Evaluation of a Soft Robotic Knee Exosuit for Assistance in Stair Ascent

by

Niveditha Muthukrishnan

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Graduate Supervisory Committee:

Panagiotis Polygerinos, Chair
Thurmon Lockhart
Daniel Peterson

ARIZONA STATE UNIVERSITY

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ABSTRACT

Muscular weakness is a common manifestation for Stroke survivors and for patients with Anterior Cruciate Ligament reconstruction leading to reduced functional independence, especially mobility. Several rigid orthotic devices are being designed to assist mobility. However, limitations in majority of these devices are: 1) that they are constrained only to level walking applications, 2) are mostly bulky and rigid lacking user comfort. For these reasons, rehabilitation using soft-robotics can serve as a powerful modality in gait assistance and potentially accelerate functional recovery. The characteristics of soft robotic exosuit is that it's more flexible, delivers high power to weight ratio, and conforms with the user's body structure making it a suitable choice. This work explores the implementation of an existing soft robotic exosuit in assisting knee joint mechanism during stair ascent for patients with muscular weakness. The exosuit assists by compensating the lack of joint moment and minimizing the load on the affected limb. It consists of two I-cross-section soft pneumatic actuators encased within a sleeve along with insole sensor shoes and control electronics. The exosuit actuators were mechanically characterized at different angles, in accordance to knee flexion in stair gait, to enable the generation of the desired joint moments. A linear relation between the actuator stiffness and internal pressure as a function of the knee angle was obtained. Results from this characterization along with the insole sensor outputs were used to provide assistance to the knee joint. Analysis of stair gait with and without the exosuit 'active' was performed, using surface electromyography (sEMG) sensors, for two healthy participants at a slow walking speed. Preliminary user testing with the exosuit presented a promising 16% reduction in average muscular activity of Vastus Lateralis muscle and a 3.6% reduction on Gluteus Maximus muscle during the stance phase and unrestrained motion during the swing phase of ascent thereby demonstrating the applicability of the soft-inflatable exosuit in rehabilitation.

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INTRODUCTION

In the United states, about 22% of the aged population face disability, 13% of which are due to functional mobility with serious difficulty in performing activities like walking or climbing stairs.[1] An increasing number of disease conditions lead to partial or complete loss of muscular ability, Stroke and Anterior Cruciate Ligament (ACL) rupture being the most common ones.[2][3]

Stroke is known to cause paresis-weakness of muscles or plegia -complete loss of muscle action, in upper and/or lower limbs depending on the severity of the stroke episode and locus of brain damage. About 65% of stroke survivors are said to have reduced ambulation capacity of which 50% of them have impaired muscle function.[4] According to reports post-stroke, gait patterns often have deviations in kinetic, kinematic and spatio-temporal characteristics such as reduced walking speed, decreased ability to produce moment of force, decreased muscle power in quadriceps, and difficulty in maintaining knee joint stability during walking.[5][6]

The second most common condition being ACL injury, reports describe that there are between 100,000 to 200,000 ACL ruptures per year in the United States. A common consequence of ACL is the quadriceps and hamstrings weakness in the injured limb that persists when individuals return to activity after ligament reconstruction. There can be a deficit of 5-40% in quadriceps strength and about 27% in the hamstrings post ACL reconstruction.[3]

With muscular weakness caused by the above-mentioned pathologies, limb muscles fail to fully activate during contraction to produce sufficient muscle torque for mobility. This prevents an individual from performing activities of daily living in an independent manner and calls for rehabilitative assistance.

Stair climbing is an integral part of everyday mobility both at home and in the community. Considerable assistance or rehabilitation therapy is needed for people with lower limb disability, especially considering the risk of falls and the amount of muscular effort required to carry out this task.[7] The peak knee flexion moments during stair ascent have been reported to be three times greater than those of level walking.[8] For this reason, stair ambulation is more difficult to do for those with decrements in motor function, balance impairments, and/or reduced lower limb function. Further biomechanical analysis of stair negotiation could enhance our understanding of the requirements of this demanding task and help develop appropriate clinical interventions to improve performance on stairs.

Though there has been a number of exoskeletons and assistive devices designed to assist level walking, there isn't still adequate literature on devices to assist stair climbing activity.[9][10][11] Therefore, determining the cause of and developing effective strategies to address muscle weakness are important.

Soft-robotics field is characterized by the application of non-rigid structures that can be made out of any material that is inherently more flexible and has less weight. In the conventional field of "exoskeletons" the materials are usually made of metals, hard plastics, or other characteristically rigid materials. The novelty of Soft-Robotics includes the capability of them to be more flexible, portable, provide unobtrusive and compliant means to interface with the human body.[12][13]

This field is rapidly expanding and gaining popularity as the technology is comfortable for the user and has high power to weight ratio. The greatest developments made in this field are those in the new design of the actuators and materials that exist in the rehabilitation field.

Exosuits made from these robots will augment the capabilities of healthy individuals in addition to assisting those with muscle weakness or patients who suffer from physical or neurological disorders. As compared to a traditional exoskeleton, these systems have several advantages: the wearer's joints are unconstrained by external rigid structures, assisting suit is capable of producing sufficient energy to the joint and the also it is extremely light.

The goal of this research is to explore the implementation of a lightweight, low-cost, body compliant soft robotic exosuit that can provide complementary assistance to the knee muscles in stair ascent. The exosuit is an undergarment that uses soft actuator (a pneumatic device that inflates and deflates to cause motion when pressurized with a fluid) technology for assistance during locomotion. This exosuit will be an affordable choice that offers bursts of assistive energy directly to the biological joint in need, while working in synergy with the limb muscles to facilitate motion. The fundamental purpose of this exosuit is to compensate the lack of muscular force in the joint, support the user’s limb to minimize loading on the affected limb and also serve as a modality for rehabilitation therapy.

CHAPTER 2

BACKGROUND

2.1 Existing Technology

2.1.1 Active Devices

A. Battery Operated Stair Lift

Figure 1. Commercially available battery powered indoor stair lift (Cortesy-Ameriglide)

Battery powered stair lifts are commercially available that can be installed along the railings of the staircase, in which the user can sit and travel up or down a flight of stairs. It is commonly utilized to assist climbing for the elderly. This lift can be used for up to 16 stairs along one stretch and requires multiple installations for higher levels. The cost involved in purchasing and installing this equipment approximately varies between $2000-$3500 which makes it an expensive choice. The stair lift is also confined to indoor applications, requires high level of maintenance and is not suitable for rehabilitation therapy.

2.1.2 Passive Devices

A. Universal stair climbing walker

Figure 2. Commercially available stair climbing walker

The most commonly used stair climbing assists are walkers consisting of a lightweight, three-sided metallic/polymer-based frame that is self-standing on four legs, must be lifted and moved forward while walking. Walkers may or may not telescope to adjust the walker's height to conform to the physical characteristics of the user. Such standard walkers can provide a firm support when used on level surfaces. However, are highly unstable and requires some degree of upper body strength and cognitive ability to use safely and can result in a fairly abnormal gait.

B. Open Patellar knee support

Figure 3. Commercially available open patellar knee brace

Open patellar knee support is an adjustable-tension strap designed to support sprained/ arthritic knee in increasing joint flexibility. This product contains a neoprene blend with natural rubber latex which may cause allergic reactions or skin irritations when used for longer periods of time.

Though the above described passive devices are available at low cost, they do not provide assistive force for real-time assistance to the user, they are designed to only help in supporting the body as they move without damaging the affected limb further. Conventional systems provide stability during walking by maintaining the knee in a fixed position and are not adaptable to individual walking patterns, this results in unnatural gait patterns and more stress in the joints. These systems have little value for retropulsion (falling over backwards while still holding their walker) and propulsion.

A comparison of the soft robotic exosuit used in this research with the commercially available devices for stair mobility was performed using a Pugh chart. Each design was ranked and a final score was generated to evaluate the most suitable choice.

Table 1. A completed Pugh chart to evaluate the exosuit against commercially available assist devices.

Criteria	Stair Lift	Stair climbing Walker	Open Pattelar Knee Brace	Soft Robotic Exosuit
Comfort	+	-	+	+
Mobility	+	+	-	+
Ability to produce joint moment	-	-	-	+
Support	+	0	+	+
Body Conforming	-	-	+	+
Suitable for rehabilitation therapy	-	+	0	+
Weight	-	+	+	+
Cost	-	+	+	+
Sum (+)	3	5	5	8
Sum (-)	5	3	2	0
Final Score	-2	2	3	8

The table summarizes some of the important criteria that are considered in evaluating a stair assist device. The Pugh chart clearly shows that the soft robotic exosuit will be the preferred choice keeping in mind the comfort it offers, being made of completely soft lightweight and flexible components, to the user. With low purchasing cost and its ability to provide assistance thereby reducing the knee flexion moment required by the user, the exosuit serves instrumental in rehabilitation therapy. The deductions made from the above table proves that the soft inflatable exosuit is an ideal choice for knee assistance.

2.2 Literature Review

In order to gain a thorough understanding on current trends in the field of assistive device development for mobility, an extensive literary review was performed.

2.2.1 The RoboKnee: An Exoskeleton for Enhancing Strength and Endurance during Walking

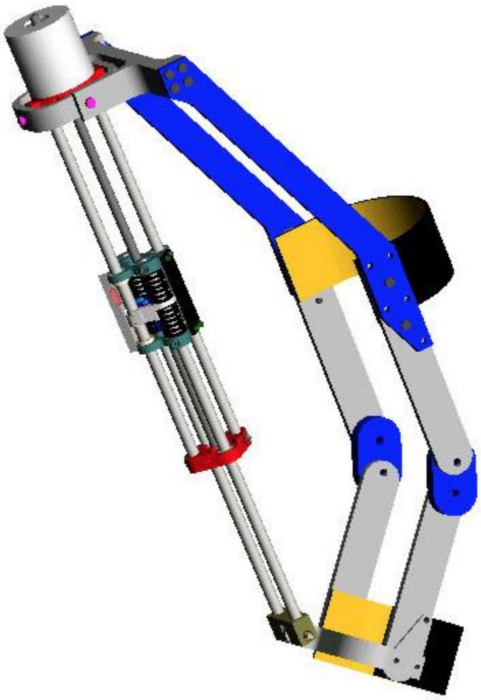

Figure 4. A model of the RoboKnee exoskeleton designed at Yobotics, Inc. OH [15]

Yobotics, Inc., Cinncinati, OH, developed a simple exoskeleton for adding power at the knee to assist in stair climbing and squatting during load carrying tasks. The device consists of a linear series elastic actuator (SEA) connected to the upper and lower portions of a knee brace, just below the hip and on the calf, respectively. The intention of the device was to apply power to the knee joint while exhibiting a physically low-impedance interface to the wearer, allowing for greater control gains while remaining safe for the user. The control of

RoboKnee utilizes the ground reaction force (in the vertical direction) and the center of pressure in the sagittal plane. This information was captured via two load cells within each pair of stiff-bottomed shoes worn by the user and used a positive-feedback force amplification control scheme of the torque at the knee. Its two most significant drawbacks are bulky nature and short lifetime between energy recharge. These two drawbacks highlight the need for more compact actuators and better energy sources.[14]

