Title:
A 3D-Printed Cycloidal Drive Actuator for Compliant Human-Robot Interaction: Design and Integration for a Low-Back Exoskeleton

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Abstract:

In the last decades the adoption of assistive devices has been spreading among different application fields, starting from the rehabilitative medicine to the industrial field. In particular exoskeletons aimed to ease the operations performed by workers have been developed in order to reduce the entity of work-related musculoskeletal disorders, limiting the inconvenience caused to the workers and reducing therapy-related costs faced by the employer or the healthcare system. However commercial full-body exoskeletons equipped with efficient, low-weight actuation systems require a huge investment (both for purchase and maintenance) which only a few companies are willing to pay. Thus the attention towards cost-effective, efficient exoskeleton focused on assisting a particular task is arising. Low-back exoskeletons in particular are capable to relieve back pain for people subjected to frequent payload manipulation. It is possible to enhance already existing passive devices (i.e. actuated by an elastic element) by implementing an active control (e.g. actuated by an electric motor), more flexible and adaptive to different operating conditions. In order to achieve high performance while limiting costs and complexity, a custom cycloidal reduction was designed: because of its back-drivability and scalability it represents a low cost solution capable to maximize the overall performances of the assistive device. In this paper the methodology to define a custom low-cost yet efficient cycloidal drive actuation is hence proposed, as well as its implementation in the design of low-back exoskeleton based on backbone kinematics.

Introduction

In the last decades in the industrial field higher attention has been directed towards assistive devices. Initially developed in the military field to augment the wearer's strength and endurance, they quickly spread also in the healthcare as a rehabilitative tool, in particular for helping stroke patients to recover

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Fig. 1: Operating principle of a low-back exoskeleton based on backbone kinematics.

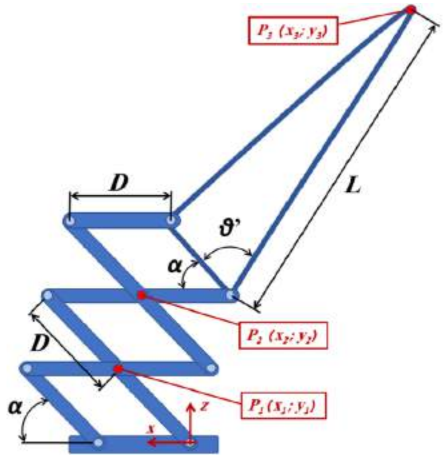

Fig. 2: Scissor hinge configuration.

mobility and dexterity [1]. It was in 2004 with the foundation of Cyberdyne that the first commercial exoskeleton made its appearance: the Robot Suit Hybrid Assistive Limb (HAL) provided the first solution as support to the workers while performing repetitive tasks for a long time. Both the company and the workers were able to benefit from the adoption of this kind of equipment: by assisting the worker in wearing operations it is possible to reduce the occurrence and the entity of work-related musculoskeletal disorders, decreasing the risk for the user of becoming invalid and limiting the costs to be faced by the employer or the healthcare system. However, while providing support to whole the body of the user, the HAL is also rather expensive (its cost ranges from $11,000 to $19,000, while the rent has a monthly subscription of nearly $1,000 [6]). Cost is often the major factor in reducing large-scale exoskeleton adoption.

In first place exoskeletons acting only on a certain part of the user's body have been developed: lower limb exoskeletons like the Lokomat [5] were initially developed to assist the gait of stroke patients on a treadmill, while lower-back exoskeletons were designed mainly to relieve the back pain which could affect the workers subject to frequent payload manipulation.

In this work, the passive low-back exoskeleton presented in [3] has been considered as starting point for the development of an active exoskeleton. The focus was aimed at the definition of an actuation system (motor+reducer) suitable for the application and the re-design of the exoskeleton in order to provide the required mechanical resistance minimizing the encumbrance and the weight of the device. Thus, the first objective of this work is the design and development of a fully-3D-printed speed reducer to couple to a brushless DC (BLCD) motor.

