Design of a Knee Joint Mechanism that Adapts to Individual Physiology

Jiun-Yih Kuan, Kenneth A. Pasch, PhD, PE, and Hugh M. Herr, PhD

Abstract— **This paper describes the design of a new knee joint mechanism, called the Adaptive Coupling Joint (ACJ). The new mechanism has an adaptive trajectory of the center of rotations (COR) that automatically matches those of the attached biological joint. The detailed design is presented as well as characterization results of the ACJ. Conventional exoskeleton and assistive devices usually consider limb joints as a one to three degrees of freedom (DOFs) joint synthesized by multiple one-DOF hinge joints in a single plane. However, the biological joints are complex and usually rotate with respect to a changing COR. As a result, the mismatch between limb joint motion and mechanical interface motion can lead to forces that cause undesired ligament and muscle length changes and internal mechanical changes. These undesired changes contribute to discomfort, as well as to the slippage and sluggish interaction between humans and devices. It is shown that the ACJ can transmit planetary torques from either active or passive devices to the limbs without altering the normal biological joint motion.**

I. INTRODUCTION

Successful augmentation of human locomotion has been an elusive goal for several decades; however, rapid advances in robotics and mechatronics over the last decade have made achieving this goal attainable [1]. To our knowledge, except the autonomous leg exoskeleton proposed by Mooney et al. [2], neither active nor passive wearable robots have quantitatively demonstrated a significant metabolic advantage for legged locomotion. Researchers and engineers are still attempting to design an effective extremity wearable system that can enhance an able-bodied human's mobility or a promising orthotic device that can restore normal function to those with a disability.

One possible reason for this is that it is not yet completely known what functions are needed from a wearable device to appropriately assist a human and how a human responds to the physical interaction between the wearable device and lower-limb joints during natural locomotion. Another possible reason is the design challenges of creating a mechanism that does not impose kinematic restrictions on the wearer's normal gait or add significant mass to the wearer's body. Both kinematic restrictions and additional mass may contribute undesired force profiles to the human body, changing the normal gait, increasing metabolic costs, and hindering the efficacy of the devices. To answer these questions and explore important biomechanical properties, a lightweight, effective wearable device needs to be developed that applies force to the human limbs without altering the normal biological joint motion.

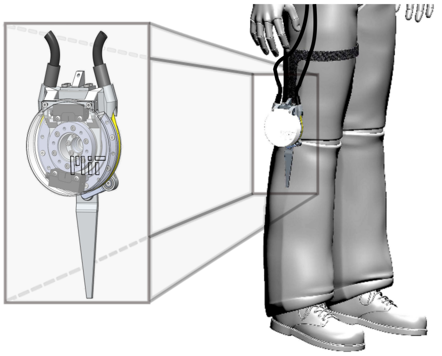

Fig. 1. A graphical rendering of the Adaptive Coupling Joint (ACJ) mechanism on a man.

To reduce the design complexity, limb joints are typically modeled as a one to three-degrees of freedom (DOFs) joint synthesized by multiple one-DOF hinge joints in a single plane. However, the biological joints are complex and usually rotate with respect to a changing instantaneous center or center of rotation (COR). For example, knee motion may be visualized as the rotation of the femur about a series of three-dimensional instantaneous axes rather than a single fixed axis. As a result, the misalignment of joints between the wearer and hardware can lead to significant undesired forces that cause undesired ligament and muscle length changes and internal mechanical changes [3], [4]. These undesired effects contribute to discomfort, as well as to the slippage and sluggish interaction between the wearer and the device.

To address these undesired effects, most commercial brace joints only loosely follow the combined translational and rotational motion that the knee undergoes during flexion and extension. A four-bar linkage in the sagittal plane was also used for the knee joint design, such as in [5], since it can be regarded as a model of the biological knee joint translation and rotation during knee flexion [6]. The unique characteristics of the linkage precisely modeled a particular subject's knee, but the inter-individual discrepancies in different subjects lead to a qualitative difference in the alignment of the coordinate systems because of small differences in the joint anatomy from person to person [7].

Only few mechanisms have been proposed to fit different wearers and to provide adjustability for the setup. For instance, the self-aligning exoskeletons utilizing a planar parallel mechanism have been proposed to avoid mismatches between human joint axes and the device axes [8], [9].

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The concept of Schmidt-coupling has been applied to a knee exoskeleton, as to allow for passive translations of the exoskeleton axis throughout the knee motion [10]. A more general concept that decouples the joint rotations from the joint translations has also proposed in [11]. However, relatively sophisticated coupling structures in these designs result in an overall increased system mass and bulky mechanisms.