2.2.2 Development of Externally Powered Lower Limb Orthosis with Bilateral-servo actuator

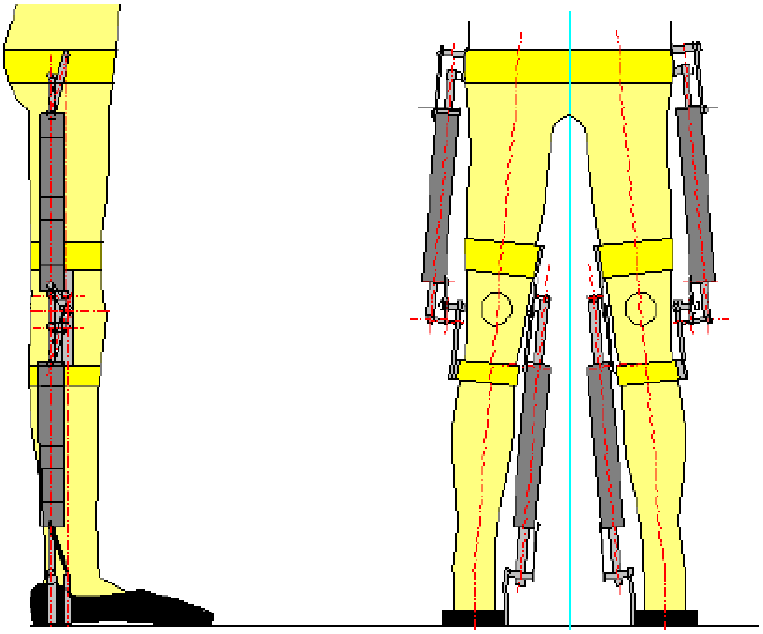

Figure 5. Functional model of the bi-articular muscle actuator. [16]

The device is a combination of powered orthosis and a powered telescoping crutch for the user's feet. This externally powered lower limb orthosis has a bilateral hydraulic transmission mechanism with smooth operation and exact position control similar to a bi-articular muscle. The orthosis and crutches are designed to assist in standing and sitting as well as in ascending and descending stairs. The control system uses outputs from a pressure sensor and a potentiometer for feedback control. The bi-lateral hydraulic transmissions system used in this orthosis makes it suitable to control two joints using a single actuator. One can imagine, however, that this strategy may lead to problems with the stability of the wearer. The drawback with this system is it's mechanical structure, heavy weight (about 7 Kgs) that can cause large fatigue with prolonged usage, low operational speed and loud noise generations.[15]

2.2.3 Power Assist Method for HAL-3 using EMG-based Feedback Controller

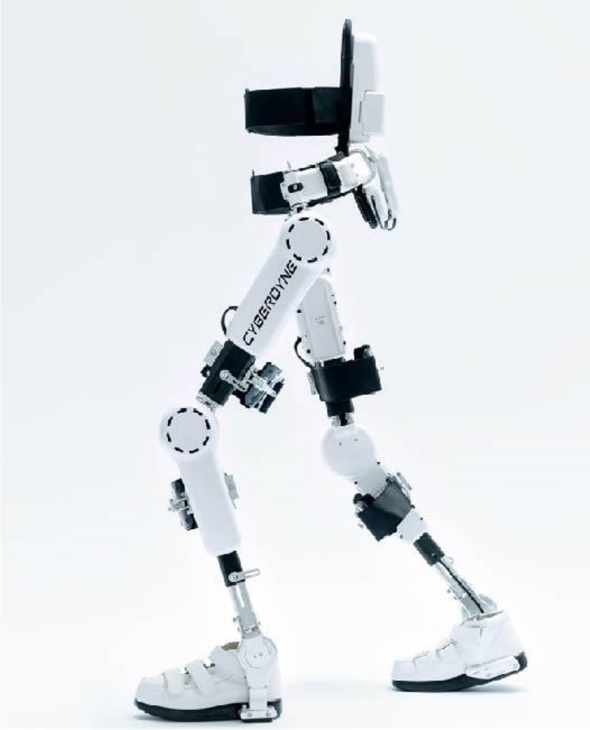

Figure 6.Final design output of the HAL-5 Bionic exoskeleton [17]

Sankai and his team at the University of Tsukuba, developed an exoskeleton concept that is targeted for both performance augmenting and rehabilitation. The leg structure of the full-body hybrid assistive leg (HAL)-5 exoskeleton powers the flexion/extension joints at the hip and knee via a dc motor with harmonic drive placed directly on the joints. The ankle flexion/extension Degrees of Freedom is passive. The lower limb components interface with the wearer via a number of connections: a special shoe with ground reaction force sensors harnesses on the calf and thigh, and a large waist belt. The HAL-5 system utilizes a number of sensing modalities for control: skin-surface electromyographic electrodes placed below the hip and above the knee on both the front and the back sides of the wearer’s body, potentiometers for joint angle measurement, ground reaction force sensors, and a gyroscope and accelerometer mounted on the backpack for torso posture estimation. These sensing modalities are used in two control systems that together determine user intent and operate the suit: an EMG-based system and a walking-pattern-based system. Reported drawbacks of the system are; it takes two months to optimally calibrate the exoskeleton for a specific user. The total weight of the full-body device is 21 kg and the effectiveness of the lower limb components of the exoskeleton are still unclear.[16]

2.2.4 Design of an Electrically Actuated Lower Extremity Exoskeleton

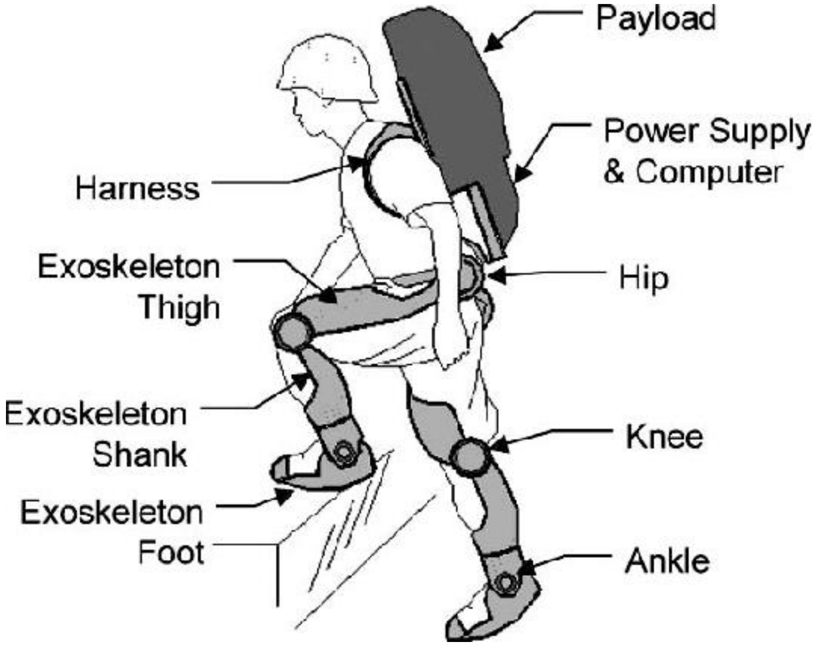

Figure 7. Image of implementation of the Berkeley's Lower Extremity Exoskeleton [12]

Berkeley's lower extremity exoskeleton (BLEEX) is comprised of two actuated anthropomorphic robotic legs that a person is made to wear. As the person moves through any maneuver, the exoskeleton legs support the backpack payload mounted to the exoskeleton's torso without the person actively driving the system. Thus, BLEEX provides the operator with load-carrying capability and endurance through versatile legged locomotion. BLEEX is the first energetically autonomous robotic exoskeleton that was successfully demonstrated to provide the operator with the ability to carry significant loads with minimal effort over any type of terrain. This is said to be accomplished through four critical features: a novel control scheme, high-powered compact power supplies, special communication protocol and electronics, and a design architecture to decrease the complexity and power consumption. The biggest concern about the device is its larger electric actuation size which is located down on the legs (especially at the ankle) and, therefore, leads to larger torque requirements during swing.[11]

2.2.5 A biologically inspired soft exosuit for walking assistance

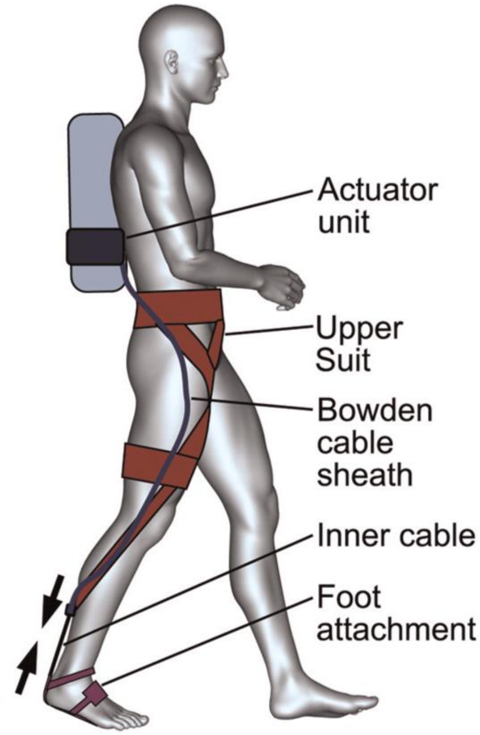

Figure 8. Bioinspired exosuit system with components. [10]

Asbeck and his team at Harvard University, developed the bio-inspired soft exosuit which is multi-articular, portable, fully autonomous, and provides assistive torques to the wearer at the ankle and hip during normal walking. The suit consists of a control system that weighs about 10.1 Kg and is worn as a backpack by the user. This suit when worn increases the metabolic cost of energy while walking which is not compensated well by the gait assistance provided by the system, hence making it more tiring for the user. The suit is not tested for stair climbing and also is not suitable for performing walking tasks for longer periods of time.[9]

Table 2. Summary of the limitations associated with the existing assist devices from the literature.

Assistive Technology from Literature	Limitations
RoboKnee	• Mechanically rigid structure with a bulky actuator system. • Duration of operation is short requiring energy recharge often.
Bi-lateral servo	• Heavy actuator system (7kgs) • Produces loud noise and is controlled by a complex system • Miniaturization and system safety tests are not accounted
HAL-5	• Control system takes approx. 2 months to custom to 1 user • Heavy weight system with complex sensing modalities • Suitable only for level walking
BLEEX	• Bulky system with large torque requirements • Not designed for pathological population
Bio-inspired Exosuit	• System has a high metabolic cost of energy for the user • Suitable only for level walking

Knee assist devices for stair gait must be designed to assist the joint by producing sufficient moment without increasing the metabolic cost of energy expended by the user. The system weight should also be within a small range of loads in order to reduce fatigue and the metabolic cost associated with it.[17] The system should also be body-conforming and made of less rigid components to enhance comfort for the user. A bulky system can result in alteration of the natural gait pattern and hinder rehabilitation. Keeping in mind the existing limitations with devices, the exosuit in this work was designed to overcome them and also align with the biomechanics of the user.

2.3 Biomechanics of Stair Ascent and Descent

Kinetic and kinematic analysis of stair ascent described below shows that the shape of the gait cycle is reproducible and is characterized by concentric muscle contraction and energy generation which refers to positive muscle work.[18] Figure. 9 shows phases of gait in stair ascent.