Preliminary Design:

The passive exoskeleton presented in [3] has been performed on the basis of the anthropometric tables presented in [2], considering data related to the 75th percentile for male subjects.

Scissor hinge mechanism:

In order for the exoskeleton to work correctly, it needs to adapt to the back of the user when bending

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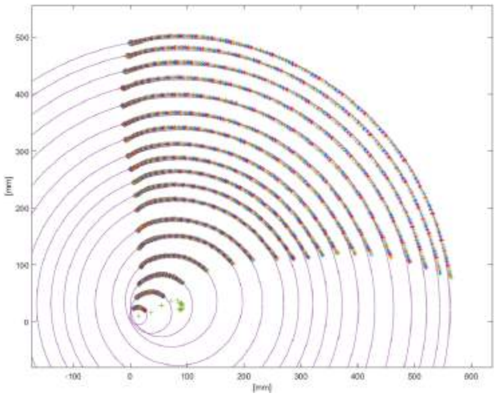

Fig. 3: Circular approximation of the motion path of the vertebrae.

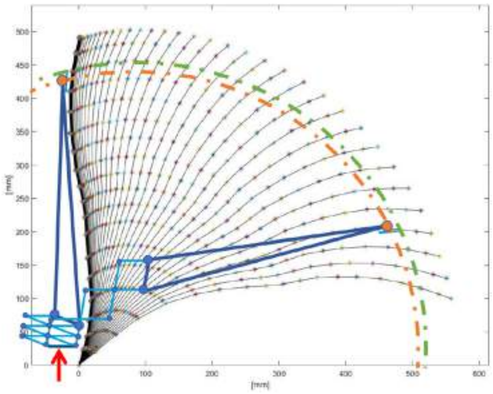

Fig. 4: Comparison between the mechanism motion (yellow) and vertebra T2 motion (green). The red arrow represents the constraint between the mechanism and the lumbar fixing.

forward. In order to guarantee this behavior a scissor hinge mechanism (Figure 2) capable to follow the backbone kinematics has been developed as presented in [4].

The human backbone is made of 33 vertebrae distributed from the base of the skull to the pelvis, where 24 of them are articulated and named accordingly to their position: 7 cervical (C1 to C7), 12 thoracic (T1 to T12), 5 lumbar (L1 to L5), 5 sacral (S1 to S5) and 3 to 5 coccygeal vertebrae. Their relative movement during the forward bending of a person was acquired through a stereophotogrammetric system capable to recognize the motion of markers applied in correspondence of the vertebrae. The recorded positions of the markers during the execution of the protocol were then processed in order to define circular paths that approximate the motion path of the vertebrae, shown in Figure 3. Finally, a 1 DoF scissor hinge mechanical system was designed in order to follow the motion of the T2 vertebra along its approximated circular trajectory (Figure 4). This design has been derived considering the kinematic of 3 points of interest (the revolute joints P_1 and P_2 and the final point P_3 of the mechanism, corresponding to the T2 vertebra):

$$\begin{cases} z_1 = D \cdot sin(\alpha); \\ x_1 = D \cdot cos(\alpha); \end{cases} \quad (2.1)$$

$$\begin{cases} z_2 = D \cdot sin(\alpha) + z_1; \\ x_2 = D \cdot cos(\alpha) - D + x_1; \end{cases} \quad (2.2)$$

$$\begin{cases} z_3 = L \cdot sin(\alpha + \theta') + z_2; \\ x_3 = D \cdot cos(\alpha + \theta') - D + x_2. \end{cases} \quad (2.3)$$

This mechanical system represents the core element of the exoskeleton and must be kept while designing the following versions of the low-back exoskeleton. Changes to one or more parts can be applied to better adapt to the characteristic of the user (height, weight, . . .), but these modifications must be consistent with the equations 2.1, 2.2 and 2.3.

