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Optimum kinematic design of a planar cable-driven parallel robot with wrench-closure gait trajectory

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ABSTRACT

We report the design of a planar cable-driven parallel robot with four cables. The design can generate a wrench-closure trajectory of the lower limb, shank, with applications in gait rehabilitation. Using such a design, any external wrench on the target limb can be balanced using cables for all poses of the limb near to the trajectory in the gait cycle. We calculate the largest wrench-closure circular zone centered at an arbitrary point of the trajectory for a given range of orientations around a reference orientation of the limb. Taking the area of such zones into account for a set of points on a given trajectory, we optimize the robot kinematics with fixed cable attachment points. However, static evaluation of the robot in the trajectory indicates that, in some part of the trajectory, a general external wrench cannot be balanced. Therefore, a reconfigurable design of the robot is investigated in which the cable attachment points on the base can move with respect to the motion of the limb in its trajectory. The area of wrench-closure zones in the trajectory can be increased using different actuation schemes, which are obtained and compared. Finally, a redundant reconfigurable robot with an optimum wrench-closure gait trajectory is proposed.

1. Introduction

Gait training or gait rehabilitation is the process of learning how to walk and is applied to patients who suffer from gait disorders. Physical therapists (or physiotherapists) generally aim to train their patients by encouraging them to practice normal gait patterns. This is typically achieved by applying the torque required by a patient at the hip and knee joints during walking. Because of the importance of proper rehabilitation, several robotic systems have been developed to aid in this therapy [1–7].

These systems are commonly classified as either exoskeleton based or end-effector based. Exoskeleton-based robotic systems attach and apply loads to several segments to derive the target limbs. They would require a precise design of the device geometry that often has to be adapted on the patient. Setting-up such device for a particular patient, especially if the device has many segments, may take a significant amount of time. Also, the limb-exoskeleton coupled systems are generally overconstrained which impose unnatuaral motion and loads at joints. Investigating muscle activation patterns with and without the aid of an exoskeleton reveals significant differences when a healthy subjects walks on a treadmill [8,9]. Comparing to the exoskeleton, end-effector systems attach to a single interface (i.e., the end-effector). Movements of the end-effector also indirectly change the position of other segments to which it is attached. By contrast to the exoskeleton system, in end-effector system the overall limb motion is less constrained by external device and thus the muscle activation patterns are more natural and comparable to those with treadmill walking [8].

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Rigid links are used with conventional robotic systems, which impose an additional mass on the system and require support. This leads to some drawbacks, such as a need for more powerful actuators, and introduces safety concerns [10]. Using cables in place of a rigid body system can overcome these limitations and hence improves the performance of the robotic system. In particular, and similar to the end-effector-based design, using cable-driven rehabilitation systems, the cables move the target limb in its trajectory by directly applying forces to the limb, rather than by actuating the joints. In this manner, the advantage of the similarity of muscle activation patterns to those of treadmill walking can be exploited when cables are used in rehabilitation. Moreover, the use of cables in a robotic system provides additional advantages, including a larger workspace, reduced manufacturing and maintenance costs, ease of assembly and disassembly, improved transportability, and superior modularity and reconfigurability.

The use of cables in place of rigid bodies has been studied for lower-limb rehabilitation in little literature [10–14]. In [10], a cable actuation system was developed to control the motion of each joint of a patient by acting on the lower limbs while the patient was lying down. In [11], a cable-driven locomotion trainer (CaLT) was developed for gait training. The design of the system in which cables are attached to the legs around the ankles, provided compliant assistance, and encouraged active involvement of the patient. However, the ability of the robot to provide balance as well as general planar wrench on the lower leg to fully control it through all points of its trajectory during the gait cycle was not demonstrated. In [12], a cable-driven loading system is used in a test rig for in vitro analysis of the knee joint behavior. In this system, a generic wrench can be applied to the tibia which is housed in a ring as the end-effector. The arrangement of the cables and their connections to the end-effector are such that the wrench provided to the platform can be practically fully decoupled. In [13], the design of a cable-driven active leg exoskeleton (C-ALEX) for human gait training is presented. The exoskeleton uses four cables and three cuffs which are connected to the waist, thigh, and shank of the wearer. All four cables are routed through the waist cuff. Two of these are attached to the thigh cuff, and the other two are routed through the thigh cuff and attached to the shank cuff. These four cables actuate two degrees of freedom of the wearer's leg: the hip flexion/extension and the knee flexion/extension. In [14], design of a lightweight, reconfigurable hybrid cable-actuated articulated multibody system in which multiple cables are attached from a ground-frame to various locations on the lower limbs is introduced. In this system, external torsion springs are attached to hip, knee, and ankle joints, respectively, to guarantee the tension force in cables and increase the workspace of the system.

