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Knee-Extension-Assist for Knee-Ankle-Foot Orthoses

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Abstract— **Individuals with quadriceps muscle weakness often have difficulty generating the knee-extension moments required for common mobility tasks. A new device that provides a knee-extension moment was designed to help individuals perform sit-to-stand and stand-to-sit. The knee-extension-assist (KEA) was designed as a modular component to be incorporated into existing knee-ankle-foot-orthoses (KAFO). The KEA loads a set of springs as the knee flexes under bodyweight and returns the stored energy as an extension moment during knee extension. The springs can be locked in place at the end of flexion to prevent unwanted knee extension while seated. When the affected leg is unloaded, the device disengages, allowing free joint motion. A prototype KEA underwent mechanical testing and biomechanical evaluation on an able-bodied individual during sit-to-stand and stand-to-sit.**

I. Introduction

Quadriceps muscle weakness (QMW) limits an individual's ability to provide sufficient knee-extension moments, thus increasing the risk of knee collapse while the affected leg is weight-bearing. QMW can be caused by peripheral neurological diseases, muscular diseases, central neurological conditions, [1] and muscle atrophy due to aging.

Many knee-ankle-foot orthosis (KAFO) designs support the knee joint and provide stability while the limb is load-bearing, during standing and walking [2-5]. However, many KAFO users are often unable to generate the required knee moments to perform common mobility tasks, such as sit-to-stand and stand-to-sit. Powered lower-extremity devices, such as the Berkeley Lower Extremity Exoskeleton [6], the Hybrid Assistive Limb 5 [7], and the Power Assisting Suit [8] can provide assistive knee-extension moments, but they use large actuators and require large power sources. As a result, these bilateral free-standing devices are predominately used to augment the strength of able-bodied users. These devices are also currently prohibitively expensive.

The Roboknee [9] is a unilateral powered lower-extremity orthosis that is, portable and provides an assistive knee-extension moment. However, the device is much heavier that typical KAFOs, has a short battery life, and precludes sitting, making it impractical for every-day use.

A small, light, and inexpensive knee-extension-assist (KEA) that does not rely on an exhaustible power supply could enhance independence and improve quality of life for individuals that have difficulty performing sit-to-stand and stand-to-sit. This paper presents the design, mechanical testing, and biomechanical evaluation of a novel KEA.

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II. Device Design

A. Design Objectives

The goal of this research was to design a device that could provide an external knee-extension moment to assist with stand-to-sit and sit-to-stand mobility tasks. For stand-to-sit, the KEA should resist knee flexion and cease to provide the extension moment once the user is seated. For sit-to-stand, the device should only provide an assistive moment when the user wants to rise from a seated position. When the affected leg is unloaded, the device should provide zero impedance to knee joint rotation. Zero device impedance permits free knee motion, allowing natural sitting and walking. The ideal device would have minimal size and weight. To avoid large and heavy actuators and power supplies, the KEA should use passive components to generate the extension moments. The KEA should be located proximally, to minimize inertial effects of the device weight on the limb. The novel device should also be modular for incorporation into any KAFO. Modularity would keep device cost low because the KEA would be added to an individual's existing orthosis and thus would not require the purchase of a new KEA-specific orthosis.

Design criteria for maximum KEA size, weight, and percent assistance were determined through consultations with professional orthotists and assistive device design experts. Weight and medio-lateral thickness were highly important to avoid prospective-user rejection of the device. A maximum KEA thickness of 20 mm and a maximum KEA weight of 0.7 kg were recommended. The design criterion for maximum anterior-posterior width was 70 mm and for proximal-distal length was 200 mm. The desired maximum knee-extension-assist moment, provided by the KEA to the affected leg, was 39 Nm at a knee angle of 90°. This moment corresponds to 50 % of the extension moment required from one leg during sit-to-stand, plus one standard deviation, for a 90 kg individual [10]. Though minimizing size and weight were priorities, the device must also be sufficiently robust to require no more than yearly servicing.

