing (DFM) principles. This includes reducing geometric complexity and standardizing components to decrease machining time and streamline assembly procedures [11], [12]. Additionally, all components are converted to the *metric system*, aligning it with global manufacturing standards, easing the procurement process,

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*This work was partially supported by the Mechanics Workshop of the Faculty of Engineering at the Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen, Germany.

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and reducing the costs associated with sourcing components. A quantitative cost analysis is not feasible because in-house fabrication differs significantly. Therefore, cost will be assessed qualitatively (Tab I, Manufacturing, Compliance & Standards). The *material selection* focuses on incorporating readily available materials that balance durability and cost-effectiveness [13]. The goal is to expand the variety and availability of materials used in the OSL, ensuring that production remains affordable without compromising the structural integrity of the device (Tab I, Material & Cost). *Cost reduction* is prioritized by minimizing labor costs, optimizing machining time through simplified geometry using standardized components, and easing serviceability. (Tab I, Cost). Finally, to guarantee *durability and safety*, Finite Element Analysis (FEA) is used to verify that the redesigned components meet the necessary safety factors, particularly under static loading conditions. Dynamic jogging requires a minimum loading capacity of $4500\,N$ [14]. Comprehensive testing for a commercial product would require static and cyclic loading in accordance with DIN EN ISO 10328:2016-12 [15]. Since it is beyond the scope of this redesign and our software capabilities to model specific dynamic used cases, the FEA will focus on static loading with $12000\,N$. However, a safety factor of 2.5, calculated as the yield strength ratio to the von Mises equivalent stress, should be achieved for the static load case to guarantee the structural integrity [16] (Tab I, Durability &Safety).

TABLE I

GROUPED REQUIREMENTS FOR THE REDESIGN OF OSL 2.0. THE RIGHT COLUMNS INDICATE IF THE REQUIREMENTS WERE MET WITH OUR VERSION

Category	Requirements	Met
Functionality	• Maintain core functionality	✓
	• Modular design	✓
	• Reduced build height	✓
	• Improve range of motion	✓
	• Enable additional sensors	✓
Manu-facturing	• Simplified geometry	✓
	• Optimized fabrication	✓
Material	• Increased material variety	✓
	• Material availability	✓
Cost	• Reduce material cost	✗
	• Minimize labor cost	✓
	• Optimize machining time	✓
	• Simplify serviceability	✓
Compliance & Standards	• Usage of the metric system	✓
	• Standardize components	✓
Durability & Safety	• Ensure structural integrity	✓
	• Appropriate safety factors	✓

Fig. 1. OSL 2.0 Knee Joint [6]. 1: Knee Connector with Pyramid Adapter, 2: Serial Elastic Actuator Output Pulley, 3: Belt Tensioner, 4: Housing, 5: Loadcell & Pyramid Adapter

III. DETAILED MODIFICATIONS

A. OSL 2.0 Key Components

The original design of the OSL 2.0 knee joint, depicted in Figure 1, exhibits several manufacturing challenges. The output connector paired with the Pyramid Adapter (Fig.1, Label 1) has intricate geometry, necessitating multiple tool changes and repositioning during machining. This increases labor costs and machining time. The use of aluminum for the adapter remains questionable. The Serial Elastic Actuator (SEA) component (Fig.1, Label 2) represents the most costly element to manufacture, primarily due to its reliance on Wire-Electrical Discharge Machining (Wire-EDM). This assembly demands high precision to properly align disks and idler pins, contributing to complexity and cost. The belt tensioner (Fig.1, Label 3) uses complex shapes to reduce material. While aesthetically streamlined, the housing structure (Fig.1, Label 4) incorporates numerous pockets, pillars, and curved surfaces, significantly increasing the machining time and labor required. Lastly, the custom Pyramid Attachment (Fig.1, Label 5) is challenging to fabricate since it must accommodate the load cell's bore pattern.

