Engineering xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng

Research
Robotics—Article

Unpowered Knee Exoskeleton Reduces Quadriceps Activity during Cycling

Ronnapee Chaichaowarat *, Jun Kinugawa, Kazuhiro Kosuge

Department of Robotics, Tohoku University, Sendai 980-8579, Japan

ARTICLE INFO

Article history:
Received 15 November 2017
Revised 3 March 2018
Accepted 24 April 2018
Available online xxxx

Keywords:
Augmentation
Cycling
Energy cost
Electromyography
Exoskeleton
Knee
Orthosis
Muscle activity

ABSTRACT

Cycling is an eco-friendly method of transport and recreation. With the intent of reducing the energy cost of cycling without providing an additional energy source, we have proposed the use of a torsion spring for knee-extension support. We developed an exoskeleton prototype using a crossing four-bar mechanism as a knee joint with an embedded torsion spring. This study evaluates the passive knee exoskeleton using constant-power cycling tests performed by eight healthy male participants. We recorded the surface electromyography over the rectus femoris muscles of both legs, while the participants cycled at 200 and 225 W on a trainer with the developed wheel-accelerating system. We then analyzed these data in time–frequency via a continuous wavelet transform. At the same cycling speed and leg cadence, the median power spectral frequency of the electromyography increases with cycling load. At the same cycling load, the median power spectral frequency decreases when cycling with the exoskeleton. Quadriceps activity can be relieved despite the exoskeleton consuming no electrical energy and not delivering net-positive mechanical work. This fundamental can be applied to the further development of wearable devices for cycling assistance.

1. Introduction

Bicycling was first introduced in the 19th century, and this classic exercise activity remains popular among more than a billion people worldwide for recreation, transportation, and sport. Cycling is not only environmentally friendly, but also the most cost-effective and time-efficient mode of land transportation for short to moderate distances in many regions. In addition, with the recent growth in global health awareness, people of all ages enjoy cycling as a low-impact activity for cardiovascular exercise. An effective closed kinetic chain exercise [1], cycling is a knee-friendly activity that is widely used as a rehabilitation exercise for improving knee-joint mobility and stability after a knee injury or surgery [2].

A thorough understanding of the complex interaction between the human body and a bicycle can not only improve the performance of competitive cyclists, but also eliminate knee injuries incurred from the pedaling activity. Studies of cycling biomechanics have reported that lower extremity joint moments vary with pedal crank rotation under different cycling conditions, using proposed human models from measured pedal forces and recorded leg kinematics [3,4]. The corresponding leg muscle activities throughout a crank cycle were also studied using surface [5,6] and intramuscular [7] electromyography (EMG) measurements. The unbalanced effort required from the knee extensor over the knee flexor is shown in Fig. 1 [4], in which the knee moment is expressed against the crank angle. The duration of rectus femoris (RF) and vasti muscle activity was almost twice that of the hamstring [8]. Therefore, this study aims to reduce the energy cost of knee extension.

Passive wearable supports that manipulate mechanical energy intelligently have been proposed for various applications. A brake control for walking support has been implemented that realizes the knee-joint rotating direction and the required knee moment [9]. Storing energy using a mechanical spring can reduce the effort required by the quadriceps knee extensor using a quasi-passive knee exoskeleton for running assistance [10]. The knee-extension-assist (KEA) module that stores energy from knee flexion with a set of linear springs [11] was designed for knee–ankle–foot orthoses (KAFOs), in order to assist people with quadriceps weakness to stand. A spring-and-clutch mechanism has been developed in an unpowered ankle exoskeleton [12] for more energy-effective walking.

* Corresponding author.
E-mail address: ronnapee@irs.mech.tohoku.ac.jp (R. Chaichaowarat).

https://doi.org/10.1016/j.eng.2018.07.011
2095-8099/

Please cite this article in press as: Chaichaowarat R et al. Unpowered Knee Exoskeleton Reduces Quadriceps Activity during Cycling. Eng (2018), https://doi.org/10.1016/j.eng.2018.07.011

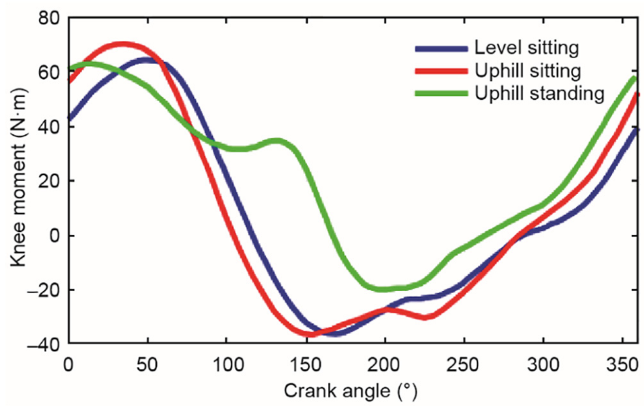

Fig. 1. Knee moments corresponding to three cycling conditions: level sitting, uphill sitting, and uphill standing, as adapted from Ref. [4]. The crank angle is measured in the clockwise (CW) direction from the crank top dead center (TDC). The knee-extension moment is positive and the knee-flexion moment is negative.

With the aim of enhancing cycling performance by reducing energy cost and maintaining the original road feel and handling characteristics, we have previously proposed a torsion spring mechanism that stores energy from knee flexion in order to support knee extension in a wearable cycling assistance device [13]. To address the kinematic compatibility required to cover a large knee angle, we designed our exoskeleton prototype to employ a crossing four-bar mechanism [14] as per the quadratic equations [15] obtained from human knee geometry [16]. We also introduced a novel three-point roller design that provides fit support to the torsion spring.

