DEVELOPMENT OF A BIO-INSPIRED LOWER EXTREMITY EXOSKELETON WITH A PASSIVE-POWERING SYSTEM

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Doctor of Philosophy in Biomedical Engineering

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Thesis submitted in partial fulfillment of the requirements for the degree
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DECLARATION

I declare that this is my own work and this Thesis does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or Institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text. I retain the right to use this content in whole or part in future works (such as articles or books).

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The supervisors should certify the Thesis with the following declaration.

The above candidate has carried out research for the Doctor of Philosophy in Biomedical Engineering Thesis under our supervision. We confirm that the declaration made above by the student is true and correct.

Name of Supervisor: Prof. R.A.R.C. Gopura, University of Moratuwa, Sri Lanka

Signature of the Supervisor: Date: 02 / 01 / 2024

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Signature of the Supervisor: Date: 02 / 01 / 2024

DEDICATION

To my loving parents,
late Mr. Hemachandra Ranaweera and Mrs. Jayanthi Samaradiwakara,
and my loving family
who keep lifting me and inspiring me in every aspect of my life.

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ABSTRACT

Manual handling is an indispensable activity in any occupational setting. It is any activity that requires the use of human force for lifting, carrying or moving an object. Such repetitive and tiring tasks may cause work-related musculoskeletal disorders and adversely affect productivity of manual workers. In that context, the goal of this research was to develop a wearable device or exoskeleton for providing lift assistance during squat lifting. The outcome of the research was to reduce human effort and improve human comfort. The objectives or contributions of the work include conceptualization of a biomechanical energy management approach for squat lifting, development of an anthropomorphic passively powered multi-joint lower extremity exoskeleton for lift assistance, and investigation of the effectiveness of the proposed lift-assist system. Initially, a literature review was conducted on lower extremity exoskeletons to identify the research gap. The analysis on the state-of-the-art of exoskeletons revealed the need for introducing sustainable powering systems and minimizing interference issues at the human robot interface. Next, the biomechanical energy management approaches were conceptualized. The work includes the biomechanical modelling of squat lifting activity and the investigation of feasibility of proposed energy recycling strategies. Subsequently, design of anthropomorphic mechanical structure for the exoskeleton, design of bio-inspired passive-dynamic powering system for ankle and knee joints, and design of passive and active controlling systems were carried out. Thereafter, prototype of the ankle knee exoskeleton was fabricated as per the design specifications. Finally, performance with the proposed lift-assist system was experimentally evaluated. Results from the biomechanical analysis show that, when wearing the exoskeleton, energetic consumption at ankle and knee got reduced by 23-24% and 38-40%, respectively. The effectiveness of proposed system was also verified by evaluating muscle activities of lower and upper leg. All in all, the ankle knee exoskeleton with proposed passive actuators made a positive influence on the lower limb's muscular system. Therefore, the proposed exoskeleton has proven to be an effective solution for industrial use.

Keywords: Bio-inspired Design, Biomechanical Energy Harvesting, Lower Extremity Exoskeleton, Leg/Squat Lifting, Motion Analysis, Passive Actuator, Power Assistance, Surface Electromyography

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LIST OF ABBREVIATIONS

Abbreviation	Description
3D	three-dimensional
AB/AD	abduction/adduction
AD	ankle device
AE	ankle exoskeletons
AFO	ankle foot orthosis
AKE	ankle knee exoskeleton
AMMR	Anybody Managed Model Repository
AMS	Anybody Modelling System
AoR	axis of rotation
AWW	ascend with weight
BF	biceps femoris
BW	bodyweight
CAD	computer-aided design
CAS	computer algebra systems
CI	confidence interval
CNC	computer numerically controlled
CoM	center of mass
CoR	center of rotation
CS	current sensor
DC	direct current
DF/PF	dorsiflexion/plantarflexion
DoF	degrees of freedom
DWW	descend with weight
EMG	electromyography
FL/EX	flexion/extension
FSRs	force sensitive resistors
GL	gastrocnemius lateral
GM	gastrocnemius medial
GRF	Ground Reaction Force
GRS	global referencing system
GUI	graphical user interface
HE	hip exoskeleton
HRI	human-robot interface

Abbreviation	Description
IN/EV	inversion/ eversion
IR/ER	internal/ external rotation
JRF	joint reaction force
KD	knee device
KE	knee exoskeleton
LCs	load cells
LEE	lower extremity exoskeletons
LSM	link-segment model
NIOSH	National Institute for Occupational Safety & Health
OPRA	Occupational Physicians Reporting Activity
PB	peroneus brevis
PCA	principal component analysis
PD	proportional-derivative
PL	peroneus longus
POTs	potentiometers
RF	rectus femoris
RMS	root mean square
RoG	radius of gyration
RoM	ranges of motion
SE	semitendinosus
sEMG	surface EMG
SO	soleus
TA	tibialis anterior
THOR-GP	Health and Occupation Research network of General Practitioners
UART	Universal Asynchronous Reception and Transmission
VL	vastus lateralis
VM	vastus medialis
WE	without exoskeleton
WRMSD	work-related musculoskeletal disorders

LIST OF APPENDICES