To solve the problems, this paper proposes the design of a new knee joint mechanism, the Adaptive Coupling Joint (ACJ), which has an adaptive trajectory of CORs that automatically matches that of the attached biological joint. The detailed design of a cable-driven knee joint mechanism is presented as well as characterization results of the ACJ. The characterization results show that this new mechanism can transmit planetary torques from an input device to the limb joint without altering the normal biological joint motion.

II. Design Principle

When modeling a knee joint, there are unique rolling cam surfaces of the tibia and the femur, so the COR of the rotating and translating tibia component is changing when the knee flexes or extends in the sagittal plane of the knee. A two-DOF mechanism can be designed to transmit torque from a pure torque source to the output and allow a varying COR of the output link. One simple possible design is a two-DOF five-bar linkage that allows torque transmitted from the input component to the output component with a slider that connects the output component to the ground component. The slider allows the output component to rotate and translate with respect to the ground component in the same plane, so that the trajectory of the COR of the output component is a function of the location of the slider.

The topology of a two-DOF five-bar linkage system providing the proposed kinematic constraints is shown in Fig. 2, wherein the ground link, the input link, the coupler, the output link, and the slider are consecutively connected via pivot joints. The lengths of the input and the output links are set the same so that the system has an almost linear transmission. The ground link as the proximal mount can be affixed to the proximal component of the limb joint, and the output link as the distal mount can be affixed to the distal component of the joint. The coupler allows the input link to exert both flexion and extension moments about the limb joint. The slider translates with respect to the ground link along the track defined by the coupled joint, which allows a varying COR of the output link. With an unfixed rotational axis, torques can still be applied to the limb from the input link to the output link via the unconstrained linkage system. Note that the track on the ground link is not necessarily linear but defined by the geometry of the coupled joint.

Fig. 3 shows a possible configuration of a two-DOF five-bar linkage system applied to a knee joint. The femur is fixed to the ground link and the tibia is fixed to the output link. Torques can be applied to the knee joint from the input link to the output link via the linkage system. The joint that can rotate and translate in the same plane provides an adaptive trajectory of CORs matching that of the biological joint. As a result, the overall system can be considered as a one-DOF system. Namely, the knee joint regarded as a kinetic pair constrains the linkage system and sets a specific trajectory of CORs of the output as a function of knee flexion angles in accordance with normal knee motion. Consequently, the mismatch between limb joint motion and mechanical interface motion is avoided.

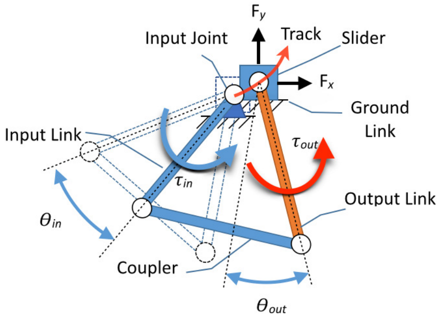

Fig. 2. A topology of the proposed two-DOF five-bar linkage system. With an unfixed rotational axis, torque τ_{in} can still be applied to the limb from the input link to the output link via the unconstrained two-DOF linkage system, in which the slider moves along the predefined track.

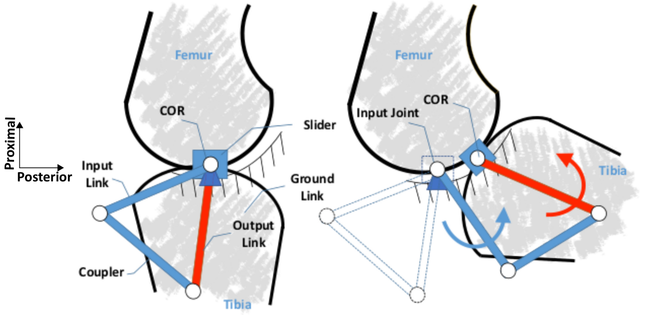

Fig. 3. A graphical explanation of the adaptive Center of Rotation (COR) technique. Accompanied by a human knee joint, the COR of the output link of the two-DOF five-bar linkage system is set by the slider following the COR of the shank in the sagittal plane. Posterior and proximal directions of the mechanism are defined in the figure.

III. Design Overview

Since the relative motion between links connected to the ground is of interest and the motion of the slider is relatively small, the design procedure for the four-bar linkage synthesis was used. To make sure there is only one possible configuration to refrain from hyperflexion, the lengths of the links were carefully selected according to the Grashof criterion so that the input and output links acted as a double-rocker system. Moreover, a unity transmission ratio is desired to have a better efficiency before considering any other energy losses, such as friction, and to avoid top-dead-center or bottom-dead-center positions occurrence. The final design parameters are shown in Table I.