B. Design Methods

Based on the design objectives and design criteria, a KEA was designed with passive spring components to provide a knee extension-assist moment (Fig. 1). Three parallel springs were used as opposed to a larger single spring to maintain minimal device thickness. The device consists of two assemblies linked by wire cables.

The spring case assembly is attached to the upper KAFO upright, located on the thigh portion of the orthosis. The three compression springs are housed in parallel in the spring case. The U-beam provides a surface for compressing all three springs in unison. The U-beam also acts as part of the locking mechanism that holds the springs in compression, while the user is seated. The locking rod, the other locking mechanism component, has multiple ratchet notches cut into one side, for stand-to-sit, and a single long notch cut into the other side, for potential use during ramp walking (Fig. 2). The locking rod spring applies a lateral force to the head of the locking rod via the locking rod spring pin. When the U-beam moves distally during knee flexion, the force from the spring pin on the locking rod causes the notches to engage automatically with the edge of the U-beam slot. The locking rod locks the springs in compression since the notches prohibit proximal U-beam movement. With the springs locked in place, no knee-extension moment is provided by the KEA. To unlock the springs, the locking rod is manually displaced to disengage the notch from the U-beam (Fig. 2d).

When the braced leg is loaded by bodyweight, a knee-flexion moment causes tension in the distal cable, which compresses the springs (Fig. 1). Load-bearing knee flexion occurs during stand-to-sit. When weight is placed on the braced leg, an air bladder underneath the foot generates pressure that activates a pneumatic actuator in the knee disk assembly (attached to the lower KAFO upright). When activated, the pneumatic actuator extends the sliding lock into a notch in the knee disk. This locks the knee disk and couples the disk to the KAFO, preventing knee-disk rotation. When the knee flexes with the knee disk locked, the distal cable wraps around the knee disk and pulls distally on the proximal cables, which in turn pull distally on the U-beam. When the distal force on the U-beam is larger than the spring extension force, the U-beam moves distally and the springs compress further.

When weight is removed from the braced leg, the actuator retracts the sliding lock and the knee disk is allowed to rotate freely. The knee disk is thus uncoupled from the KAFO and the KEA allows zero impedance to knee-joint rotation, as desired.

To accommodate seats of different heights, the multiple ratchet notches permit the springs to be locked at different knee angles. For potential use in incline walking, the single long notch allows free knee motion below a preset knee angle and provides an extension moment at a greater angle. The preset angle can be set to the knee angle at foot-strike for incline walking, and thus allow for more natural incline gait.

The KEA had a total weight of 0.67 kg, maximum thickness 27 mm, and maximum width 70 mm. The device had a total length of 351 mm (106 mm long spring case assembly, 150 mm long knee disk assembly, and 95 mm gap spanned by the wire cables).