2.3.1 Gait Cycle

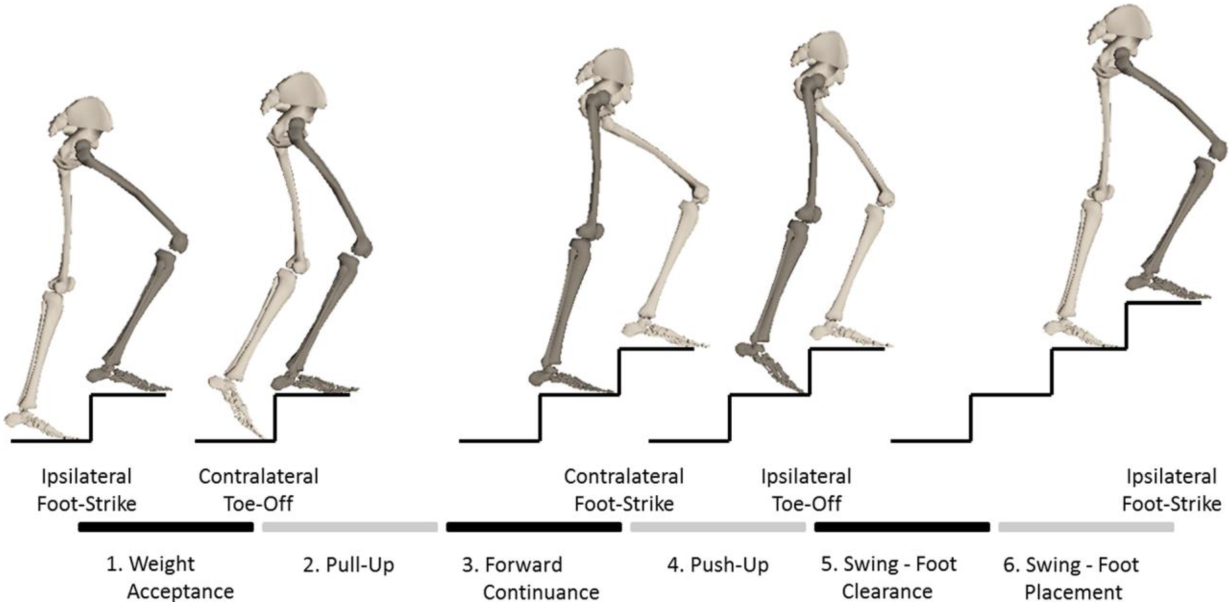

Figure 9. The six regions of the ipsilateral (dark shaded) leg gait cycle: (1) weight acceptance (ipsilateral foot-strike to contralateral toe-off), (2) pull-up and (3) forward continuance (contralateral toe-off to contralateral foot-strike divided into two equal sections), (4) push-up (contralateral foot-strike to ipsilateral toe-off), (5) early swing and foot clearance and (6) late swing and foot placement (ipsilateral toe-off to ipsilateral foot-strike divided into two equal sections). The six regions of the gait cycle were adapted from previous studies.[19]

Stair Ascent is described for each stride normalized from 0% referred as first contact (heel strike) to 100% that refers to subsequent contact of the same foot (ipsilateral foot) with the ground. Normal Stair Ascent (SA) includes both stance and swing phases. The entire stance phase is averaged to about 65% of the SA cycle. Stance sub-phases include: Foot Contact

(0-2% SA cycle); Weight Acceptance (0-17% SA cycle); vertical thrust or Pull-up phase (2-37% SA cycle); single limb support (17-48%); forward continuance (37-51% SA cycle); and double support (48-65% SA cycle). The swing phase is subdivided into two specific sub phases: 1) foot clearance and 2) foot placement.[20]

2.3.2 Joint Angles

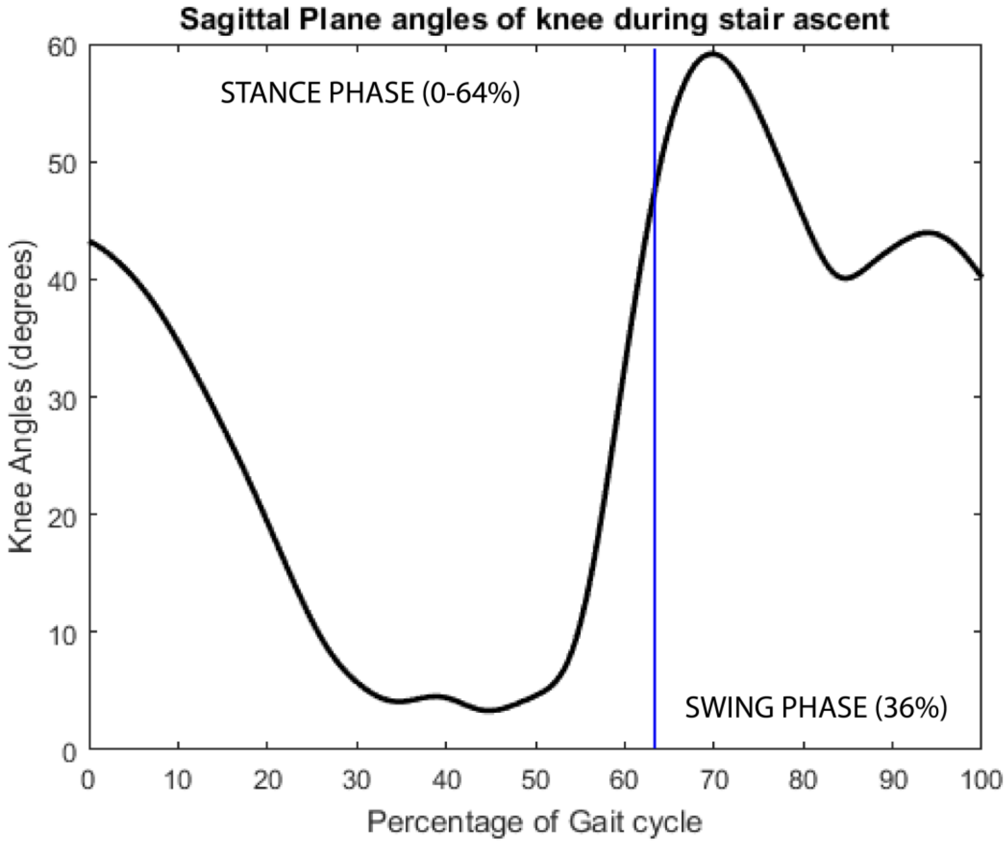

Figure 10. Sagittal Knee flexion angles measured during a stair gait cycle

Studies of stair kinematics have revealed that the greatest Range of Motion (ROM) occurs in the sagittal Plane, with the amount of flexion, particularly at the knee, dependent on stair dimensions.[21] Stair ambulation ROM at the knee requires approximately 10 to 20 degrees more knee flexion compared to that of level walking; Similar to that of the knee, the hip joint has a ROM, requiring approximately 15 to 20 degrees more during stair climbing than level walking. Also, with higher ROM, ankle plantarflexion ranges from 10 to 30 degrees and ankle dorsiflexion ranges from 20 to 30 degrees during stair ascent. Unlike the sagittal plane, the range of movement in the frontal plane is quite small at all three joints with studies indicating less than 15 degrees ROM at the ankle and less than 10 degrees at the knee and hip joints compared to the maximum magnitudes in the sagittal plane during stair ascent stance.[14]

2.3.4 Joint Moments

Previous studies have indicated that knee moments are approximately 12 to 25 percent greater than that of level walking, with the largest moments occurring in the sagittal plane.[22] Peak knee flexion moments range from a low of 0.69 Nm/kg to a high of 1.50 Nm/kg.[23] Of studies that have examined frontal plane, researchers have reported magnitudes from 0.42 Nm/kg to 0.46 Nm/kg occurring at the knee joint. Furthermore, frontal plane moments are higher: during late stance in stair ascent and variability in the hip moment patterns was reported due to difference in trunk positions.[18][24] During stair ascent, external flexor moments are reported to be about 0.8 Nm/kg. At the ankle, an internal plantar-flexor moment is reported with maximum peak magnitude occurring during late stance ranging from 1.2 to 1.5 Nm/kg.

2.3.4 Joint Powers

While moments, identify the muscle(s) that are contracting, power identifies the function of the muscle contraction whether the muscle is absorbing energy to deaccelerate or brake, or to do external work.[23] During stair ascent, positive power/energy is produced at all joints, with a large amount of power being produced primarily at the knee joint during stance as well as at the hip; power production at the ankle occurs later in the stance phase.[25]

2.3.5 Ground Reaction Forces (GRF)

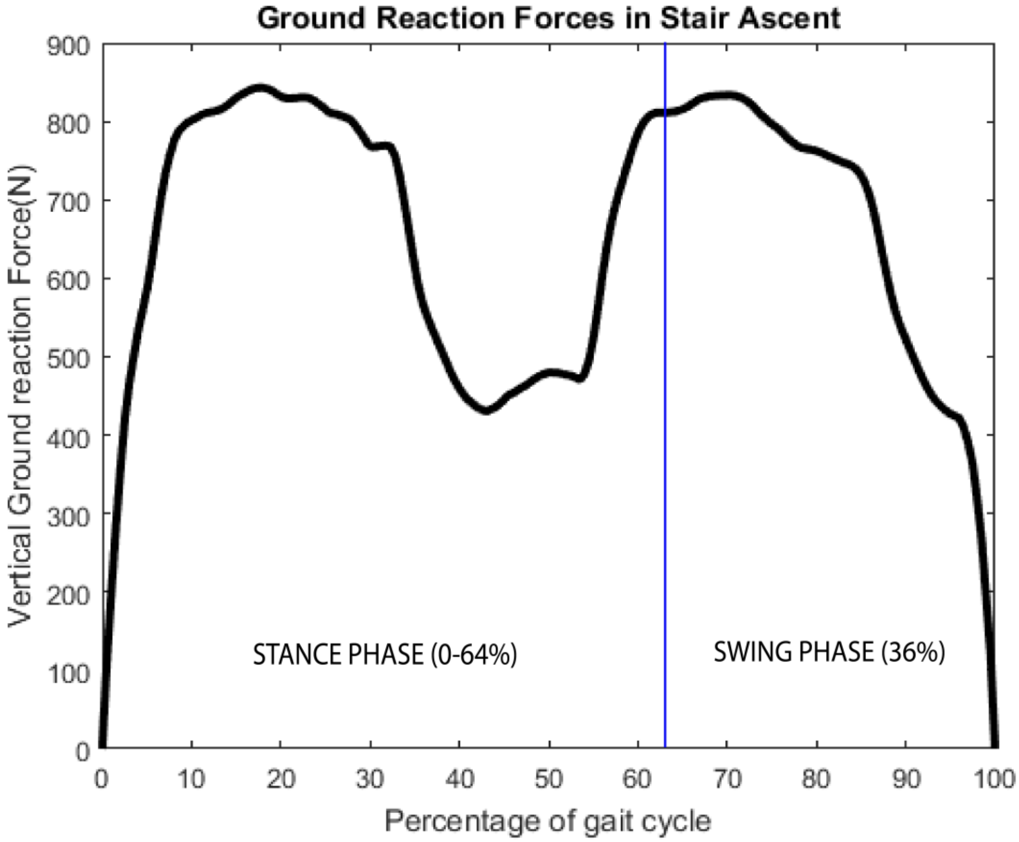

Figure 11. Vertical Ground Reaction Forces measured for one complete stair gait cycle

