Optimal design of cable differential actuation for 2-DOF wrist robots: effect of joint misalignments on interaction force

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***Abstract*—We present our on-going research on the development of low-impedance robots to study wrist rotations under haptic feedback for research in motor control. Our current work aims to quantify the effect of joint misalignments on interaction forces measured for 2-DOF wrist rotations. We present two wrist robot designs that result in variable levels of the trade-off between design complexity and kinematic compatibility, with the ultimate goal of providing quantitative results to optimize the design of human-interacting wearable robots.**

I. Introduction

Kinematic compatibility is a crucial criterion in the development of human-interacting robots, as it avoids unwanted interaction forces that may cause pain, injury, or perturbation of natural motion [1].

In anthropomorphic exoskeletons, complete kinematic compatibility can be achieved only with perfect alignment of robotic and anatomical joints. An alternative approach, as discussed in [1, 2, 3], is to include additional passive joints in the robot kinematic chain, enabling isostaticity, i.e. possibility of complete control of the addressed degrees-of-freedom (DOFs) via exchange of interaction forces that do not cause pain or discomfort to the user.

In wrist robots, perfect alignment is difficult as a consequence of the wrist's complex kinematic structure and high inter-subject variability of joint parameters [4]. Yet, to reduce robot complexity, in previous wrist robot designs, passive DOFs were not always added in number sufficient to guarantee isostaticity for arbitrary misalignments. Although it is known that interaction force can perturb motor control strategies [5], it is currently unknown what levels of force are acceptable for devices developed in the context of research in neurorehabilitation or motor control.

II. Methods

We have developed two wrist robot designs based on a cable differential transmission [6], to measure and assist wrist rotations about the flexion/extension (FE) and radial/ulnar deviation (RUD) axes. The cable differential is an ideal transmission for 2DOF wrist robots, as it results in near-isotropic dynamic properties with minimal friction, enabling placement of both the actuators on a stationary frame. A cable differential transmission provides rotations about two orthogonal axes intersecting in one point, which is usually internal to the robot structure. This fact, coupled with the complex kinematics of the wrist joint, introduces potential kinematic incompatibilities.

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We have pursued two approaches to avoid such kinematic incompatibilities. One approach is based on adding passive DOFs to achieve isostasticity, the number of which was determined based on the Grubler-Kutzbach mobility criterion and confirmed by a kinematic analysis of the resulting parallel manipulator. The second approach involves a modification to the cable differential design to enable co-location of the wrist joint center with the robot's center of rotation.

III. Results

The non-colocated design, shown in Fig 1A, requires four passive joints to guarantee isostaticity for every distance between the robot and wrist center of rotation. Even in presence of moderate misalignments, our kinematic analysis predicts that significant interaction forces for coupled rotations involving both FE and RUD joints with magnitudes above 30 degrees (Fig 1C) are obtained in the absence of passive joints.

With the second design (Fig 1B), perfect isostaticity cannot be guaranteed due to unavoidable micro-misalignments [1]. While this feature is appealing because of its reduced complexity, co-location of the wrist with the cable-differential axes results in a system with overall greater dimensions. As a consequence, the reflected inertia may increase compared to the previous design, due to a doubling of the size of the cable differential pulleys that is required to guarantee a sufficient range-of-motion (± 90 deg for FE, ± 30 deg for RUD).

In future work, we will quantify the impact of the two different designs on the resulting misalignments and device transparency measured during normal conditions of operation.

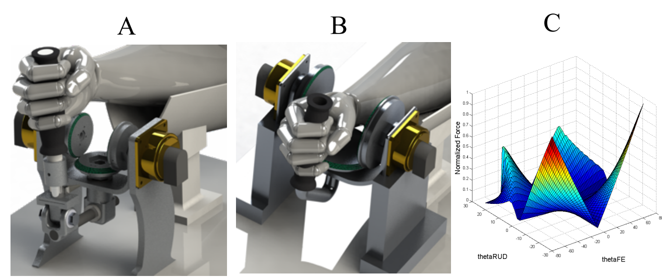

Figure 1: (A) Non-colocated cable-differential wrist robot. (B) Co-located cable-differential wrist robot. (C) Normalized misalignment force across the robot workspace.

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