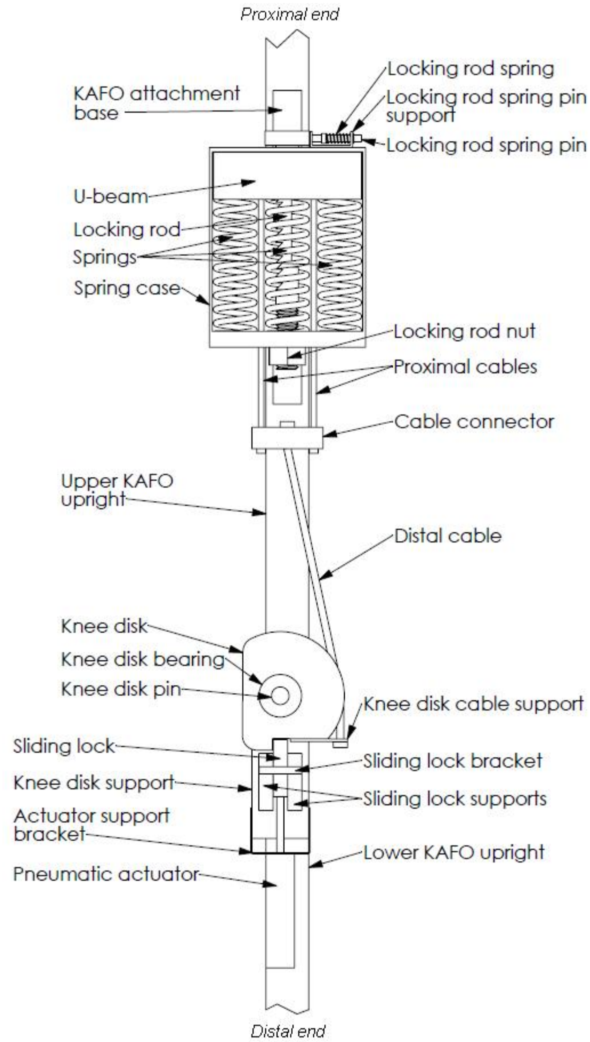

Fig. 1. Knee-extension-assist (KEA) components.

III. Evaluation and Results

A. Mechanical Testing

The KEA spring force during spring compression and the extension moment provided by the KEA during joint flexion and extension were measured on an Instron 4482 Universal Tester with a KEA prototype (Fig. 3). For all tests, ten trials were performed.

The maximum spring force, from directly loading the distal cable, averaged 1334.6 ± 2.7 N. The maximum force was measured at 40 mm of spring compression, which corresponded to the compression at a seated-user knee angle of 90°. The maximum spring force was 89% of the theoretical 1500 N maximum.

By loading the upper and lower uprights in the testing machine, the extension-assist moment was determined. In spring compression during KEA flexion, the average extension moment at 90° was 42.9 ± 0.46 Nm, 5.4 Nm larger than the theoretical maximum moment provided by the KEA and 8% more than the design target value. During KEA extension, the average extension-assist moment at 90° was 28.4 ± 0.28 Nm, 76% of the theoretical device performance and 36% of the required sit-to-stand extension moment for a 90 kg individual.

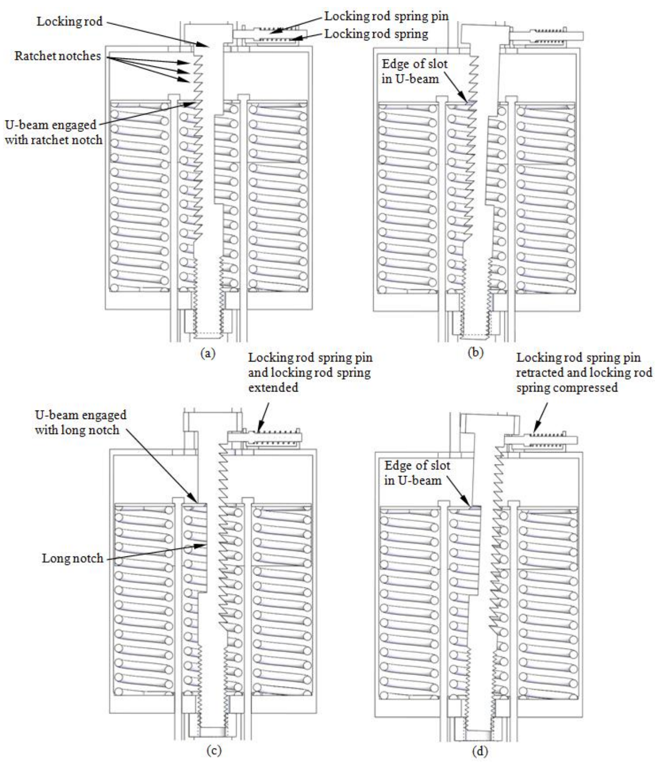

Fig. 2. Cross-section of the spring case assembly showing the U-beam (a) engaged with a ratchet notch to lock the springs in compression for stand-to-sit, (b) disengaged with a ratchet notch to permit spring extension during sit-to-stand, (c) engaged with the long notch to maintain the preload for ramp walking, and (d) disengaged with the long notch to permit removal of the ramp walking preload.