TABLE II
SPECIFICATIONS COMPARISON TO THE OSL 2.0 [8]

Property	**Specification OSL 2.0**	**Specification Redesign**
Force Sensors	1x 6-axis load cell (below the knee)	2x 6-axis load cell (below knee, below ankle)
Additional Sensors	1x hall effect encoder (14bit) at each joint	circular mounting array at output shaft
ROM Ankle	60°(fixed)	240°(adjustable)
ROM Knee	120°(fixed)	240°(adjustable)
Joint Torque Rated / Peak	19.92 Nm / 87.67 Nm	to be tested
Peak Joint Speed	7.29 (rad/s) (at 33.3 VDC)	to be tested
Device Weight	Approximately 5.7 kg	without electronics 4.1 kg
Device Dimensions	Width: 12 cm, Height: 58.6 cm	Width: 11 cm, Height: 46.2 cm
Usage Limits	100 kg (at 2.5 mph)	>100 kg (FEA-Simulation)
Voltage	33.3 VDC	10 - 48 VDC

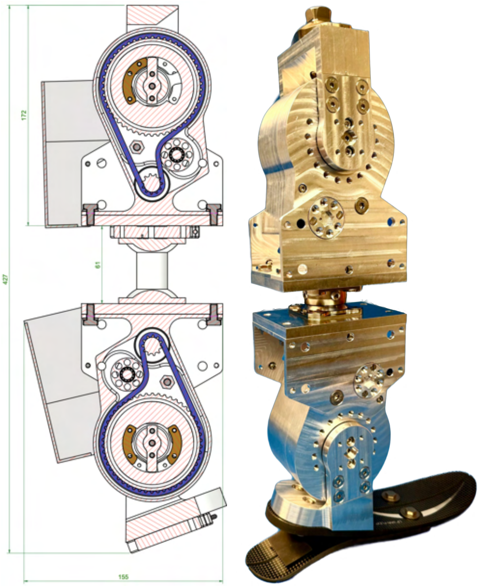

Fig. 2. Left: Technical drawing of the redesigned model. Right: Built version. Hardware designs are available as open source at [10] and [6].

B. *Functional Enhancements*

We incorporated several modifications over the original OSL 2.0. These changes are listed in Table II. The range of motion (ROM) for the ankle and knee joint was increased from a fixed 60° and 120° to an adjustable 240° using brass inserts, as shown in Fig. 4. Both joints now use to the same standardized housing design. This enables multiple configurations: left, right, or dual transtibial leg mode. Height reduction was achieved by moving the electronics to the outside. A second 6-axis load cell was integrated below the ankle for sensing capabilities, above and below the actuation unit, alongside a circular sensor mounting array around the output gear (see Fig. 2).

C. *Design Optimization and Manufacturability*

Our design was optimized to enhance manufacturability by reducing complexity and machining time. Key components shown in Figure 1 were re-engineered to streamline production processes. As illustrated by the Knee-Connector-Shaft in Figure 3, changes included the preference for flat surfaces and toolpath-friendly roundings (Fig 3, Label 1) and the substitution of small radii with rectangular corners (Fig 3, Label 3) to decrease tooling requirements. Additionally, complex features such as slanted walls and rounded edges were eliminated (Fig 3, Label 2) to simplify CNC machining. These design principles were also applied to other components, including the housing, to optimize manufacturing efficiency by adding features (e.g., pillars, end-stops) during assembly (see Fig. 4). The SEA, was replaced with a rigid module. This change reduced tolerance requirements and simplified both the production and assembly processes. Following extensive discussions with experts and machine operators, the design was streamlined to address impractical and complex features in the original concept. For instance, replacing Wire-EDM-specific cutouts (e.g., for the belt tensioner) with simpler CNC-machinable shapes drastically reduced production complexity and time. Similarly, converting all components from imperial to metric measurements simplified procurement by aligning with global and EU standards was common sense. The reliance on specialized tools was reduced by

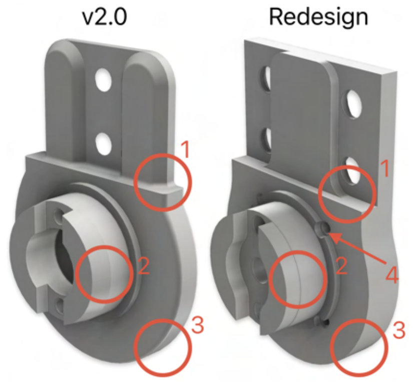

Fig. 3. Exemplary comparison of OSL 2.0 and the redesign: (1) Flat surface finishes are favored. Rounding remains where it aligns with the tool path. (2) Slanted and sloped areas are avoided (3) Use of fillets and chamfers is minimized. (4) Mechanical adjustments adding to the functionality (e.g., aiding ball bearing removal ducts)

