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Research paper

Position solution and kinematic interference analysis of a novel parallel hip-assistive mechanism

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ABSTRACT

In recent years, multiple powered exoskeletons, typically focused on one-DOF (degree of freedom) flexion/extension assistance, have been developed to aid the elderly or patients with hip motion disability. To achieve two-DOF adduction/abduction and flexion/extension assistance, a novel parallel hip-assistive mechanism was proposed, consisting of a waist unit, a leg unit and two parallel driving branches. As the mechanism is connected to the human hip, a human-robot closed chain with three parallel branches is formed. The structure of the parallel assistive mechanism, featuring a bearing-like leg unit prototype to remove the restriction on hip internal/external rotation, was introduced. Subsequently, the mobility assessment of the human-robot closed chain, the position solution of the assistive mechanism and the test approach of branch interference were addressed, with the assumption that the flexible distortions of human bodies are negligible. Finally, the joint motion ranges and branch interference of the mechanism were analyzed, throughout a hip gait cycle. Obtained results indicated that the joint motion ranges are small, with no apparent branch interference, meaning that the proposed parallel mechanism can successfully assist the operation of the hip. Consequently, these results could be used as original design parameters of the assistive mechanism.

1. Introduction

Exoskeletons are mechatronic devices worn by people in need, which work cooperatively, in parallel with the human body. Depending on their application, wearable exoskeletons can be classified into three main categories: powered exoskeletons for increasing human capabilities of healthy persons [1,2], assistive exoskeletons to help the elderly or patients with weakened motor function perform daily activities [3,4], and rehabilitation exoskeletons for the treatment of patients with impaired mobility due to both injuries and nervous, joint or muscular diseases [5,6]. As the population ages, increasingly more individuals suffer from impaired mobility and gait disorders [3,7], making walking assistive exoskeletons effective solutions in helping these people regain their locomotor function and the ability to live independently [8]. Due to the close physical human-robot interaction (pHRI) [9], walking assistive exoskeletons are required to have low inertia, high actuation efficiency and the ability to smoothly interact with the users. Accordingly, during structure design, mechanistic aspects, such as light weight, compact structure, kinematic compatibility [10,11], motion range and force transmission character, must be taken into consideration, to increase the feasibility of proposed mechanical designs. Furthermore, the actuation and control

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of exoskeletons should be able to recognize the motion intention of the wearers, follow human motion without hindrance and provide assistive torque at the wearer's joints safely.

The hip joint plays an important role in human locomotion and weight support. Due to the heavy burden and intensive labor, the motor function of the hip joint is easily weakened, eventually resulting in critical limitations of walking and other daily activities [12–14]. In recent years, a variety of serial powered hip exoskeletons have been developed, mainly for flexion/extension (FL/EX) assistance. For example, Ferris et al. presented a powered exoskeleton capable to assist hip FL/EX rotation, which is a modified prefabricated orthosis, driven by artificial pneumatic muscles [15,16]. Giovacchini et al. developed a light-weight active pelvis orthosis (APO) for hip FL/EX assistance [17,18], aiming to enhance the kinematic compatibility and comfort of the pHRI, while achieving desired dynamic character. The APO was designed with some distinct structural aspects, including large carbon-fiber components used to reduce inertia, two passive revolute joints which allow the APO to follow human gait motion out of the sagittal plane, and a novel series elastic actuator (SEA) [19] unit, designed to increase the mechanical compliance between actuators and the human-robot interface. Another example is the powered hip exoskeleton (PH-EXOS) proposed by Wu et al. [20], featuring a Bowden cable actuation unit designed to achieve mechanical characteristics such as structure simplicity, light-weight, and flexible driving. In addition, two passive joints (one universal joint and one prismatic joint) were added into each unilateral branch of the PH-EXOS, to improve the kinematic compatibility, and hence passively follow hip adduction/abduction (AB/AD) and internal/external (IN/EX) rotations. In another study, Olivier et al. designed an assistive motorized hip orthosis (AMPO) for assisting the sagittal plane movement of the human hip joint [21], in which five passive DOFs were added to minimize the effect of the undesired interactional loads, and thereby improve the pHRI performance of the AMPO. Based on the AMPO kinematic chain, two assistive hip orthoses, using different actuation mechanisms, were sequentially proposed and their technical features were systemically compared [22].