At foot contact, a rapid increase in the vertical GRF is observed, reaching the first of two maxima at the start of single limb support (17% SA cycle). Vertical GRF gradually decreases until mid-stance (34% SA cycle), after which it again increases, reaching its second maximum as double support is initiated (51% SA cycle). The magnitude of the mediolateral shear component of the GRF (lateral GRF) increases from foot contact until single limb support (17% SA cycle), reaching the first of two maxima. Lateral GRF, like vertical GRF, gradually falls until mid-stance (34% SA cycle). After mid stance, it again increases, reaching its second maximum at the initiation of double support (51% SA cycle). At foot contact, the magnitude of the anteroposterior shear component of the GRF (A/P GRF) is initially directed posteriorly (0 .4% body weight). By the end of the foot contact phase (2% SA cycle), this force has reversed direction and gets directed anteriorly. Maximum anterior shear is reached during weight acceptance. Just prior to single limb support, A/P GRF is again directed posteriorly, crossing the zero position as forward continuance is initiated. The greatest posterior shear force is reached 56% into SA (between 51% and 59% SA).[20]

2.3.6 Muscle activity

During stair ambulation, the knee joint has heavy demands placed on it, requiring both the knee flexors and extensors to take primary responsibility for knee joint stabilization. During ascent, there is increased extensor activity as the extensors hoist the body vertically against gravity as the body progresses. Extensor activity is most pronounced from the beginning of stance to the end of stance and acts as a source of power. During the swing phase, extensor activity is reduced, becoming slightly more active during the final placement of the foot. Flexor activity is increased during the swing phase, playing a key role in knee flexing to allow for stair clearance, crucial in stair ascent. [8][26]

Consistent with findings of McFadyen and Winter [24], the knee extensors, Vastus Lateralis and Vastus Medialis (Quadriceps-VAS), play a primary role in supporting the body during the first half of stance. The hip and ankle extensors, Gluteus Maximus (GMAX) and Soleus (SOL), are the other two important muscles that contributed to the elevation of the Center of Motion (COM) during the same period of stair ascent. The function of the largest muscle in the human body, GMAX, is of clinical relevance in terms of preventing backward falls during stair ascent by supporting the body. It also contributes greatly to the forward acceleration of the COM during stair ascent. This contribution to the body's forward movement during stair ascent may be the main mechanism that moves the COM closer to the center of pressure during the first double support period in stair ascent. Also, the ankle extensors, SOL and GAS, dominates vertical support during the second half of stance in stair ascent. Studies also reported that VAS and SOL were the two major extensors to prevent the body from collapsing under the force of gravity and controls its speed.[27]

Table 3. Evaluation of functional requirements of the exosuit with the biomechanical parameters of stair gait

Functional Requirements	Specification	Rational
Comfort	Comfortable	Easy to wear and comfortable extended periods of application
Weight	< 200 gms	Heavy loads on limb extremities increases moment and causes fatigue [11][17]
Cost	< $200	Affordable to larger sections of population
Joint Angle	2 – 60 degrees	Follow the natural gait pattern
Joint Moment	4.5 Nm	Provide 15% of the required moment
Assistance Phase	0-60%	Inflate during the stance phase
Walking speed	0.5-1.0 m/s	Adapt to normal walking speeds
Safety	Safe	Safe to use

Based on observations from conducted biomechanical analysis of the stair ascent task and results from existing literature, the functional requirements of the exosuit is evaluated for stair gait assistance. The table below describes the required specifications for the device with corresponding rational.

2.4 Thesis Overview

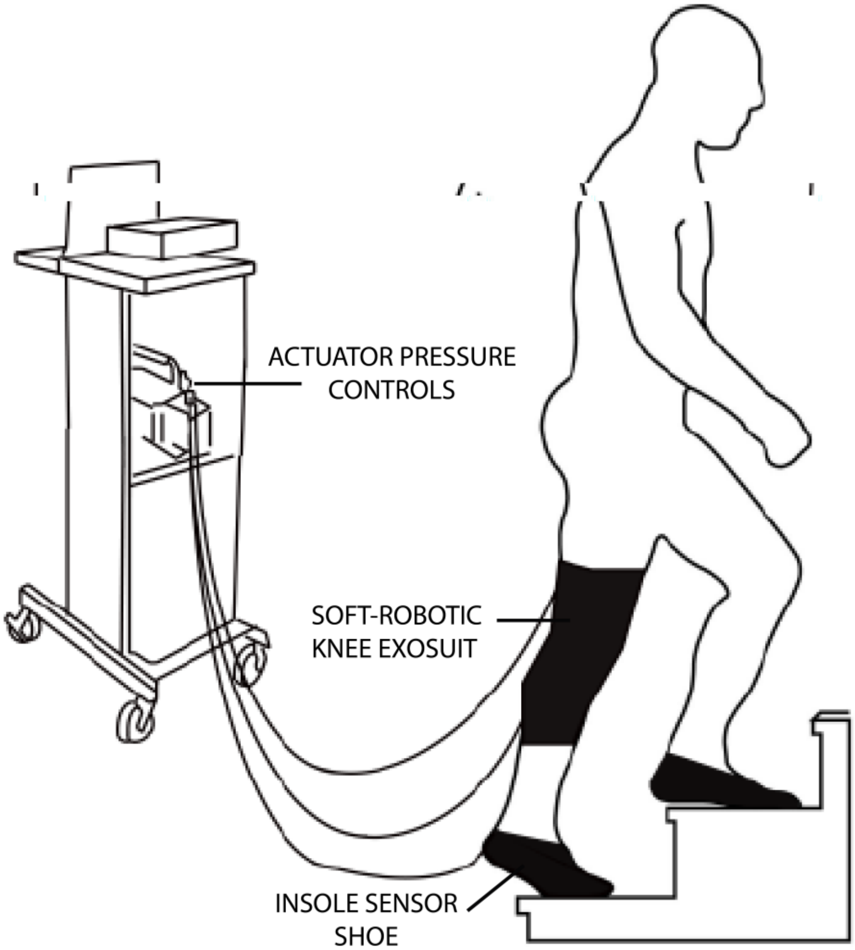

Figure 12. Illustration of the soft robotic knee exosuit assisting stair ascent in accordance to the outputs from insole sensors

The system shown in Figure 12. was developed to decrease the amount of muscle effort applied to the user's knee in stair mobility. The device is lightweight, comfortable, and assists during the stance phase of the stair gait cycle while providing minimal resistance during the swing phase, thus helping the user to carry out unrestrained motion. From analyzing the needs of the user and understanding the biomechanics of stair ascent, the portion of the gait cycle during which forces on the knee are the greatest was identified to be from the start of the Pull-up sub-phase (2-37% of SA cycle) till the about the end of Forward Continuance sub-phase (59% of SA cycle).

From these initial findings, functional requirements for the device were determined to design the exosuit. This design consists of two soft-inflatable actuators encased within a spandex suit stitched to conform to the knee joint geometry secured using velcro straps around the user's joint. The sensing part of the device consists of an FSR insole sensor, to help detect gait phases, accompanied with electronics to control the actuation of the exosuit and assist in joint motion.[28] Following the design of the device, evaluation and human subject testing was conducted in order to quantify device performance. The soft-inflatable exosuit assisted the wearer's knee joint starting from Pull-up (beginning of the inflation of the exosuit actuators) to the early swing phase of the gait cycle after which the actuators will deflate to allow the user free-joint motion.

Initial user testing showed a decrease in muscle activity of about 16% in the chosen quadriceps muscle, 3.6% in Gluteus maximus muscle, while the user ascended the rehabilitative stair. This device operates to reduce torque during the stance phase of ascent and disengages during the swing phase to avoid inhibition of the natural gait.

By researching an often-overlooked area of human gait assistance, this thesis will benefit and promote future research targeting stair climbing assistive devices. This thesis presents a wearable, lightweight device. This is a low-cost solution that will help the active, elderly, and physically impaired alike by decreasing muscle fatigue, decreasing risk of overuse injuries, increasing independence, and improving overall quality of life.

CHAPTER 3

DESIGN

Figure 13. Components of the soft-robotic knee exosuit used for evaluation in stair ascent [28]

3.1 Actuator Fabrication

The exosuit consists of two inflatable soft actuators with an I-shaped cross section created out of thermoplastic urethane (TPU) with thickness of 0.1515 mm (DT2001, American Polyfilm Inc., Branford, CT). The fabrication of the specified I cross-section is done by drawing out rectangular strips of TPU with markings as per the amount of moment required to be generated. The cut urethane material is folded and sealed multiple times along the markings to create an I cross-section with center seams heat sealed to keep the structure intact when inflated. Slits that act as channels were made to allow air to flow between layers of the actuator for uniform distribution of pressurized air throughout the material. Both the top and bottom ends of the actuator are heat sealed and two provisions are made to attach tube fittings at about 2.5cm from the sealed ends, in & out nozzle attached, to be connected for pressurizing. The chosen dimensions for the actuators is based on the proportions of the femur and tibia for accurate fitting, and the number of required actuators (2 in this case). [28]

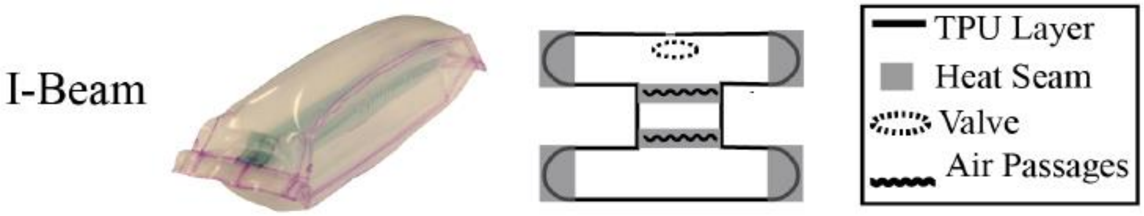

Figure 14. Model of a fabricated I cross-section soft-inflatable actuator [26]

In order to be worn as an exosuit, the actuators were encapsulated within an elastic spandex fabric that was stitched in accordance to the joint geometry. The fabric pockets are sewn such that the inflatable actuators make an equal lever arm at the knee joint to provide maximum assistance when inflated. Hook and loop straps are attached to the elastic sleeve allowing for adjustment depending on the comfort of the user. Apart from adjustability, the straps aid in the uniform distribution of the generated forces to the thigh and the calf, thus providing maximum force transfer to the body.

3.2 Sensing and Control Electronics

Two force-sensitive resistors (FSRs) are placed and casted into a thin (4.5 mm), soft-silicone insole (Ecoflex 30 Smooth-On Inc., Macungie, PA) that is inserted inside the wearer's shoe. One sensor is located at the ball of the foot to measure the toe-off forces while the other is at the heel to measure heel-strike forces. The 2 sensors are placed at the location assuming that majority of the users use the heel to begin their step placement. For user's who step using other foot placement strategies, it will be useful to increase the number of sensors placed on the insole at (1) 1st and 5th metatarsals, (2) Ball of the foot and the (3) Heel and use an algorithm to average their output information in order to utilize them for gait detection to control the actuator pressurization.