Fig. 4. Open view of the OSL 2.0 (left) and redesigned housings (right). The gearbox is removed to highlight the brass end plates and the streamlined housing geometry.

eliminating small radii and slanted walls, enabling faster machining processes. Based on feedback from manufacturing specialists, these modifications reduced the estimated machining time by approximately up to 70% depending on the part.

D. Cost Efficiency and Material Optimization

The complex geometries of the Pyramid-Adapter components were replaced with off-the-shelf titanium adapters, eliminating the need for custom parts and providing greater strength than aluminum. Reducing complexity and the required tolerances also led to further cost reductions. Specifically avoiding the intricate assembly labor of the SEA in favor of a simplified all-in-one solution. The redesign also facilitated using less

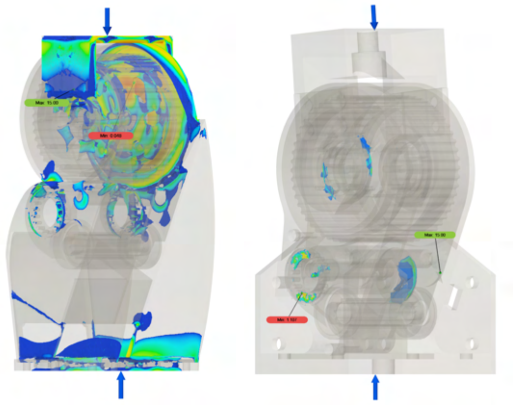

Fig. 5. Knee housing comparison between the OSL 2.0 (left) and the redesigned model (right). A static force of 6000 N is applied on both sides, indicated by blue arrows. Safety factors are color-coded as blue (≈ 8), green (≈ 4), and yellow (≈ 3). (Left) Finite Element Analysis (FEA) reveals a safety factor of 0.048 and several orange-red areas where structural integrity is compromised. (Right) Red markings indicate regions with a minimum safety factor of 1.107.

expensive materials, such as 5000 series aluminum, by increasing wall thickness where necessary to ensure adequate strength and durability. Further cost savings were realized by replacing the four ultra-thin ball bearings in the output pulley ($482 each, see [6] BOM) with standard DIN 625 SKF 61805 bearings (€12 each). To improve maintenance, leveling was achieved using cost-effective idler plates, and service bores were added to simplify the removal of bearings (see Fig. 3, Label 4).

E. Durability and Safety Enhancements

FEA with a static load of 6000 N was applied to the redesign from both sides, to ensure durability and safety. Fusion360 was used with fixed constraints and area-distributed forces to simulate loading. The analysis showed a safety factor of at least 1.107 in critical areas, compared to a safety factor of 0.048 in the OSL 2.0 design, which indicated potential failure points (Fig. 5). For a load of 1000 N, corresponding to the maximum load of the OSL 2.0 [8], the FEA analysis presented a safety factor of 6.643 for our version, demonstrating that the redesign did not compromise the structural integrity of the device despite cost-saving measures.

IV. DISCUSSION

A. Implications of the Prosthetic Redesign

While amending and redesigning the OSL 2.0, we primarily targeted manufacturability and accessibility, addressing critical barriers in adopting and adapting advanced prosthetic technologies. The project significantly reduced the acquisition costs and technical barriers associated with custom prosthetic fabrication by simplifying the geometric designs and integrating commercially available components. This shift not only makes the technology more accessible but also enables more rapid iteration and customization in clinical and research settings. However, while using standardized metric components facilitated global manufacturing compatibility and reduced costs, it introduced constraints on the prostheses' customization capabilities. The modular design attempts to balance these limitations by allowing some adaptability. This presents a trade-off between standardization for cost-efficiency and the need for personalized prosthetics, which are critical for user satisfaction and functional performance. However, a comprehensive mechanical evaluation of the joint's peak performance has not yet been conducted. Given that the gearbox ratio and motor specifications (AK80-9) remain unchanged, we anticipate no significant deviation in performance in future studies.