Fig. 4 shows a rear isometric view and a sectional view of the designed cable-driven mechanism that employs the proposed design principle. The mechanism comprises two cable conduit anchors, a driven drum and a torsion spring, a

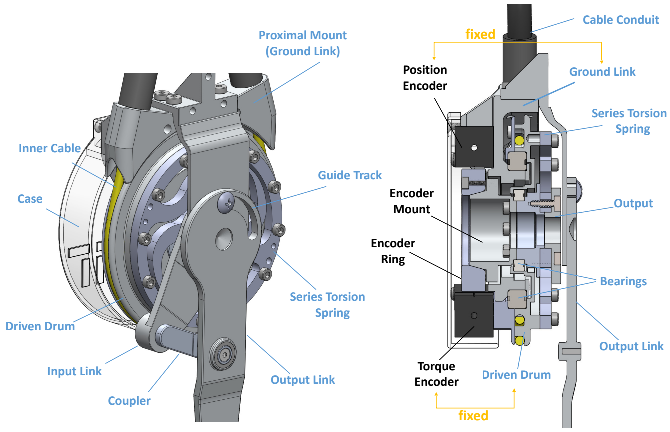

Fig. 4. Knee joint mechanism design. It allows the COR of the output link to have a deviation from a fixed axis, while having an almost linear relationship between the input and output angles.

TABLE I

DESIGN PARAMETERS

Parameters	Values
Range of Motion	$0^\circ - 120^\circ$
Input Link/Coupler/Output Link Lengths	50 / 26 / 50 mm
Size	100 x 100 x 53 mm
Weight (onboard)	$\sim 600g$
COR Deviation Allowance	$0 - 20mm$
Joint Stiffness	21 Nm/deg
Max Output Torque	110 Nm
Torque Resolution	$\sim 0.0023Nm$

proximal mount, an output link, and rotary optical encoder modules. The proximal mount is fixed to the brace attached to the wearer's proximal limb while the output link is fixed to the brace attached to the wearer's distal limb. Accompanied by the guide track on the output link, the pin on the proximal mount acts like the slider while the guide track acts like the track on the ground link in Fig. 2. It allows the output link to translate with respect to the proximal mount along the guide track of the output link. Note the guide track is used to confine the positions of the COR of the output link to the allowance of COR deviations, which are usually within $0 - 20mm$ in the both proximal and posterior directions. It allows a varying COR of the output link while avoids large deviations from the proximal mount in the same plane. The device provides a pure rotational constraint when there is no mismatch between rotational axes of the limb joint and the mechanical joint, whereas the device provides specific planar constraints when there is a mismatch between rotational axes of the limb joint and the mechanical interface. In the embodiment, the driven drum is actuated by an inner cable inside of the two conduits in the pull-pull configuration, driving the limb joint via the output link with small friction due to four-point contact bearings incorporated in the ground link and the output link. The four-point contact bearings can also resist high radial force caused by the cable tension.

Torque sensing is achieved by using a linear torsion spring. The inner part of the spring is fixed to the input link and the outer part of the spring is affixed to the driven drum. An encoder ring is mounted on the encoder mount affixed to the input link. The encoder ring, the encoder mount, the spring, the input link and the output link rotate simultaneously. One position encoder mounted on the proximal mount, can measure the relative rotational angles between the ground link and the input link. One torque encoder mounted on the driven drum can measure the relative rotational angles between the input end and the output end of the spring, and thus is used to measure the output torque by Hook's law. The joint states are collected as the feedback information for both real-time control and subsequent analyses. A case is used to protect encoder readers and the encoder ring.

IV. DESIGN CHARACTERIZATIONS

As a consequence of the two-DOF five-bar linkage system and the adaptive nature of varying CORs, the ACJ has a nonlinear transmission. In order to verify the effect of this nonlinear behavior on the relationship between the output and the input, adaptive COR capacity and its characteristics associated with different wearers, two knee joint COR trajectories, Data 1 and Data 2, adopted from [7] were used. However, the data adopted do not cover the full range of motion of the ACJ, so the data were interpolated and extrapolated using second-order linear equations.

In simulations, the COR of the output link of the device followed the given COR trajectories. The linear least-squares fitting was used to verify the linearity of the output angles of the device corresponding to Data 1 and Data 2. The relationships between the input angles and two trajectories of the output knee flexion angles are nearly linear, as shown in Fig. 5. An R^2 value of 0.99 implies that the relationship between input and output angles can be still regarded as a simple linear function for different wearers, so there is no need to modify the control for different wearers. The net transmission from the input to the knee joint is a nonlinear function of the knee flexion angle and the COR of the coupled knee joint. It can be seen from Fig. 6 that, from 0° to 120°, the transmission ratios associated with Data 1 and Data 2 were 0.8079 ± 0.0595 and 0.8074 ± 0.0400, respectively. The mean of transmission ratios was fairly consistent when the COR changed, while the variations of the transmission ratio were not ignorable.