To incorporate the monitoring and control electronics of the knee sleeve, an additional small fabric pocket is sewn. The electronics include a microcontroller with links to a custom board that facilitates connections to the FSR -insole sensors, valves controller, and fluidic pressure sensor. The electro-pneumatics of the systems include three pneumatic valves (MHE3-MS1H valves, Festo, Hauppauge, NY) that are placed in series to control venting of air pressure during pressurization or depressurization. A single fluidic pressure sensor (ASDXAVX100PGAA5, Honeywell International Inc., Morris Plains, NJ) is added to the system to monitor the internal pressure of the inflatable actuators. The actuators are pressurized using a pneumatic line that is connected to a pneumatic supply source, as well as a vacuum pump (DV-85N-250 pump, JB Industries, Aurora, IL), which facilitates faster depressurization rates (at 0.00142).

Safety is a crucial aspect to consider when developing a system that is used to aid those who are injured because injured users are more susceptible to further injury. One of the major failure modes of the device is the eruption of the bladder due to over pressurizing it. Failure tests were conducted during the design process to find the average failure pressure.

This pressure was noted to be several times higher than the pressure required by the actuator to operate in joint assistance. This safety factor, coupled with the capability of the device to achieve maximum torque, made this exosuit suitable for assistance.

3.3 Modeling of Knee motion

To understand the biomechanics of knee and the characteristics of the stair activity, results from an experimental study conducted by Zabala et. al., [29] to compute 3-dimensional knee moments during stair ascent and descent was used. In this study, all subjects performed several trials of stair ascent (step height 20 cm; tread 25 cm) over a force plate (Bertec, Columbus, OH) at a normal self-selected speed until three successful trials had been collected for each activity. Lower-limb kinematics were measured using an optoelectronic motion capture system (Qualisys, Gothenburg, Sweden) and a redundant set of 21 reflective markers were used.[18][30] Knee moments were calculated by inverse dynamics using the inertial properties of the segments. The knee moments were expressed as external moments relative to the tibial anatomical frame. Moments were normalized to percent bodyweight and height (%Bw Ht). Two maxima peaks (1st and 2nd half of the stance phase) were used to describe the flexion moments. Table below describes the knee moments during the two maxima peaks of the stair ascent cycle.

Table 4. Knee moments during stair ascent [28]

Phase of gait cycle	Anatomical Plane	Peak Amplitude (% BW x Height)	p-value
1st Peak	Knee Flexion	6.587 ± 1.07	< 0.001
2nd Peak	Knee Extension	1.97 ± 1.25	0.012

3.4 Actuator evaluation

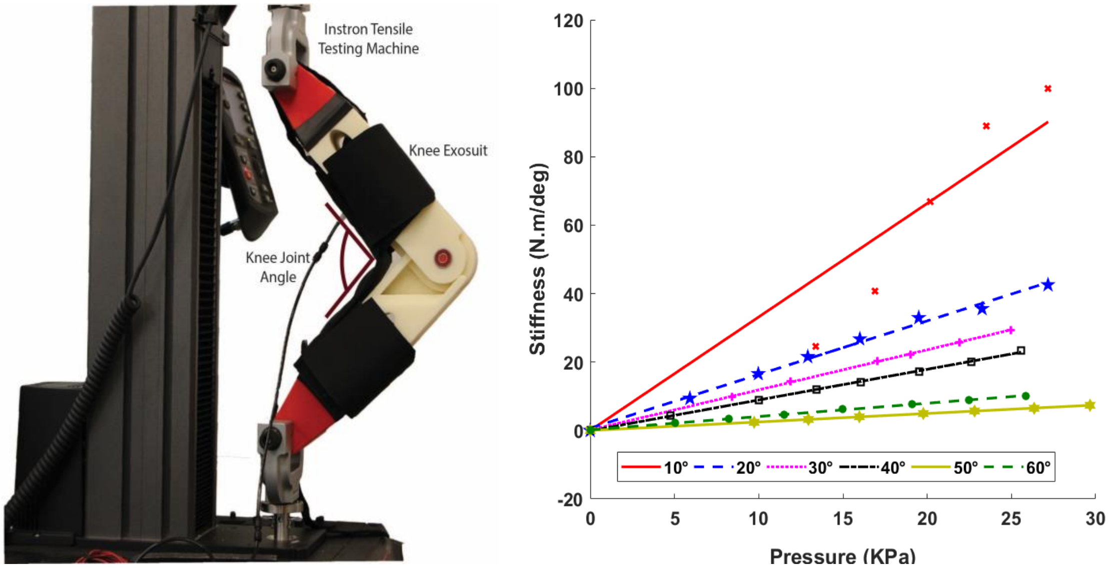

Figure 15. Left: Stiffness testing set-up used for analyzing the actuator characteristics; Right: Results from the measured Actuator stiffness model

A biologically-inspired knee joint was fabricated by assembling two pieces, with ball bearings for rotating mechanism, of acrylonitrile butadiene styrene (ABS) plastic (Fortus 450mc, Stratasys, Eden Prairie, MN) that mimics the bones femur and tibia of a human leg. The rotating joint allows 135° of rotation and a frictionless motion. To securely mount the actuator to the joint, a fabric sleeve for the actuator was fitted with hooks and straps and hold the actuator at equal distances from the kneepit. For testing, the actuator was placed at different orientations on the knee joint. To measure the force output from the inflatable actuators, the knee joint was mounted securely on a universal tensile testing machine equipped with a load cell (Instron 5944, Instron Corp., High Wycombe, United Kingdom) to capture the force data, as shown in Figure 15. The knee-extension angle on the test apparatus was set at different angles as per knee-flexion angles during the stance phase of stair climbing. For the tests, multiple force output readings were collected as the actuators were inflated at intervals of 10 degrees by varying the pressure values. The torque exerted by the inflatable actuator about the knee is computed by resolving the obtained forces from the universal testing machine, perpendicular to the surface of the test apparatus and multiplying it with the moment arm of the force. It is determined that to produce a torque of 4.5 Nm actuators supplied with 28 KPa would be required.

CHAPTER 4

TESTING AND RESULTS

4.1 User Testing

The effectiveness of the exosuit was validated using surface Electromyographic (sEMG) sensors (Delsys® Trigno®, Delsys, Natick, MA). Three sets of muscles were chosen viz., Biceps Femoris, Vastus Lateralis, and Gluteus Maximus, according to their contributions in carrying out the stair ascent, based on the literature.[8][31] The sensors were placed following EMG guidelines suggested by the International Society of Electrophysiology and Kinesiology (ISEK), that enables physiological interpretation of EMG data, and muscle activity of 2 healthy participants was recorded for two conditions: (1) When the device is inactive (Baseline mode), (2) When the device is active (Device active mode). To prepare for the experiment, the skin was treated with rubbing alcohol solution before the sensors were placed. A test protocol was formulated where the participant would walk on a rehabilitative stair (Dimensions: Width: 30 inches, Risers: 7 inches, Tread: 10 inches) for about three minutes per trial, at a very slow speed of about 0.5- 1.0 m/s. Post completion of a trial, the participant is allowed to rest for two minutes to recover from any fatigue that might have occurred in the muscles. Safety measures such as emergency stops and quick deflation of the exosuit were incorporated in case of any discomfort caused to the test subject. Prior to the actual recording, a set of 3 trials were performed by the user with the exosuit to make sure the user is comfortable, and the suit gets accustomed with their walking pattern on the stair. A total of six trials were performed on a single participant – three with the exosuit active (Device active mode) and three with the exosuit inactive

(Baseline mode) following the study protocol. The raw sEMG data collected during trials were processed to compare the exosuit effectiveness on different phases of the task. Six gait cycles were averaged for both the Baseline and the Device active modes for the 3 muscle groups chosen and plotted along with their standard deviations.[27]

4.2 Analysis

EMG data recorded from the 3 sets of muscles post-processing was filtered using a fourth order butterworth filter to remove noises and motion artifacts with cut of frequencies ranging between 10-15 Hz. The processed signal was then normalized using the Maximum Voluntary Contraction (MVC) data at the rest state and maximum activation state respectively, recorded for each muscle in accordance with the SENIAM sensor protocol. Identification of different gait events in EMG was achieved by visual inspection of each of the muscle’s raw EMG signals at the heel strike and toe off of the ipsilateral leg using the Vicon marker data and correlating it with the kinematic data obtained from the system in accordance with the literature.[26] Extracted gait cycles were plotted for each muscle for both Device active mode and Baseline mode across all the trials to analyze quantitative change in muscle activity. An average of the 6 trial gait cycles measured was computed to plot the muscle activity for both Baseline as well as the Active modes. The trials used to compute muscle activity was picked from the second step in order to give the user sufficient time to accustom with the task and the exosuit.

The Device active data was compared to the Baseline data for each participant using two methods and reduction was computed. The first method was finding the maximum data of each set, representing the peaks of muscle activity for both the sets along the different stair gait phases. The maximum peak of the Device active tests was compared to the Baseline tests peaks to show the reduction in maximum activity at the knee joint.

The second method involved finding the integral of the plotted muscle activity graph during each test. Again, the muscle activity for the Device active tests over the average of the trials was compared to the Baseline tests to show reduction of muscle activity through the entirety of the tests. The region of comparison for these tests are between 0-60% of the gait cycle when the exosuit operates by inflating its actuators.

To qualitatively assess the exosuit, a device satisfaction survey form was generated and was given to the users to fill out. The form was prepared with the help of some existing surveys for orthotics and prosthetics designed by the American Board for Certification in Orthotics and Prosthetics.[32] This form consisted of a small questionnaire where the users scored the device on a scale of 1 to 4 (4 being the maximum value) on the comfort, assistance and aesthetics of the exosuit. The results from this survey is attached in the appendix section of the document.

4.3 Results

The visual representation of the EMG data from the 3 sets of chosen muscles are plotted below along with their standard error. Figures 16-19. shows muscle activity for Vastus lateralis, Gluteus maximus and Biceps femoris muscles respectively, that were averaged from 6 stair gait cycles over three trials. Muscle activity from Baseline mode trials are plotted in red, and Device active mode trials in blue. The portion of the gait cycle during which the device was actively assisting (Inflation period) and providing a resistive torque is marked with a green band on the gait cycle axis.

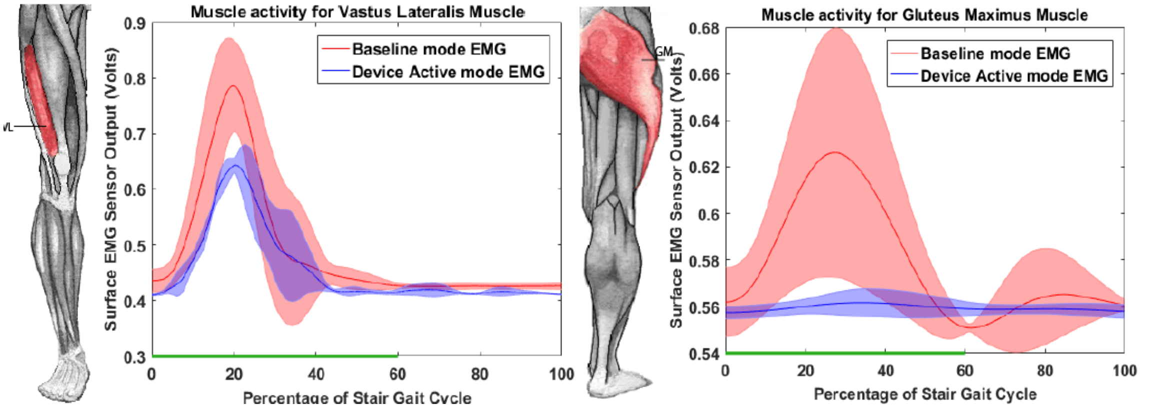

Figure 16. Normalized sEMG signals (n=6) of muscles for User 1: Vastus lateralis (Left) and Gluteus maximus (Right).