User-exoskeleton interface:

In order to prototype an exoskeleton capable to adapt to different anthropometries, different sizes

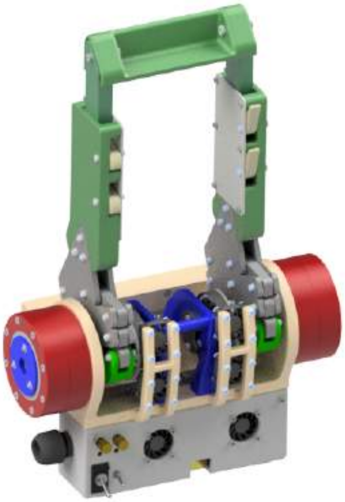

Fig. 5: Exoskeleton assembled.

for the hip-to-shoulder wearability have been defined in order to adapt to the height that different users can presents. The interface has been achieved by means of soft links: backpack-like straps has been implemented for the shoulder constrains, at the waist was added an ergonomic belt while for the lower limbs elastic bands were added to the leg bars, guaranteeing sufficient comfort when wearing the device.

Assembly of the exoskeleton:

The assembly of the exoskeleton is shown in Figure 5.

The feasibility of the assembly have to be validated through a step-by-step simulation of the exoskeleton building to guarantee the the coupling of all the elements.

FEM analysis:

In order to reduce the risks of immediate failures of the exoskeleton after its assembly, it is mandatory to validate the mechanical resistance of all its components before the printing phase in order to avoid spending time and materials in the manufacturing of non-compliant components. This validation can be performed by means of the Finite Element Analysis: thanks to the tools provided by Inventor, it is possible to simulate the stresses present in the elements of the device during its functioning; these estimated values are then compared with the mechanical properties of the material (i.e. yield strength) composing the piece in order to verify the compliance of the component for the current application.

The materials adopted in structural components are two. The first one is Nylon PA12+CF15, used for the custom speed reducer and for the other components of the exoskeleton.

Conclusions:

The proposed work presented the design methodology for a custom back-drivable cycloid transmission and its implementation on a new active back-support exoskeleton, based on backbone kinematics.

After a first overview of a passive low-back exoskeleton and its operative principle, it has been defined the main requirements for the definition of an actuator aimed to integrate an active control compliant for

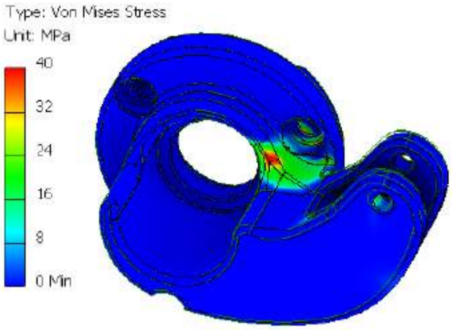

Fig. 6: FEM analysis of the scissor mechanism's actuated hinge.

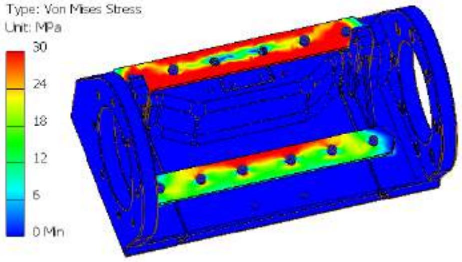

Fig. 7: FEM analysis of the hip support.

the assistive device: back-drivability, high performances, low cost. All the requirements were met with the design of a custom cycloidal reducer. The newly defined actuating system has been integrated into the low-back exoskeleton prototype by performing several design iterations of its components in order to achieve a compliant human-robot interaction. Finally a validation of the final model has been performed, both evaluating the kinematic of the device and simulating the mechanical response through a FEM analysis.

The result of this process is a new design for an active low-back exoskeleton which main advantage is found in its scalability: by modifying the dimensional parameters of some elements (i.e. reduction, scissor hinge and upper-back interface) it is possible to re-design in a relative short time an assistive device capable to fully adapt to the anthropometry of the final user, enhancing the overall efficiency, before starting the manufacturing phase.

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