# Design and Evaluation of Passively Powered Knee Exoskeleton (PPKE) for Squat Lifting


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**Abstract**

This paper proposes a passively-powered knee exoskeleton (PPKE) to provide power assistance during squat lifting of objects from the ground. The passive powering mechanism is designed to capture 20% of the waste mechanical energy available at the biological knee joint during decent phase and to release the stored energy in ascending phase in a complete squatting cycle. The effectiveness of proposed system was verified by experiments using surface electromyography (sEMG) signals under different test conditions. PPKE reduced the peak root-mean-square averages of sEMG signals of knee extensor muscles by 15% during squatting.



*Keywords*: knee exoskeleton, energy harvesting, passive mechanisms, squatting.


## 1. Introduction

Exoskeletons systems are mainly developed focusing on two different user groups, namely physically incapacitated population and able-bodied population.[1] According to literature, limited number of full lower-extremity exoskeletons or joint-level exoskeletons have been developed to carry out work related tasks by providing power-assistance.[1] The application areas are mostly limited to either locomotion assistance, tool holding or lift assistance.[1] Although functionality of autonomous externally powered robotic exoskeletons are satisfactory, wearer's performance is notably compromised.[2] In particular, such devices struggle to reduce the human effort. The main cause is the inability of the system to match the complex kinematic and kinetic requirements demanded by human biological joints. Here, limitations of the complementing technologies such as gear drives, actuators, sensors, and power sources resulted in formulation of bulky and heavy electromechanical systems that is slow in operation.[2]

Alternatively, recent research studies indicate that passive-dynamic powering systems are effective at metabolic cost reduction and enhancing overall human performance.[3] The body-powered exoskeletons are energetically autonomous and soft lightweight transmissions provide superior biomechanical compliance.[3] However, performance and endurance augmentation through biomechanical energy harvesting still remains an open challenge. A wearable energy harnessing and releasing system that is capable of recycling the waste mechanical energy dissipated in the human body can help reduce metabolic energy consumption during activities of daily living.[3] Complementing limb muscles energetically will augment the joint strength and moreover enhances endurance limits of muscle fatigue. As a result, exoskeleton wearer's productivity will improve over a period of time.

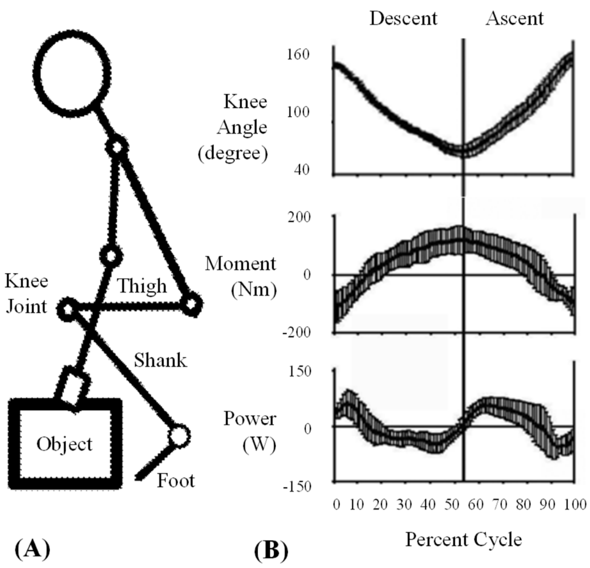


Fig. 1. Technique (A) and biomechanical data (B) of squatting adapted from Ref. 4 and 5.

In this context, a design of a passively powered knee exoskeleton is proposed to provide power assistance during squat lifting of objects from the ground (see Fig. 1(A)). The bio-inspired powering system is designed to recycle the mechanical energy at the knee joint during descending and ascending phases in sequence to help lift wearer's own mass during a squatting cycle. The knee exoskeleton shall not pose any restrictions for walking and passively controlled locking mechanism only engages during a lifting task to capture and release mechanical energy. The design considerations for the knee exoskeleton targeting squat lifting and walking are described in section 2. The design details of the exoskeleton and the working principle of the passive powering mechanism is presented in section 3. The device was evaluated using surface muscle signals while performing semi-squats under different test conditions and results are compared in section 4.