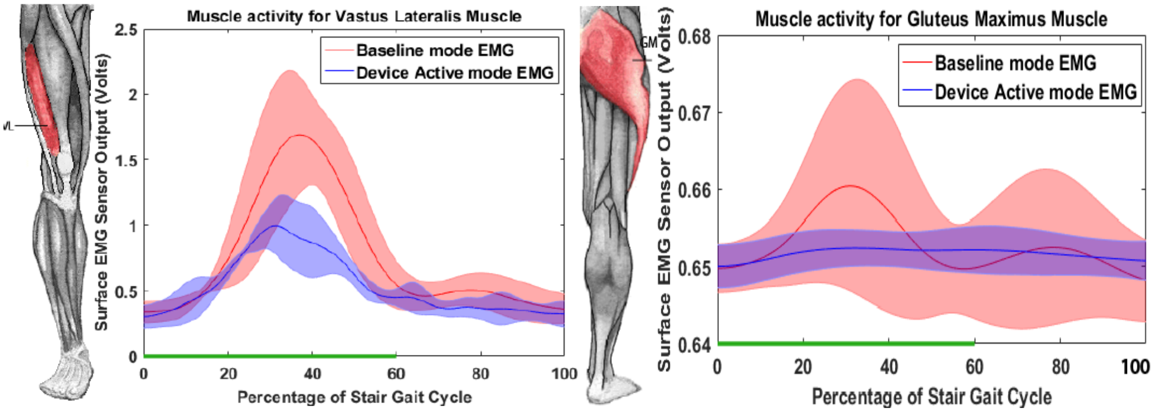

Figure 17. Normalized sEMG signals (n=6) of muscles for User 2: Vastus lateralis (Left) and Gluteus maximus (Right).

From the graphs, we see that there is a reduction in peak muscle activity, as a result of exosuit assistance, for both Vastus lateralis and Gluteus maximus muscle groups in the 2 recorded users.

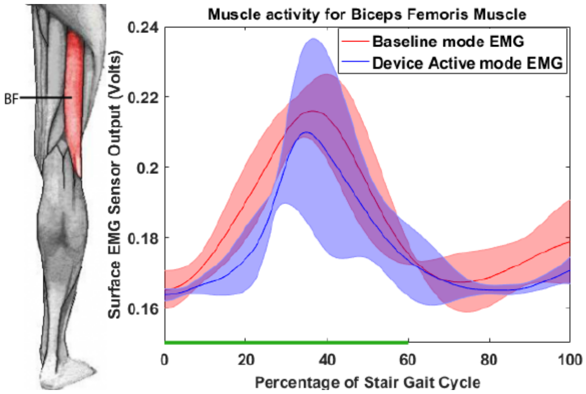

Figure 18. Normalized sEMG signals of Biceps femoris muscle for User 1 (n=6).

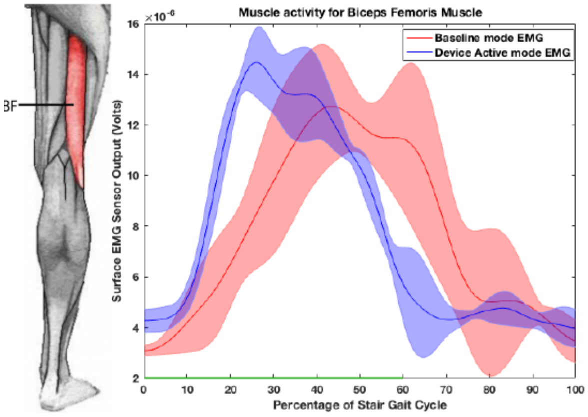

Figure 19. Normalized sEMG signals of Biceps femoris muscle for User 2 (n=6).

Processing of the sEMG data showed reduction in muscle activity of the Vastus lateralis and Gluteus maximus muscle group during testing with the exosuit active, the average reductions computed per individual muscle across the participants were 16% for Vastus lateralis and 3.7% for Gluteus maximus respectively. The three sets of data pertaining to one single participant demonstrate consistent results with all sets of data having similar amounts of reductions. A promising reduction in the muscle activity was observed in the chosen muscles but further investigation into the other muscle groups of the quadriceps need to be performed for more conclusive results. A narrow increase (about 2.7% on average) in the activity of muscles in the hamstrings was recorded. The possible reasons for the increase in muscle activity include passive resistance provided by the exosuit to the knee joint during flexion and the delay in the deflation of the exosuit during the gait cycle. Overall, the exosuit assists the quadriceps of all the test participants at the cost of a small increase in the muscle activity of the hamstrings. The plots also indicate that the reduction occurs only when the device is actively assisting while post early swing phase it closely follows the baseline curve with mild to no reduction. This implies that the device resists knee during swing slightly, but the overall gait pattern is unaltered.

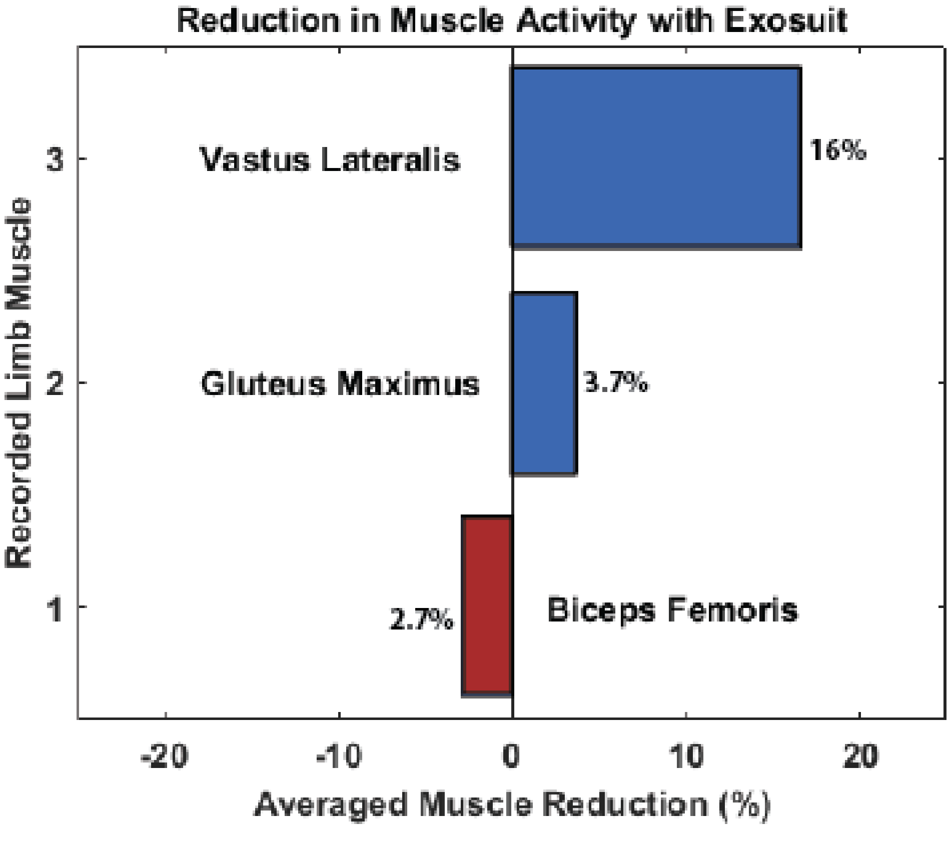

Figure 20. Averaged Muscle Reduction plots from the sEMG results

The bar plot in figure 22. represents the overall reduction activity with the device active during stair ascent. The Vastus lateralis shows a statistically significant 16% decrease in muscle activity, the Gluteus maximus activity shows a 3.6% decrease and there was an observed increase in muscle activity of about 2.6% in the Biceps femoris between the baseline and device active modes. A positive value in the average muscle reduction indicates the assistance provided by the exosuit at the knee joint. Additionally, no gait abnormalities were visually observed during data collection. This confirms that the device can be used during stair climbing without overly constricting the natural gait of the user.

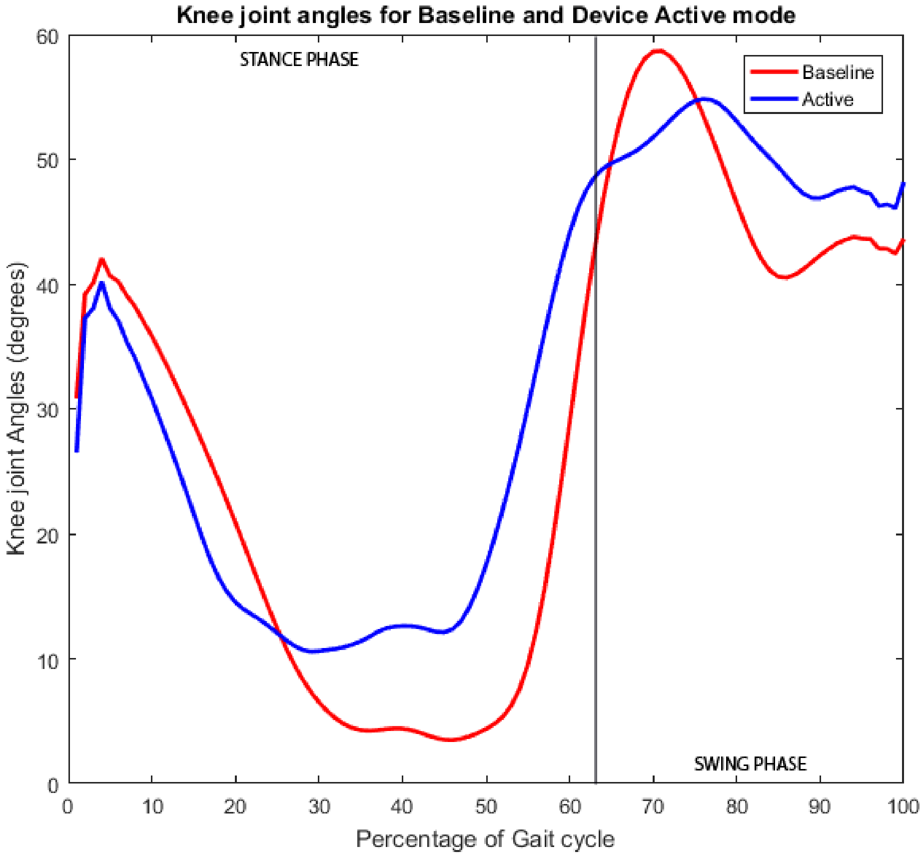

Figure 21. Results from the kinematic analysis of the knee joint Baseline mode and Device active mode

Figure 23. depicts the results from the kinematic analysis of joint angles performed in Baseline mode and Device active mode. The assistance using the exosuit closely followed the natural gait pattern of the user with gross changes in the joint angle, emphasizing our hypothesis. This change in joint angle is observed at the end of assistance period which could be due to a small delay in the actuator to completely deflate or due to the pressure exerted by a small amount residual air left behind in the actuator.