The problem of balancing the general wrench on an end-effector and ensuring full control is challenging with cable-driven parallel robots (CDPRs), whereby cables are employed to control the end-effector postures. With CDPRs, if all f degrees of freedom (DOFs) of the end-effector with respect to the base are controlled by n cables, this is referred to as fully-constrained [15–19]. The minimum number of cables, n, that are necessary to fully control the output motion is equal to the number f. However, since cables may only exert tensile axial forces, a redundancy of control actions, $n>f$, is usually necessary, in order to guarantee full control is preserved for a generic loading condition [20]. Conversely, a CDPR is under-constrained if the ability of the robot to balance an arbitrary external wrench on the end-effector is lost [21–23]. A CDPR is naturally under-constrained when $n<f$ whereas when $n\geq f$, it operates as such when mechanical equilibrium would require a negative tension in some cables. Here we use a fully-constrained CDPR to control and move the lower limb, including the shank, which is considered as an end-effector. The trajectory is controlled using a number of cables attached to the limb. Consequently, the thigh is also guided through its trajectory by following the movement of the shank, and the foot of the other limb is guided by a moving treadmill. As regards the human walking pattern in the sagittal plane, in general, the shank preserves three DOFs, which must be restrained completely. To fully control these three DOFs of the end-effector, although the minimum number of three cables are necessary, mostly four cables are required because cables can only exert tensile axial forces. However, even in fully-constrained CDPRs, full control of all f DOFs of an end-effector may be lost when the number of cables that effectively contribute to control is less than f. This may happen if balance of a generic exerted wrench on the end-effector would require a negative tension in some cables, which cannot be provided as the cables can exert only tensile forces. Consequently, the relationship between a pose and the feasible wrenches at the end-effector is a fundamental issue for CDPRs [18]. This problem has led to several definitions of the workspace of CDPRs [18,19,24–26]. One definition of the workspace relationship between the poses and wrenches at the end-effector is wrench-closure workspace (WCW), which provides a strong tool for the general design of CDPRs [18]. The WCW is the set of end-effector poses for which any wrench imposed can be balanced by the tension force of the cables. A comprehensive method to compute the WCW of 3-DOF planar parallel mechanisms was addressed in [18]. Using this method, a WCW with a constant orientation of the end-effector can be computed exactly as a bounded subset of the plane whose boundary is composed of sections of quadratic curves. Then the exact WCW can be obtained as the common areas computed for different orientations of the end-effector. However, calculating the exact geometry of the WCW can be complicated and time-consuming, with information that is superfluous for the purpose of CDPR design.

Instead, by ignoring small parts of the WCW, the approximate geometry and size can be calculated using a simple geometry, e.g., a circle, to enable easy and rapid computation. This simplification has received much interest when the size of a WCW must be calculated iteratively. Using a simple method, we calculate the wrench-closure circular zone around an arbitrary point within the workspace of a CDPR. The property of this zone is that as long as the poses of the end-effector are within this zone, the robot has a wrench-closure configuration for a given range of orientations of the end-effector. However, with a broad range of orientations of the end-effector, the size of this zone is often limited or even non-existent. Nevertheless, for gait rehabilitation, it is important that the robot be in wrench-closure configuration for a limited range of orientations of the shank around the desired orientation when the poses of the shank are close to its trajectory. Mathematically, this can be interpreted as the existence of wrench-closure zones for all poses of the shank in its trajectory. Clearly, enlargement of these zones yields a robot with a wrench-closure configuration for the poses of the shank in a wider area around its trajectory, which may be the aim of the design.