The COR positions versus output knee flexion angles of two different specimens and COR positions in the distal and posterior directions of the knee join are shown in Fig. 7 and Fig. 8, respectively. The corresponding mechanism configurations at two boundaries are also shown in Fig. 8. The trajectories of the CORs of the output link matched the given trajectories, which demonstrated no mismatch between limb joint motion and mechanical interface motion even given the anatomical variation from subject to subject.

V. CONCLUSIONS AND FUTURE WORK

In this paper, unlike the typical designs, the biological joint was regarded as a kinematic pair and an additional constrain of the device. The biological knee joint constrains

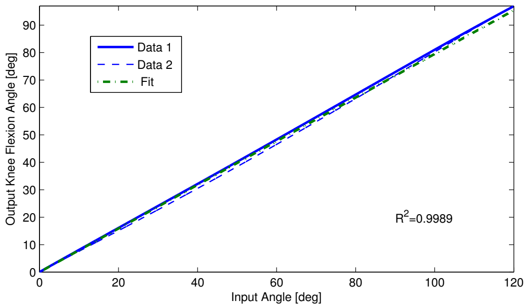

Fig. 5. Input angles versus output knee flexion angles. The output angles of the device used with Data 1 and Data 2 and the linear least-squares fitting result show that the relationship between input and output angles can be regarded as a simple linear function for different wearers.

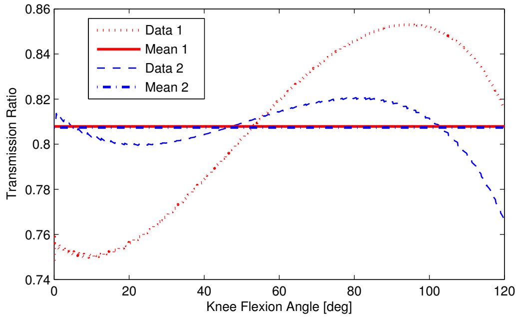

Fig. 6. Transmission ratio versus output knee flexion angles. The results show that the transmission ratio is a nonlinear function of the knee flexion angles and COR positions.

the designed linkage system and sets a trajectory of CORs of the output in accordance with normal biological joint anatomy while an external pure torque source can apply the torque to the joint simultaneously. The mismatch between limb joint motion and mechanical interface motion can be avoided, as well as can undesired slippage and sluggish interaction between humans and devices.

The ACJ is being manufactured and readied for further bench testing. There will also be human trials to determine its efficacy. In the future, the ACJ could potentially enhance the ambulation of able-bodied persons or individuals with movement pathology. For use in able-bodied individuals, the purpose of using it is to enhance locomotory function, such as walking, running, and squatting either associated with professional duties or not. Furthermore, another purpose is the treatment or relief of gait dysfunction resulting from movement pathology, or restoration of age-related reduced locomotory function.

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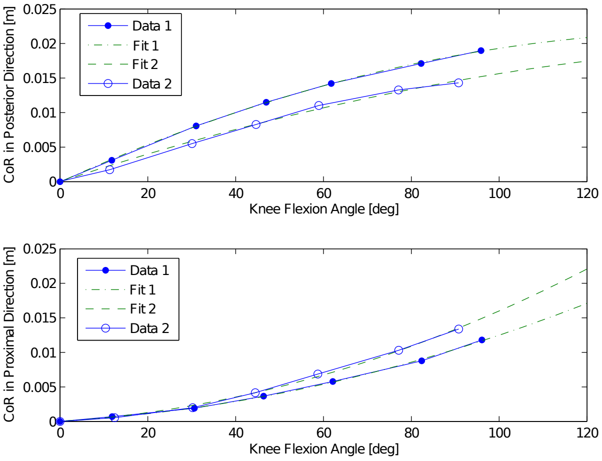

Fig. 7. The COR positions versus output knee flexion angles. Since the data adopted do not cover the full range of motion of the ACJ mechanism, the data were interpolated and extrapolated using second-order linear equations.

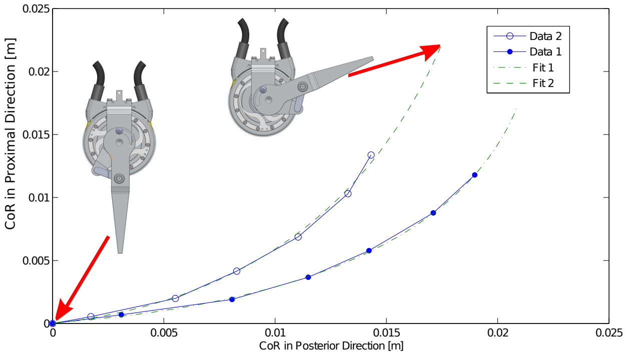

Fig. 8. The COR positions of two different specimens. The corresponding ACJ configurations for Data 1 at two boundaries are shown in the figure.

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