Small changes in joint angle observed between Device Active mode and Baseline mode could be eliminated with the use of a control algorithm that is capable of switching inflation and deflation at a much faster pace and also by using a stronger vacuum unit to enable higher rates of pressure deflation from the actuator.

4.4 Discussion

4.4.1 Variation in Joint Angles between the Users

A change in the gait characteristics was observed between the two participants while analyzing EMG and kinematic data. One of the reasons for this change in gait pattern could be variation in the normal walking speeds between the two users and mild variations in speed between trials of the same user. Kinematic and EMG patterns have been investigated in the literature at various speeds of walking and have shown a decrease in the magnitudes of joint moments and muscle activations with a decrease in speed. Previous studies have also showed a decrease in range of motion and decreased maximum flexion for all joints and decreased magnitude of EMG while the subjects walk at slower speeds. Joint angles were found to vary significantly, as well. Internal joint flexion moments did not change significantly for ascending stairs with changing speed. Peak ground reaction forces were found to increase with speed. And, average peak EMG activations and activation timing was found to increase as speed increased for most of the muscles, as well. However, further investigation is necessary on the kinematic data for each user at different walking speeds to confirm the observed variability. [33][34] Unlike experiments using treadmill for gait analysis, where the user is made to walk at a set speed, no preset setting could be established to control the timing with which the user could maintain a perfectly uniform speed in climbing the stair. The protocol just specified the user to walk as constant as possible with their normal walking speed throughout the experiment. This variation in the walking speed could have caused a change in the kinematic characteristics of the recorded gait.

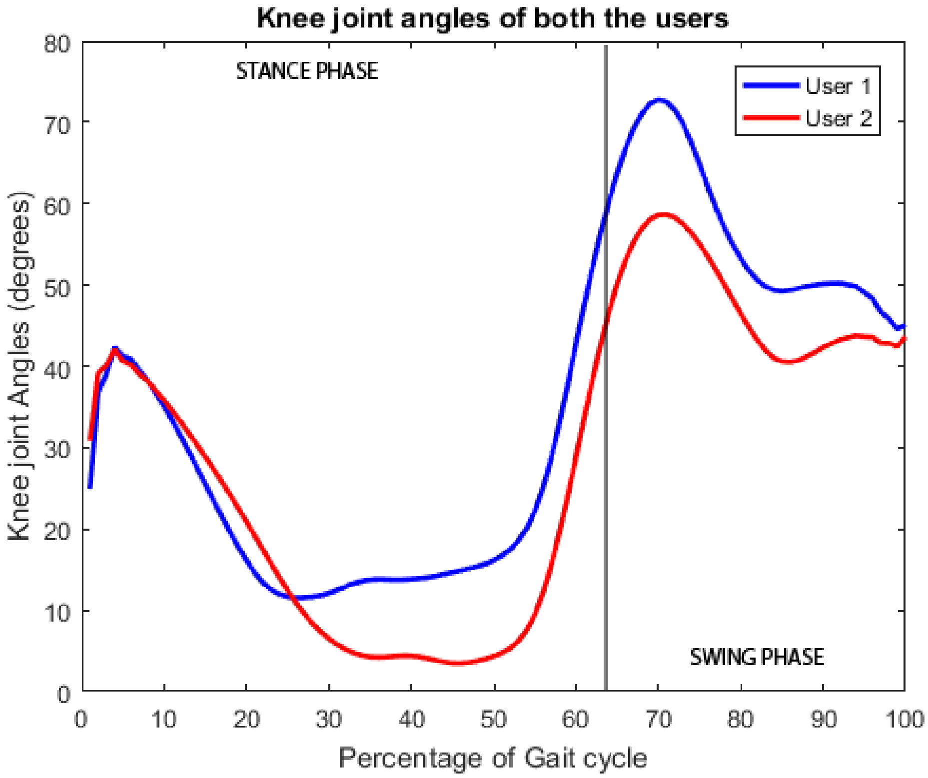

Figure 22. Sagittal joint angle data for the two users.

4.4.2 Variation in Kinematics between the Baseline and Device Active mode

Second being a minor variability in the magnitude of knee joint angles. Variability in the joint angle measurements could be because of 1) differences in the placement of the markers at the exact anatomical location of the limb between users, 2) with variations in gait patterns associated with the orientation of foot placement on the step and also 3) with the distance of the step placement from level grounds at initial contact.

4.4.3 Variation in Gait Characteristics in the Exosuit User with Time

Third, it is important to consider the changes in gait characteristics with the user getting accustomed to the exosuit over a period of time. From our observation during the preliminary evaluation, the user adapted to walking with the exosuit within the first few trials. With this in mind, it is expected that the user will be able to ascend the stair at a much larger speed, with more stability and reduced risk of falls over continued usage of the exosuit. There will also be a quick stable progression to the next step as the user gains control of the somatosensory feedback information he gains with prolonged usage of the exosuit.[35]

4.4.4 Muscle Activity Changes during Stair Ascent

During the first half of the stance phase (from weight acceptance through pull-up), Along with Vastus Lateralis (VL), the primary contributor to vertical propulsion of the body COM, additional contributions from Soleus (SOL), Gluteus Medialis (Posterior and Anterior) are also utilized in forward propulsion. To propel the COM vertically, both VL and SOL generate power in the vertical direction to the trunk and ipsilateral leg. During the second half of leg stance (from forward continuance through push-up), the plantar flexors (SOL and Gastrocnemius(GAS)) are the primary contributors to vertical propulsion with additional contributions from VL, while Hamstrings (BF) opposes vertical propulsion. Gravity is also a critical contributor to the vertical GRF throughout stance. SOL, GAS, and VAS all generated power directly to the trunk and ipsilateral leg. Similar to the results obtained from VL and GM the secondary contributors Gluteus Medialis, Vastus Medialis will show a reduction in the muscle activity with mild increase in the Hamstring activity with the exosuit active.

4.4.5 Implementation of Exosuit with Alternate Gait Patterns

Finally, effects of different gait patterns used to ascend stairs by the user is an important parameter that should be considered to evaluate the exosuit performance. Generally, healthy individuals use a traditional step-over-step (SOS) gait pattern during stair ambulation; however, patients, older adults, and disabled population may be forced to adjust their stair gait pattern because of decrements in muscular strength, decrease in proprioceptive acuity, and altered balance mechanisms associated with age and pathology. Therefore, those populations with decrements in motor function often adopt alternate gait patterns, such as increased handrail use, sideways motion, or a step-by-step (SBS) pattern (placing both feet on the same step before ascending or descending) that deviate from the traditional SOS gait pattern.

Studies have reported that on the basis of the range of motion, the traditional SOS stair ambulation pattern is different from the compensatory SBS pattern: the step length is longer for the SOS pattern and results in an increased stride velocity. The magnitude of joint flexion moment for the progressing leg in both the gait patterns however were almost equal. The joint flexion moment for the supporting leg in SBS pattern is lower than that in SOS pattern.[36]

The kinematic data reported in literature about the similarity in magnitude of the joint flexion moment of the progressing leg (leg with the exosuit) proves that the system proposed in the work could be applied to the SBS gait pattern as well retaining the same design characteristics for assisting users.

CHAPTER 5

CONCLUSION & FUTURE WORK

In this work, we evaluated a soft-inflatable exosuit for assisting the knee joint during stair ascent to offer gait rehabilitation to post-stroke and ACL reconstructed patients. The soft exosuit, integrated with a smart insole shoe system (for gait phase detection), was used to achieve phase-specific assistance. A reduction in the sEMG activity of the Vastus lateralis and Gluteus maximus muscle groups with a slight increase in the hamstrings was observed during the gait cycle for 2 test participants. As stated, the goal of evaluation of the soft inflatable exosuit, i.e. to assist the knee during extension, the overall positive muscle effort reduction proves the feasibility and leaves room for further exploration on how assistance of multiple muscle groups associated with the knee joint can be accomplished. Apart from quantitative kinematic and sEMG results, a survey on the comfort, assistance, and aesthetics of the exosuit was conducted to qualitatively asses the exosuit. As per all participants, the soft exosuit provides assistance in knee extension with slight perceived resistance in walking.

Future investigations will include implementation of an improved controller using feed forward algorithms, wireless transmission of sensor data to the exosuit, use of advanced sensors to detect gait instances, testing of impaired participants to investigate biomechanics and the effectiveness of the suit in them, and evaluation of the exosuit to assist stair descent. In order to validate the results obtained, more healthy users have to be recruited to test the exosuit and provide conclusive results with a higher statistical significance.

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APPENDIX A

DEVICE SATISFACTION SURVEY FORMS

For User 1:

Table 5. Completed device satisfaction survey for User 1

Characteristic	**User Satisfaction Score**			
1. **Fits well**	1	2	[✓ 3]	4
2. **Comfortable throughout the course of testing**	1	2	[✓ 3]	4
3. **Skin is free of abrasions & irritation**	1	2	[✓ 3]	4
4. **Clothes are free of wear & tear**	1	2	3	[✓ 4]
5. **Looks good**	1	2	3	[✓ 4]
6. **Weight is manageable**	1	2	[✓ 3]	4
7. **Pain free to wear**	1	2	3	[✓ 4]
8. **Easy to put on**	1	2	[✓ 3]	4
9. **Causes fatigue**	[✓ 1]	2	3	4
10. **Hinders movement**	[✓ 1]	2	3	4

For User 2:

Table 6. Completed device satisfaction survey for User 2

Characteristic	User Satisfaction Score			
1. **Fits well**	1	2	3	[✓ 4]
2. **Comfortable throughout the course of testing**	1	2	3	[✓ 4]
3. **Skin is free of abrasions & irritation**	1	2	3	[✓ 4]
4. **Clothes are free of wear & tear**	1	2	3	[✓ 4]
5. **Looks good**	1	2	3	[✓ 4]
6. **Weight is manageable**	1	2	3	[✓ 4]
7. **Pain free to wear**	1	2	[✓ 3]	4
8. **Easy to put on**	1	2	[✓ 3]	4
9. **Causes fatigue**	[✓ 1]	2	3	4
10. **Hinders movement**	1	[✓ 2]	3	4