B. Biomechanical Testing

One able-bodied, 70 kg participant performed sit-to-stand and stand-to-sit, with the KEA active and deactivated (free knee motion at all times). The KEA was mounted onto a traditional KAFO (Fig. 4). Ground reaction force data for each foot and 3D motion data were collected using two side-by-side force plates and a seven-camera Vicon motion capture system, tracking a six degree-of-freedom marker set on the trunk, thighs, shanks, and feet. The force and motion data were used to calculate joint kinematics and dynamics. Surface electromyography (EMG) data were collected for the rectus femoris, vastus medialis, and gluteus maximus of both legs, and the biceps femoris of the unbraced leg to determine muscle activation levels. Raw EMG data were rectified, filtered using a moving average with a 50 ms window size, and normalized to percent maximum voluntary contraction. Kinematic, dynamic, and muscle activation level results were compared between trials with and without the extension-assist to examine the effect of KEA use on sit-to-stand and stand-to-sit.

The KEA extension assistance allowed the participant to perform both stand-to-sit and sit-to-stand more slowly and thus in a more controlled manner than when unassisted. Mean hip and knee angular velocities were reduced by 21% with the extension-assist. Maximum knee moments varied little between unassisted and assisted trials.

For stand-to-sit, the knee-extension assisted trials had a mean maximum knee-extension net joint moment of 55 Nm, which was 7% greater than unassisted knee moments. The KEA provided a mean maximum knee-extension moment of 45.5 Nm, 82 % of the maximum net joint moment.

For sit-to-stand, the mean maximum knee-extension net joint moment was 50.5 Nm, a 1% decrease from unassisted trials. The KEA provided a mean maximum assistance of 28.5 Nm, 56% of the net joint moment. Quadriceps muscle activation levels decreased an average of 38% with KEA use, while quadriceps muscle activation levels for the unbraced limb increased an average of 3%.

Fig. 3. Prototype KEA used in testing.

Fig. 4. Prototype KEA mounted on a KAFO for biomechanical testing.

IV. Discussion

The KEA successfully provided knee-extension moments to assist with sit-to-stand and stand-to-sit. For sit-to-stand, the KEA provided 28.5 Nm which was 56 % of the required knee-extension moment for the 70 kg participant. Biomechanical tests showed a reduction in quadriceps activation by 38% when using the KEA. The target sit-to-stand assist of 39 Nm (50 % for a 90 kg individual) was not achieved. The design criterion for the KEA weight was met and the size was very close to the design targets. The thickness was 7 mm greater than the design target, but this was determined to be acceptable by the assistive-device experts. The total KEA length was greater than the design criterion, but each assembly was below the target length and located on separate parts of the orthosis.

Mechanical testing showed that the KEA provided a lower knee-extension moment than theoretical calculations, due to two main factors: lower spring force than the manufacturer's specifications for a given compression and friction. The measured spring force was 11% lower than expected for 40 mm of compression, causing a reduction in the overall KEA extension-assist moment. Due to friction between the proximal cables and the distal end of the spring case when the cables were pulled during flexion and released during extension, the maximum knee-extension moment was 14.5 Nm lower than the maximum flexion moment. Guides or rollers could reduce the force between the proximal cables and the distal end of the spring case to reduce friction in the next design iteration. Upon addressing the issue of friction, a 5% improvement in extension assistance could be expected without further modifications.

The total prototype cost was estimated at $3114, with a materials cost of $114. Outsourcing machining and assembly and a production run of 100 units could considerably reduce the cost to less than $1400, a much more acceptable cost for a passive knee-extension-assist device.

V. Conclusions

A new knee-extension-assist was designed for individuals with quadriceps muscle weakness to assist in common mobility tasks. In biomechanical tests of an able-bodied person, the KEA successfully provided a knee-extension moment to assist both sit-to-stand and stand-to-sit, allowing for decreased quadriceps muscle activation levels while permitting slower and thus more controlled task completion.

Future research will reduce cable-case friction and biomechanical testing will be continued to examine the KEA effects on incline walking and on individuals with QMW.

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