## 2. Design Considerations

Load lifting is a typical industrial activity that is energy intensive.[4] It involves moving an object from one position to another while traversing in vertical and/or horizontal directions. Considering the requirements for squatting as well as for walking, design considerations in relation to the knee joint were identified under functional and biomechanical points of view.

### 2.1. *Functional*

Among different lifting techniques the most commonly used approaches are squat lifting and stoop lifting.[5] The knee exoskeleton is envisioned to assist wearer's knee joint to lift moderately heavy loads. Hence squat or semi-squat lifting is selected as the technique in focus for developing the proposed device, as it also promotes use of biomechanically more favorable approach.[5]

The device should essentially allow the wearer to ambulate freely in-between lifting tasks and pose no restriction for knee flexion during swing phase of human gait. The knee joint's limits of ranges of motion over the sagittal plane is measured to be -$10^0$ of hyper-extension and $140^0$ of flexion.[4] According to gait data, [6] maximum flexion of knee joint during swing phase is $60^0$.

### 2.2. *Biomechanical*

Muscle activity of thigh muscles are of interest when performing a squatting cycle.[7] Notably, the quadriceps show greater muscle activity than the hamstrings during the complete ascent phase.[4] The focus is to relieve muscle groups of the burden of having to concentrically and eccentrically work to control motion.

Biomechanical data during squatting (see Fig. 1(B)) were analyzed to identify the role of lower limb joints to generate the mechanical power for lifting.[4] The notion is to recover the potential energy dissipated as a result of lowering the center of gravity of human body which henceforth referred to as passive energy. Here, hip and knee joint dissipate energy through eccentric contraction of the major muscle groups on lower extremity during entire decent phase (2 seconds period).[4] Similarly, during the entire ascending phase (2 seconds period), energy is generated while undergoing concentric contraction.[4] In contrast, during initial stages (0-15% cycle) of the decent phase, the knee flexor muscles act concentrically followed by extensor muscles acting eccentrically for the remainder of the descent (15-53% cycle).[4] The positive power is assumed to unlock the knee to initialize the descent. Throughout the start of the ascending phase (53-85% cycle) power is generated by knee extensor muscles by acting concentrically.[4] However, towards end of the phase (85-100%) knee flexor muscles started to dissipate energy gathered using knee flexors acting eccentrically.[4] Negative power is assumed to help prevent undesirable levels of hyperextension of knee joint.