B. Modular Design for a reference platform

Our redesign's modular approach tackles the significant cost and practicality issue of needing separate left and right leg versions. Previously, motor orientation and fixed housing ROM prevented swapping the OSL 2.0 between configurations. By unifying the housing design, we simplify construction and eliminate component distinctions since both joints use the same gear ratio. Including adjustable end-stops with brass inserts allows for customizable ROM, catering to various needs and facilitating easier repairs. Adopting the Euro-4 Pyramid connector enhances versatility by supporting specialized adapters as needed. For research institutions without force sensing requirements, the modular design accommodates spacers with bore patterns, replacing expensive load cells without compromising prosthetic functionality. Additionally, load cells can be freely positioned to measure compliance impacts at the anchor point or near the ground interface, providing valuable biomechanical insights.

C. Analyzing Finite Element Analysis Limitations

Our prosthetic leg's Finite Element Analysis (FEA) was deliberately simplified to enhance mesh quality, focusing on the housing's load-bearing capacity. However, this simplification introduces limitations that may fail to accurately represent the prosthetic's structural resilience under real-world conditions. Additionally, the projected total load of 12000 N, intended to simulate running, likely exceeds typical walking demands. This led to over-engineered design requirements; while the OSL 2.0 marginally meets the 100 kg limit, the new design significantly surpasses it, raising questions about the necessity for such robust specifications.

D. Reevaluating Material Choices and Structural Over-Engineering

The redesign continued using Al 7075 over the alternative Al 5055. This decision was influenced by Al 7075's proven performance. Although Al 5055 could offer a more cost-effective solution with adequate structural properties for typical prosthetic use, thicker wall structures were kept. While more durable and easier to manufacture, this choice inadvertently increased the prosthetic's weight, potentially affecting user comfort. The trade-off between over-engineering for safety, optimizing for practical use and cost-effectiveness remains controversial.

E. Addressing the Controversial Downgrading of Output Pulley Bearings

The decision to downgrade the output pulley bearings to standard bearings is a topic of considerable debate. This change was made understanding that the standard bearings would undergo faster wear due to the repetitive, sinusoidal movements typical in prosthetic use. However, this was mitigated by design features that allow easier bearing replacement, framing regular maintenance as an integral part of ensuring ongoing functionality. The cost savings from standard bearings justify their more frequent replacement, aligning with a maintenance strategy prioritizing overall cost-efficiency and prosthetic longevity.

F. Integration Challenges and Material Considerations

The approach to externally attach the electronics aids maintainability and supported a lower build height with a unified design, yet introduces risks from environmental exposure. This is adequate for a research platform, but a marketable product would require better protection. Although optimizing for CNC processes addressed some concerns, Wire-EDM was still required to ensure proper belt fit for gearbox longevity and performance. Proposing materials like Al 5055, while cost-effective, also prompts further trade-offs between weight, strength, and long-term durability.

V. CONCLUSION

In the scientific context of hardware development, our redesign of the OSL [10] addresses a critical issue: the balance between manufacturability, cost, accessibility, and functionality. While some may argue the merits of maintaining the status quo, it became clear that a comprehensive overhaul was necessary. Despite being a validated reference, the existing design was hindered by prohibitive costs for those wishing to purchase it and by design complexities that made in-house fabrication impractical for many. It was evident that access to this technology should be democratized truly. The OSL needed significant improvements to make it more accessible and feasible for a broader range of users and developers.

Looking forward, the OSL project embodies the dynamic interplay between technological innovation and the ethos of open-source collaboration. It serves as a blueprint for future endeavors in prosthetic development and beyond, highlighting the importance of community engagement, interdisciplinary research, and user-centric approaches to design. As we advance, we must continue to foster an environment of open dialogue, critical assessment, and creative problem-solving to navigate the complexities of creating technologies that are inclusive and universally accessible.

ACKNOWLEDGMENT

We thank the Mechanics Workshop staff of the, Friedrich-Alexander-Universität Erlangen-Nürnberg, for their expertise and support.

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