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Research paper

Design of variable impedance actuator for knee joint of a portable human gait rehabilitation exoskeleton

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ABSTRACT

This paper presents the design of a variable impedance actuator, called BAFSA, for the knee joint of a portable human gait rehabilitation exoskeleton. Such an actuator is specifically tailored to this joint, aimed at the application of robotic-assisted gait training therapies to restore the normal function of the impaired knee, taking into account kinematics, kinetics and anthropometric requirements along the gait cycle. Mechanical design and functioning of the actuator are thoroughly shown, with particular emphasis upon the variable stiffness mechanism, which consists of an axial floating spring, bidirectionally actuated in an antagonistic way. This is combined with a complimentary system, named BLAPS, that allows to vary automatically the preload stiffness, and sustain it before external loads with no further energy cost to the actuator motors. Simulations reproducing a normal gait cycle on level terrain are carried out to demonstrate the feasibility of the design, considering both power and energy consumption to validate the actuator performance. Thus, the actuator here developed is suitable to implement different rehabilitation strategies on the impaired knee joint. Finally, complete disclosure is achieved by presenting the technical specifications of the BAFSA, which fulfills all the requirements that were initially established as design criteria.

1. Introduction

Robotic advancements applied to wearable devices have enhanced rehabilitative possibilities in humans. Rehabilitation exoskeletons are the pinnacle of such biomechatronic systems, which may restore the lower limb motion of physically impaired persons [1–3]. In particular, patients with spinal cord injuries or after stroke usually need gait rehabilitation for relearning the basic functions of gait [4–7]. This requires intensive and task-specific training suitable to be applied via a robotic device, such as an exoskeleton. The idea is to evolve from repetitive slow motion of the legs to a more fluent sequence of gait phases, toward an increasing participation of the patient until full, or at least, reasonable recovery of the mobility functions [8–10]. For this, it is important to modulate the level of force exerted on the legs, either for making movements or assisting movements during gait, in accordance to the specific level of impairment presented by the patient treated along a given therapy. Hence, such a rehabilitation process via a robotic device must involve modulation of the compliance of the joint actuators to impose, assist-as-needed, or follow a human joint pattern during walking [11–13].

Exoskeletons are electronically-controlled multi-joint orthoses, which may be tethered or portable. Among the tethered exoskeletons, *Lokomat* (Hokoma AG) [14] and *LOPES* (University of Twente) [15] are counted as the most prominent with gait

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List of nomenclature

F	Normal contact force between each cam roller and cam disk
F_z	Vertical component of normal contact force between each cam roller and cam disk
F_θ	Horizontal component of normal contact force between each cam roller and cam disk
τ_θ	Resulting torque on a cam disk due to action of F_θ
τ_{LOAD}	External torque applied to the actuator at its output link
q_1, q_2	Angular position of main motors of the actuator
q_{r1}, q_{r2}	Angular position of cam rollers
n_1	Spur gear transmission ratio between main motors of the actuator and cam rollers
σ	Stiffness setting angle of the actuator
φ	Deflection angle of the actuator at its output link due to an external load
$s(\theta)$	Function that describes the height of the cam disk surface
θ	Positioning variable of function $s(\theta)$ with domain in $[0, 8\pi/9]$
θ_{min}	Angle θ along the cam surface that corresponds to the minimum of $s(\theta)$
r_c	Effective radius of cam disks
k	Stiffness constant of the floating spring of the actuator
z_0	Preload of the floating spring of the actuator
n_2	Bevel gear transmission ratio at the output link of the actuator
τ	Output torque of the actuator
K	Output stiffness of the actuator
q_K	Angular position of the output axis of the actuator
q_s	Angular position of the straight sided spline shaft
n_{GB1}	Transmission ratio of gearbox of the main motors of the actuator
$\dot{q}_1$, $\dot{q}_2$	Angular speed of main motors of the actuator
$\dot{\sigma}$	Position change ratio of σ
$\dot{q}_K$	Angular speed of the output axis of the actuator
V	Induced voltage of main motors of the actuator
I	Current of main motors of the actuator
k_q	Velocity characteristic constant of main motors of the actuator
k_τ	Torque characteristic constant of main motors of the actuator
R	Electrical resistance of main motors of the actuator
$\dot{q}_3$, $\dot{q}_4$	Angular speed of motors of the BLAPS
$\dot{q}_w$	Linear speed of power screw of the BLAPS
N	Number of threads of screw of the BLAPS
P	Pitch of screw of the BLAPS
n_{GB2}	Transmission ratio of pulleys system of the BLAPS
K_f	Stiffness value applied by actuator during stance flexion sub-phase of gait cycle
K_e	Stiffness value applied by actuator during stance extension sub-phase of gait cycle
W	Weight of patient
H	Height of patient
q_{BLOCK}	Angular position of miniature stepper motors of the BLAPS
σ_{min}	Minimum relative position between the cam rollers ($=0$)
σ_{max}	Maximum relative position between the cam rollers

rehabilitation purposes. These allow to use the body-weight supported treadmill training technique, which has become an established therapy to treat patients with dysfunctional gait after stroke or spinal cord injury since the 1990s [4,16–18]. This technique involves partially bearing the patient's weight through a harness, while he or she walks on a treadmill by means of applying external forces on their legs, either by therapists or a robotic device, or simply by his/her own legs movements. Initially, this was applied with a fixed gait-pattern, but further research demonstrated that gait rehabilitation was noticeably encouraged with gait pattern adaptation [7,15,19]. In [7] and [19], Jezernik et al. exploited the principle underlying the gait-pattern adaptation using the *Lokomat* in such a way that the interaction between the device and the patient is minimized, as the former follows the volitional forces exerted by the latter. Similarly, in [15], Veneman et al. aim to use a device that allows near-to-normal free walking or a wide range of possible content of training and supportive actions. In this case, the scope with the *LOPES* is open through three different operation modes: (1) patient-in-charge, (2) robot-in-charge and (3) therapist-in-charge. However, most of these treadmill training-based exoskeletons are only accessible at large rehabilitation centers or hospitals, therefore limiting their reach to patients needing this kind of therapy [20].

As for the portable exoskeletons, these enable gait assistance and training at outpatient rehabilitation centers or home settings. Several commercial models are now available, counting *Ekso* (Ekso Bionics), *REX* (REX Bionics) and *ReWalk* (ReWalk