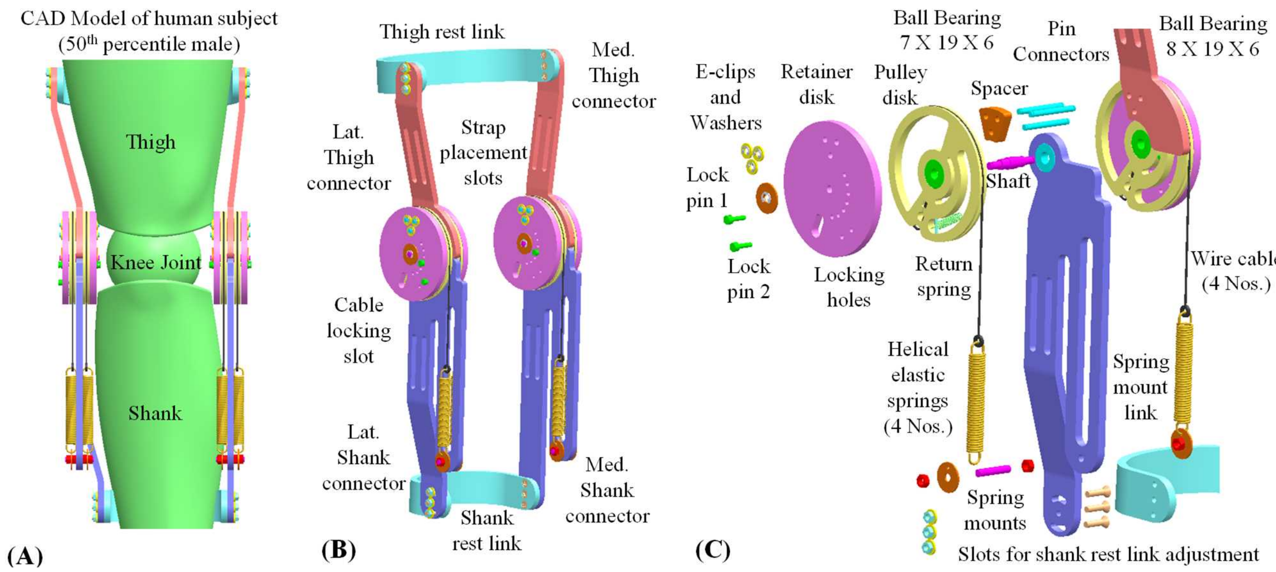


Fig. 2. PPKE on human model (A), PPKE with passive-powering mechanism (B), and exploded-view of PPKE (C).

## 3. Design of Passively Powered Knee Exoskeleton

Design objectives were to develop a simple, lightweight and affordable knee exoskeleton with ergonomic conformance and provide power assistance during squat lifting while posing least resistance for walking. Design specifications were derived for 50$^{th}$ per. male population.

### 3.1. *Material Selection*

Acrylic glass is considered as material of choice for developing the PPKE. Acrylic glass sheets can be easily cut in to various contours using computer numerically controlled laser cutting machines and formed in to complex shapes using thermoforming methods at an affordable cost. Acrylic is also considered to be non-toxic to human skin and environmental friendly. Thus making it a suitable option that has not been previously explored in exoskeleton development. In order to counter the lower tensile strength of acrylic material (approx. 70 MPa), the design of the exoskeleton should be satisfactory. The flow of forces through the acrylic structure should be entirely compressive in nature. Bending or shear forces have been eliminated by effectively utilizing the symmetricity of the design.

### 3.2. *Structural System*

A computer-aided design model of a human subject was prepared using scanned data. The sizing and shaping of the structural system was then performed over the frontal and sagittal planes (see Fig. 2(A)). In order to avoid collision of thigh rest and shank rest at full squat position, shank connectors were designed with longer legs (see Fig. 2(B)). Thigh connectors were shorter in length to minimize interference at the medial side. The structure is held firmly on the limb segments using four Velcro straps placed through the linear slots on the connectors. Resting links can be easily replaced to accommodate varying limb cross-sections, if needed. The curved slots at the hinged end of the rest links provide the ability to adjust relative angular position of rests with the connectors. The slender acrylic structure assume the body shape over the frontal plane if contact forces are significantly high. The compliant structure hence reduce the possibility of internal joint injuries due to misalignments.

### 3.3. *Passive Powering Mechanism*

It is assumed that industrial workers are more likely to assume a semi-squat position during lifting tasks. Hence, the design has been planned for parallel-squat operation, where the knee bends approx. $70^0$ to $100^0$. In addition, wearer need to have freedom to ambulate at normal walking speed[6] (1.3 m/s). Consequently, the knee flexion should be left unconstrained up to $60^0$. The springs should engage to capture the negative energy when the knee flexes beyond this limit. Assuming the maximum knee angle happens up to $90^0$ in a regular squat lifting task, the effective angular displacement of $30^0$ can be utilized to energize a collection of linear elastic elements.