Apart from serial mechanisms, the parallel mechanism was also applied to hip motion assistance. For example, Pan and coworkers presented a 3-PUU parallel mechanism-based hip exoskeleton to assist the AB/AD, FL/EX and IN/EX rotations, which was designed on the basis of anatomical character analysis of the human hip structure [23,24]. Yu and coworkers developed a three-DOF parallel hip-assistive exoskeleton [25,26], in which the 3-UPS parallel mechanism was adopted as the main mechanical structure. Moreover, to evaluate and improve the assistive performance, a manipulability inclusive principle was proposed by the authors, and the dimensional parameters of the hip-assistive exoskeleton were optimized. Compared to serial hip-assistive exoskeletons, the parallel ones have the advantages of short power transfer path, high supporting rigidity and large load capacity. Furthermore, they are able to always maintain the revolute center of the movable platform at the human hip revolute center, effectively resolving the axis misalignment issue [27] seen with serial hip exoskeletons. However, due to the parallel allocation of branches, the limited space between the human body and exoskeletons, and inertias of more parts, their structure design and kinematic interference between the parallel branches could be problematic.

Considering that during a human gait cycle the motion range and power consumption of hip IN/EX rotation are smaller than those of the FL/EX and AD/AB rotations, a novel parallel assistive mechanism for hip FL/EX and AD/AB assistance is presented. The assistive mechanism is composed of a waist unit, a leg unit and two parallel driving branches, forming a human-robot closed chain with three parallel branches when connected to the hip complex. In this paper, the kinematic structure of the assistive mechanism was introduced, addressing the mobility and the position solution issues of the human-robot closed chain, with the hypothesis that the flexible distortions of human bodies are insignificant (thus, were neglected). Based on the proposed position solution, the joint motion ranges of the assistive mechanism and the interference test between the parallel branches were analyzed, throughout a typical hip-assistive gait cycle. The results show that the joint motion ranges are small and no kinematic interference occurs between the branches, which means that the safety and reliability of the operation of the assistive mechanism could be ensured. Hence, the presented mechanism is suitable for the hip FL/EX and AD/AB assistance, and obtained results could be used as original parameters for the kinematic design of a parallel hip-assistive mechanism.

2. Parallel hip-assistive mechanism

The diagram of the parallel assistive mechanism (Fig. 1a), the kinematic model of the human hip complex (Fig. 1b) and the formed human-robot closed chain (Fig. 1c and d) are shown in Fig. 1. According to anthropotomy, the human hip complex is composed of the femoral head, the cotyle and the ligaments, with the femoral head being able to freely turn in the cotyle [28]. Hence, the hip complex can be regarded as a three-DOF spherical joint S, which allows hip FL/EX, AD/AB and IN/EX rotations. As shown in Fig. 1(a), the assistive mechanism consists of a waist unit and a leg unit, connected by two parallel branches. The first branch includes a universal joint (U_1), a prismatic joint (P_1) and a universal joint (U_3); the second branch is composed of a universal joint (U_2), a prismatic joint (P_2) and a spherical joint (S_3); the setting angle between the two parallel branches are $2\theta_0$ (marked by the arrows in Fig. 1a). The prismatic joints P_1 and P_2 of the two branches are the active joints of the assistive mechanism, whereas all the others are passive joints. In the parallel assistive mechanism shown in Fig. 1(a), R_C stands for the passive revolute joint, connecting the leg unit to the human thigh. To remove the restriction acting on the hip IN/EX rotation, while increasing convenience when wearing the device, a bearing-like prototype of the leg unit is proposed (structure design is addressed in Section 6). As shown in Fig. 2, the leg unit is mainly composed of two outer clamping plates, two ring slide ways, two ring sliders, two inner clamping plates and straps, which constitute