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Geometric design of eight-bar wearable devices based on limb physiological contact task

Nina Robson[a], Gim Song Soh[b,*]

[a]Department of Mechanical Engineering, California State University, Fullerton, California 92831, United States
[b]Engineering Product Development, Singapore University of Technology and Design, Singapore 487372, Singapore

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ABSTRACT

This paper describes a geometric design method for the motion generation of mechanical wearable devices based on desired limb physiological contact task, parametrized by first and second order motion specifications. Specifically, our approach combines the higher order motion task specifications with anthropometric back-bone chain to synthesize planar eight-bar linkages that achieve the desired motion task. The method is demonstrated by an example that offers a novel alternative approach for wearable devices design: a comprehensive systematic process to create devices, based on a backbone chain that is sized according to the physical dimensions of the human limb. Once it is ensured that the backbone chain motion is close to the physiological one, the rest of the multi-loop wearable device is designed. In the end of the process the wearable device is attached, so that the backbone chain parallels the human's limb itself to provide the skeletal structure for the limb yet passively follow its motion. This results in mechanical devices with compact size, minimal actuation and better wearability.

1. Introduction

Recently, there has been a need to reduce the number of actuators within robotic limbs, so as to provide better reliability and lower cost. This was achieved by coupling the motion of multiple joints, leading to designs with fewer actuators than its degrees-of-freedom. Such limbs termed “under-actuated” or “minimally-actuated” have demonstrated significant benefits especially in grasping applications due to their passive adaptability nature between the degrees-of-freedom, thus allowing the fingers to conform to the environment shape without the need for sensing.

There are generally two types of under-actuated robotic limbs proposed in literature. The first type is based on tendon-actuated systems and the second type is based on mechanical linkages. A tendon driven robotic hand can be usually designed with compact size and dexterous operation. However, such systems suffer from friction and elasticity issues during operation and are limited to small grasping forces [1]. On the other hand, linkage mechanisms are preferable for applications where high stability and large forces are expected. Gosselin and Laliberte [2] designed a flexible and versatile linkage based mechanical gripper for industry applications. The TUAT/Karlsruhe Hand [3] and mechanical finger [4] are driven by single degree of freedom linkages meant for prosthetics applications.

* Corresponding author.
E-mail addresses: nrobson@fullerton.edu (N. Robson), sohgimsong@sutd.edu.sg (G. Soh).

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Some of the current developments in the field of wearable devices and exoskeletons in particular, focus on restoring abilities lost due to injury or compensating for persistent disabilities. For example, exoskeletons have been developed for rehabilitation after neurologic injury such as stroke or traumatic brain injury. These robotic devices have been developed for a variety of tasks, including gait rehabilitation (such as [5,6]) and upper extremity rehabilitation (see [7,8] for reviews). For hand rehabilitation, Wang et al. [9] designed an exoskeleton based on 4 bar linkage for an index finger rehabilitation and Yihun et al. [10] recently designed a non-anthropomorphic wearable device based on eight-bar linkage for thumb rehabilitation. Wearable devices and exoskeletons have also been designed and developed for the purpose of augmenting and amplifying the ability of humans (for reviews see [11,12]). Human augmenting and amplifying exoskeletons have been developed for both military and industrial applications. Examples include leg exoskeletons for hauling heavy loads [13] and upper-extremity robots for strength augmentation [14].

The most important requirement for the design of wearable devices is safety and is usually achieved through some form of mechanical range stopper or the design itself [15]. The key approach is to design the wearable device with its rotation axis coinciding with that of the human joint so as to mimic its workspace. This way, even though there is a failure on the device controller, the exoskeleton will not force the user to move in an unnatural manner resulting in damage to his limbs. There are a few ways in which one could achieve this. The most direct manner is to match the joint centers directly [16]. However, this approach requires structural space on the side of the limbs. Alternatively, a remote center of rotation structure can be considered [17,18].

The requirement of having both the limb and wearable device to coincide can be disregarded if flexible or underactuated structures are used. An approach of making it flexible is to adopt a linkage with redundant degrees of freedom [19]. Another way is through tendon-driven mechanisms [20,21] or soft pneumatic actuators as part of a wearable system [22]. Underactuated wearable devices are usually achieved by attaching and controlling the movement of the distal segment directly [23].

It is important to note, that while most of the above mentioned devices show satisfactory performance, there still does not exist a systematic methodology for the design of these systems. The aforementioned highlights the need for the development of novel design techniques for underactuated linkage skeletal structures that are sized according to the wearer's limb dimensions. Our original intent is to seek inspiration from nature, as similar to many insects or animals, where the exoskeleton supports or protects an animal body and is shaped according to the shape and size of a particular insect or animal. In this paper we extend upon our initial work in Robson et al. [24] and show that the ability to first identify the desired human motions and then mathematically describe them as physiological task, using higher order motion specifications, opens the possibility of creating mechanical limbs with minimal number of actuators and better wearability. Here, we would like to note that unlike other wearable device design techniques that use parallel mechanical linkages [25-27], we offer a novel alternative approach: a comprehensive systematic process to create wearable device that incorporate anthropometric backbone chain with the physical dimensions of the human limb and a physiological task, compatible with the contact constraints between the limb and objects or the environment. Since the backbone chain provides the skeletal structure of the whole system, once it is ensured that its motion is close to the physiological task, then the rest of the multi-loop kinematic system is designed. In the end of the process, the wearable device is attached, such that the backbone chain braces its human counter part. This approach is particularly useful for synthesizing mechanisms that require physiological contact task during motion such as walking or grasping.

2. Physiological contact task identification, using sensor data

Our goal is to design mechanical linkage skeletal structures, based on anthropometric data from a human limb that can be easily attached, avoiding collision between the linkage and the wearer's limb, yet incorporating higher order kinematic constraints for contact tasks such as walking or grasping. In particular, for this paper, we chose the design of an index finger of a wearable grasping device as an example to illustrate the usefulness of this approach. Grasping devices are tools that are used for manipulation and handling tasks, which require the limb(s) to be in contact with an object. The paper is inspired by Howard and Kumar [28], who show that the stability of a grasp depends not only on the magnitude and direction of the contact forces but also on the local curvature of the contacting bodies. Another inspiration for the current paper are the works of Rimon and Burdick [29,30] who analyze the mobility of bodies in contact to show that first order theories based on positions and velocities are not sufficient to define the local behavior of a linkage mechanism. The authors take a step further to show that the acceleration properties of movement are related to the curvature of the contacting bodies and can be used to effectively constrain a rigid body for grasping applications. In order to define the contact requirements for each finger, our research builds upon the above-mentioned works, by incorporating velocity and acceleration task requirements into our synthesis procedure.

Our design approach starts by obtaining experimental data of subject(s), performing desired grasping task(s), using 3D motion capture system. In order to identify the human motion and its derivatives Robson et al. [31] has been working on inertial measurements combined with the finger motion capture data obtained from a Vicon motion capture system. For example in [32], the authors develop a cost-effective glove prototype to obtain position and higher order derivative information of each fingertip (see Fig. 1).

The sensor-glove device consists of tri-axis accelerometers located at the fingertips and optical markers placed in accordance with a reduced marker protocol. The information from the accelerometers and the markers is used to obtain human finger motion data based on position, velocity and acceleration. The latter is then used to define the physiological contact task for the synthesis of the single degree-of-freedom multi-loop kinematic chain. For example, we chose a set of two task specifications such that PV_{start} defines the start position and velocity and PVA_{end} defines the end position, velocity and acceleration of the limb