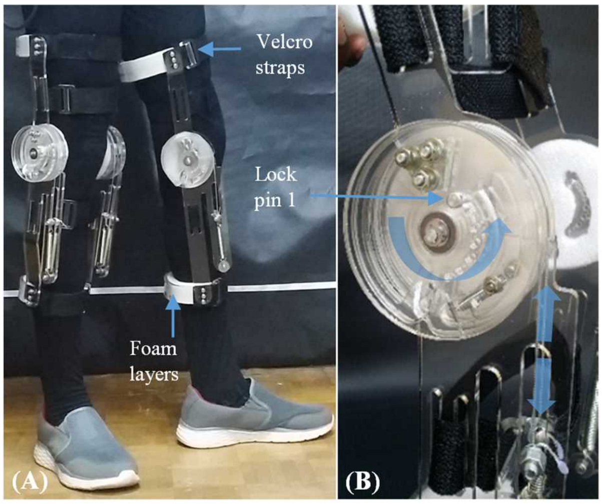


Fig. 3. Working model of PPKE on male subject (A) and close-up view of passive powering mechanism (B).

The proposed mechanism to achieve this function is comprised of energy capturing springs held parallel to shank, wire cables, pulley disks, smaller return springs and pins (see Fig. 2(C)). The pulley disks are fitted on bearings and are free to rotate about the axis of the shaft. However, by form the mechanical limits are in place to prevent rotation of the pulley in opposite or counter-clockwise direction. The clockwise rotation will be prevented by the smaller return springs that is held between the retainer disk and the pulley disk using set of pins. The lock pin 1 can be inserted in to a pulley disk locking hole that are spaced $20^0$ apart over a range of $0^0$ to $120^0$. If the lock pin is removed the knee joint can be easily flexed without notable restriction from the exoskeleton. Here the stiffer springs act as a rigid body causing the flexible return springs to extend. As a result the pulley disk will rotate in a clockwise sense to maintain wire cable length unchanged. When the knee traverse back to the rest position, the return spring gives way and the pulley disk returns to its initial position. By placing the lock pin 1 in position number-one ($0^0$) the pulley disk gets immediately locked with retainer disk. Consequently, when the knee gets flexed the stiffer springs starts to load gradually capturing energy of decent. If the lock pin is inserted in to position number-two ($20^0$), the knee is free to flex up to the same limit and the pulley disk will come to a stop as the lock pin 1 traverse and reach the mechanical limit over the curved slot. If PPKE is supposed to allow free flexion during walking, the lock pin 1 should be inserted in position number-four ($60^0$). As a result, during rest of the decent phase up to $90^0$, available passive energy is harnessed.

The spring selection should be done to maximize the energy retention. Considering the limited tensile strength of acrylic glass and the overall size of the device, the maximum force applied on a single spring is limited to 150 N. The limits were determined by analyzing the stress distribution over the critically loaded acrylic components of the exoskeleton. In particular, the shank connectors and pulley disks were subjected to compression loadings and torsional loadings respectively. Finite element simulation provided an insight on the safety limits for the same. To accommodate manufacturing and material defects, the factor of safety were maintained at 1.5 and above for all acrylic parts. The structure and powering mechanisms are capable of withstanding such heavy loads as a consequence of symmetrical positioning of passive actuators.

The energetic response of the proposed passive energy recycling system can be mathematically modeled as follows. If a bilateral system with elastic helical springs having 5875 N/m stiffness coefficient is used, the total strain energy stored in the system over a $30^0$ knee angle can be determined using,

$$E = \frac{1}{2} k x^2 \qquad (1)$$

Where, $k$ – stiffness coefficient (N/m), $x$ – spring extension (m) and $E$ – accumulated energy (J or Nm).

The total energy dissipated and generated at the knee joint during decent and ascent phases from biomechanical studies were found to be 45 J and 50 J respectively. The selected springs thus have the capacity to collectively (eight springs on two PPKE units) capture and return approximately over 20% of total mechanical energy required considering loses due friction. Here, the maximum spring force is evaluated to be approx. 133 N.