All major leg muscle groups (i.e., the quadriceps, hamstrings, and gluteus maximus) cooperate to push the pedal while cycling. The RF is most important as a knee extensor [17], since the primary action of this muscle occurs during the power phase, when the hip and knee are extending [18,19]. A time–frequency analysis of surface EMG data can be obtained via a continuous wavelet transform (CWT) [20]. During repetitive maximum dynamic knee extensions, the decrease in the EMG mean power spectral frequency (MNF) upon contraction time was related to force decreases due to the progression of localized muscle fatigue [21]. However, there was no significant sign of localized muscle fatigue in 30 min cycling tests on an ergometer [22], since the decrement in the instantaneous MNF during the exercise was always lower than 5% of the initial value.

The contribution of this paper is as follows: We examined a passive knee exoskeleton for cycling assistance [13] as participants cycled on a trainer with constant speed and against a constant torque. We developed a wheel-accelerating system that uses a friction drive technique to initially spin the rear wheel in order to reach the desired cycling velocity and then automatically disengage from the tire surface. Since the influence of variations in muscle activity on the spectral component of surface EMGs is still ambiguous, we performed two power cycling tests based on the assumption that quadriceps activity increases with cycling power at the same leg cadence. We conducted a time–frequency analysis on the EMG data recorded from the RF; we then compared the median power spectral frequency (MDF) of cycling tests with and without the exoskeleton. Using a torsion spring as a passive joint actuator without requiring an angular position sensor, the unpowered knee exoskeleton can reduce the quadriceps activity in cycling while consuming no electrical energy.

Section 2 explains the fundamental idea of supporting the knee-extension moment using a torsion spring; Section 3 reveals our exoskeleton design; Section 4 describes the experimental setup and testing procedures; Section 5 discusses the EMG results; and Section 6 summarizes our key findings.

2. Passive cycling support

2.1. Supporting knee-extension moment

Fig. 2 shows a cycling leg–pedal diagram that defines the crank and knee angles. Crank angle θ_C is measured in the clockwise (CW) direction from the pedal crank top dead center (TDC). Knee angle θ_K indicates the orientation difference between the upper leg (thigh) and the lower leg (shank) on the sagittal plane. Adapted from a study of cycling biomechanics [4], the knee angle is expressed against the crank angle in Fig. 3(a). The maximum of 105° knee flexion occurs at a crank angle of around 330° prior to the crank TDC. With full knee extension, the minimum knee angle at 28° occurs prior to the crank bottom dead center (BDC). The original knee moment (uphill sitting) is also expressed against the crank angle in Fig. 3(b), where the knee-extension moment is positive and the knee-flexion moment is negative. The duration of the knee-extension moment takes half a cycle from a crank angle of around 80° prior to the crank TDC (360°) to 100° after the crank TDC. However, the magnitude of the knee-extension moment is dominant, with the maximum up to twice that of the knee-flexion moment.

Taking advantage of the unbalanced effort required from the knee extensor and flexor muscles, passive cycling support that stores energy from knee flexion and releases it to support knee extension was originally proposed by our group in Ref. [13]. Considering a torsion spring stiffness k_θ activating when knee angle θ_K is greater than starting angle θ_{K0}, the supporting knee moment τ_{Kspr}, varying with the knee angle, is written as follows:

$$\tau_{Kspr} = \begin{cases} k_\theta(\theta_K - \theta_{K0}), & \theta_K \geqslant \theta_{K0} \\ 0, & \theta_K < \theta_{K0} \end{cases} \tag{1}$$

Assuming that there is no human–device interfacing loss, the resultant knee moment τ_{Kres} required from the leg muscle under the influence of the supporting knee moment can be predicted from the original knee moment τ_{Korg} as follows:

$$\tau_{Kres} = \tau_{Korg} - \tau_{Kspr} \tag{2}$$

Applying a 0.25 N·m per degree torsional stiffness about the knee joint with a 55° starting angle, the supporting and resultant knee moments, respectively, can be obtained via Eqs. (1) and (2),

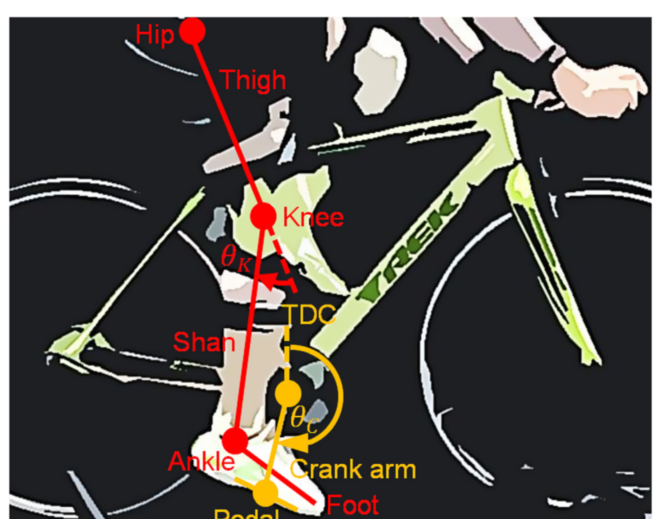

Fig. 2. Cycling leg–pedal diagram illustrating the crank and knee angles on the sagittal plane.