## 4. Evaluation of PPKE

Overall mass of PPKE (see Fig. 3) is approx. 900 g inclusive of helical springs made of spring steel. In order to evaluate the effectiveness of the proposed system, a preliminary study was set up and conducted with a healthy average male subject (Age: 37 years, Weight: 72 kg, Height: 177.8 cm). Test protocols were developed to measure relative changes of muscle activity for squatting

- without the exoskeleton (WO),
- with exoskeleton minus passive powering (UPO),
- with exoskeleton having passive powering (PO).

### 4.1. *Experimental Set-Up*

Squatting exercises were performed to monitor possible benefits of using the passive energy recycling system to enhance strength and improve endurance limits of thigh muscles. Each of the tests were conducted for a period of 100 seconds with an ascent-descent cycle of four seconds that ranged over $0^0$ to $100^0$ knee angle. Wired surface electromyography (sEMG) electrodes connected to Bagnoli Desktop EMG system were placed on muscle bellies of rectus femoris (RF) and bicep femoris (BF) muscles on both limbs to measure the electrical signals.

### 4.2. *Results and Discussion*

The root mean square (RMS) average of the electrical potential of RF and BF muscles were post-processed using raw sEMG signals. When considering the first ten squatting cycles (see Fig. 4(A)), the RF muscles show a decrease in peak RMS values when wearing exoskeleton with the passive powering system by 15%. Alternatively, during the last ten cycles (see Fig. 5(A)), the peak RMS values are greater when wearing the exoskeleton with or without the powering system. Interestingly, BF muscles respond in an opposite manner as the cycles elapsed. During the first ten cycles of squatting (see Fig. 4(B)), exoskeleton tend to increase the peak RMS values than the norm, which is especially evident when it is worn without the assistance of the powering system. However, towards the latter end, in particular during last ten squatting cycles, the peak RMS values when wearing the exoskeleton remain consistent while for the case of no exoskeleton a notable increase in noted (see Fig. 5(B)). Therefore, the preliminary study has revealed that PPKE has both positive and negative impact. Considering the relative significance of quadriceps muscles to perform squat lifting, device has successfully satisfied its purpose.

## 5. Conclusion

PPKE is energetically autonomous, adaptable and nimble thus making it ideal for industrial use. Working model served as a proof of concept, but clinical testing with metabolic cost estimation over wide range of participants is essential to assess the design for further improvements.

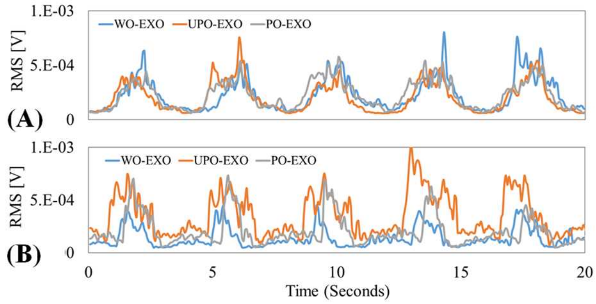


Fig. 4. RMS values of (A) RF and (B) BF muscles on right lower limb during first five squatting cycles.

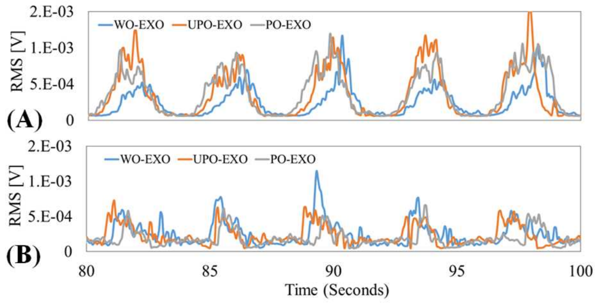


Fig. 5. RMS values of (A) RF and (B) BF muscles on right lower limb during last five squatting cycles.

**Acknowledgements**

Authors acknowledge Senate Research Council of University of Moratuwa (Grant No. SRC/CAP/2014/08).

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