APPENDIX B

SENIAM PROTOCOL FOR MAXIMUM VOLUNTARY CONTRACTIONS

1. Sensor Location, Clinical test details for Gluteus maximus muscle

Muscle

Name	Gluteus
Subdivision	Maximus

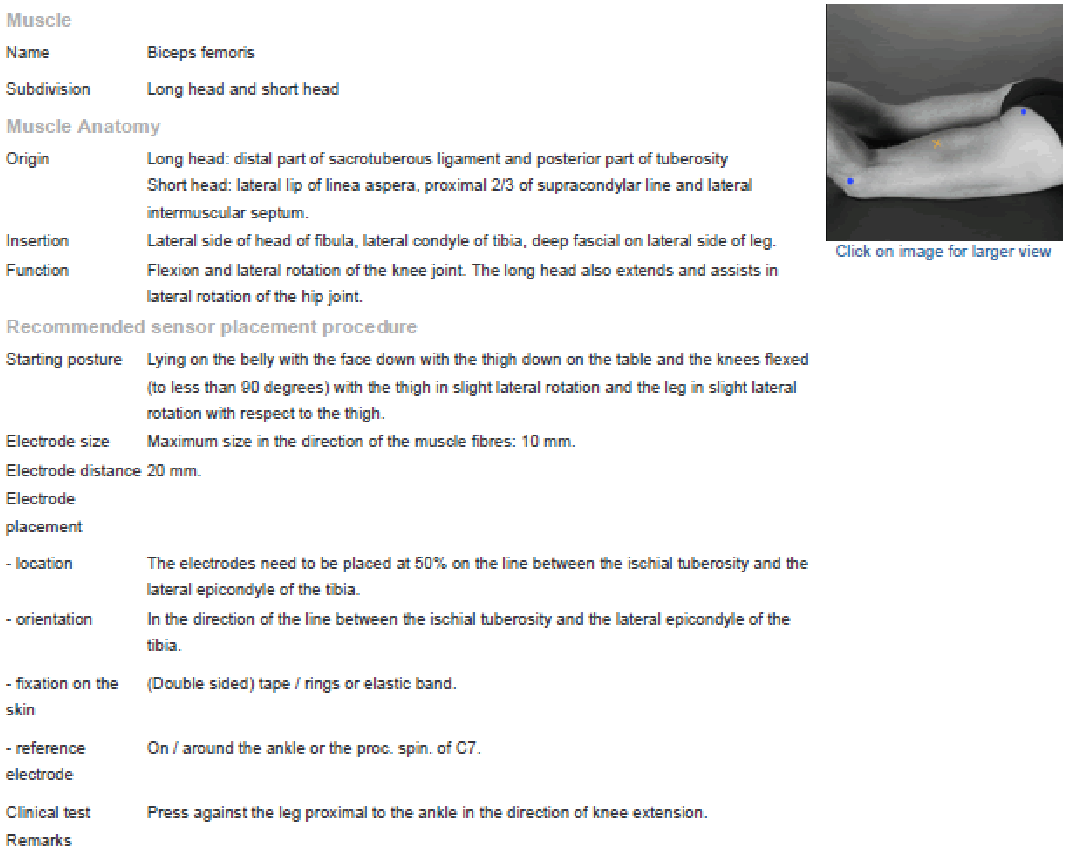
Muscle Anatomy

Origin	Posterior gluteal line of ilium ad portion of bone superior and posterior to t, posterior surface of lower part of sacrum, side of coccyx, aponeurosis of erector spinea, sacrotuberous ligament and gluteal aponeurosis.
Insertion	Larger proximal portion and superficial fibres of distal portion of muscle into iliotibial tract of fascia lata. Deeper fibres of distal portion into gluteal tuberosity of femur.
Function	Extends, laterally rotates and lower fibres assist in adduction of the hip joint. The upper fibres assist in adduction. Through its insertion into the iliotibial tract, helps to stabilise the knee in extension.

Recommended sensor placement procedure

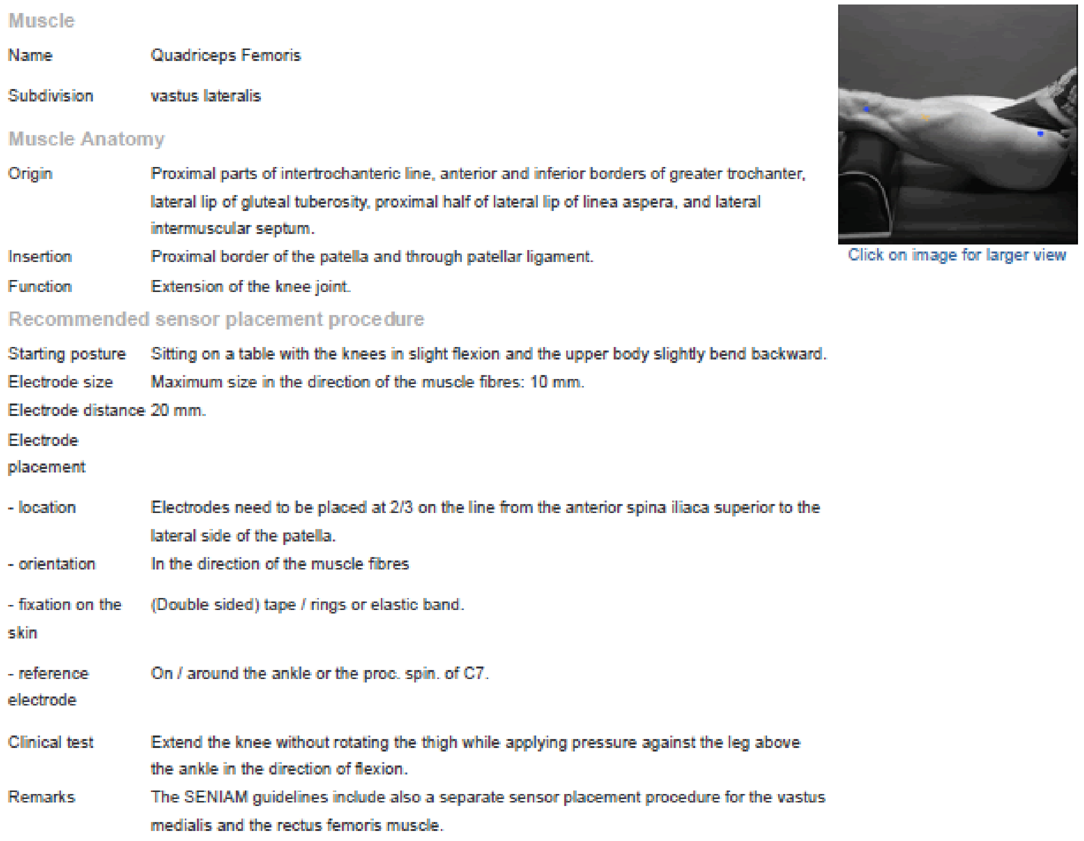
Starting posture	Prone position, lying down on a table.
Electrode size	Maximum size in the direction of the muscle fibres: 10 mm.
Electrode distance	20 mm.
Electrode placement	
- location	The electrodes need to be placed at 50% on the line between the sacral vertebrae and the greater trochanter. This position corresponds with the greatest prominence of the middle of the buttocks well above the visible bulge of the greater trochanter.
- orientation	In the direction of the line from the posterior superior iliac spine to the middle of the posterior aspect of the thigh
- fixation on the skin	(Double sided) tape / rings or elastic band.
- reference electrode	On the proc. spin. of C7 or on / around the wrist or on / around the ankle.
Clinical test	Lifting the complete leg against manual resistance.
Remarks	The SENIAM guidelines include also a separate sensor placement procedure for the gluteus medius muscle.

2. Sensor Location, Clinical test details for Biceps Femoris muscle



Muscle	
Name	Biceps femoris
Subdivision	Long head and short head
Muscle Anatomy	
Origin	Long head: distal part of sacrotuberous ligament and posterior part of tuberosity Short head: lateral lip of linea aspera, proximal 2/3 of supracondylar line and lateral intermuscular septum.
Insertion	Lateral side of head of fibula, lateral condyle of tibia, deep fascial on lateral side of leg.
Function	Flexion and lateral rotation of the knee joint. The long head also extends and assists in lateral rotation of the hip joint.
Recommended sensor placement procedure	
Starting posture	Lying on the belly with the face down with the thigh down on the table and the knees flexed (to less than 90 degrees) with the thigh in slight lateral rotation and the leg in slight lateral rotation with respect to the thigh.
Electrode size	Maximum size in the direction of the muscle fibres: 10 mm.
Electrode distance	20 mm.
Electrode placement	
- location	The electrodes need to be placed at 50% on the line between the ischial tuberosity and the lateral epicondyle of the tibia.
- orientation	In the direction of the line between the ischial tuberosity and the lateral epicondyle of the tibia.
- fixation on the skin	(Double sided) tape / rings or elastic band.
- reference electrode	On / around the ankle or the proc. spin. of C7.
Clinical test	Press against the leg proximal to the ankle in the direction of knee extension.
Remarks	

3. Sensor Location, Clinical test details for Vastus Lateralis muscle



Muscle

Name	Quadriceps Femoris
Subdivision	vastus lateralis

Muscle Anatomy

Origin	Proximal parts of intertrochanteric line, anterior and inferior borders of greater trochanter, lateral lip of gluteal tuberosity, proximal half of lateral lip of linea aspera, and lateral intermuscular septum.
Insertion	Proximal border of the patella and through patellar ligament.
Function	Extension of the knee joint.

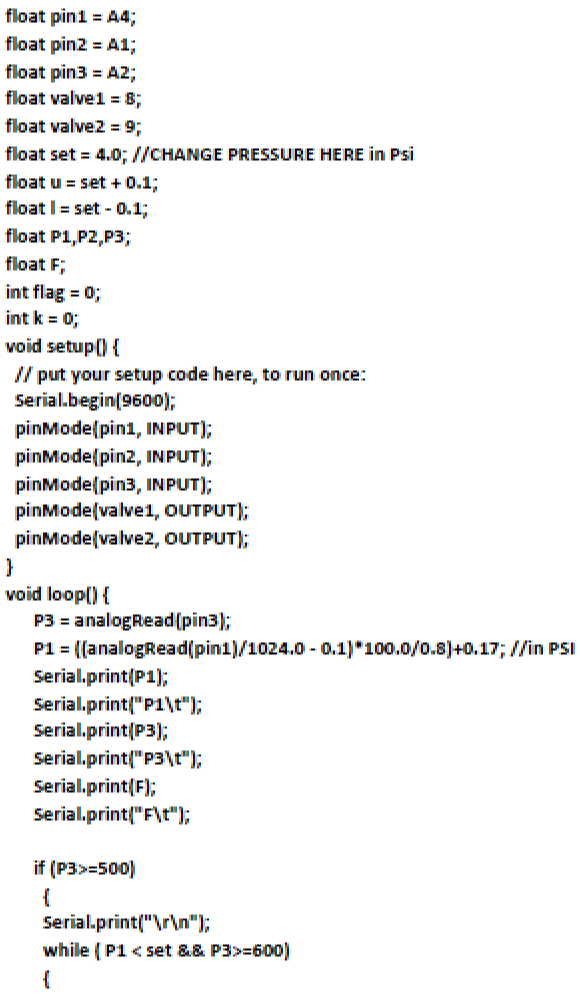
Recommended sensor placement procedure

Starting posture	Sitting on a table with the knees in slight flexion and the upper body slightly bend backward.
Electrode size	Maximum size in the direction of the muscle fibres: 10 mm.
Electrode distance	20 mm.
Electrode placement	
- location	Electrodes need to be placed at 2/3 on the line from the anterior spina iliaca superior to the lateral side of the patella.
- orientation	In the direction of the muscle fibres
- fixation on the skin	(Double sided) tape / rings or elastic band.
- reference electrode	On / around the ankle or the proc. spin. of C7.
Clinical test	Extend the knee without rotating the thigh while applying pressure against the leg above the ankle in the direction of flexion.
Remarks	The SENIAM guidelines include also a separate sensor placement procedure for the vastus medialis and the rectus femoris muscle.

Click on image for larger view

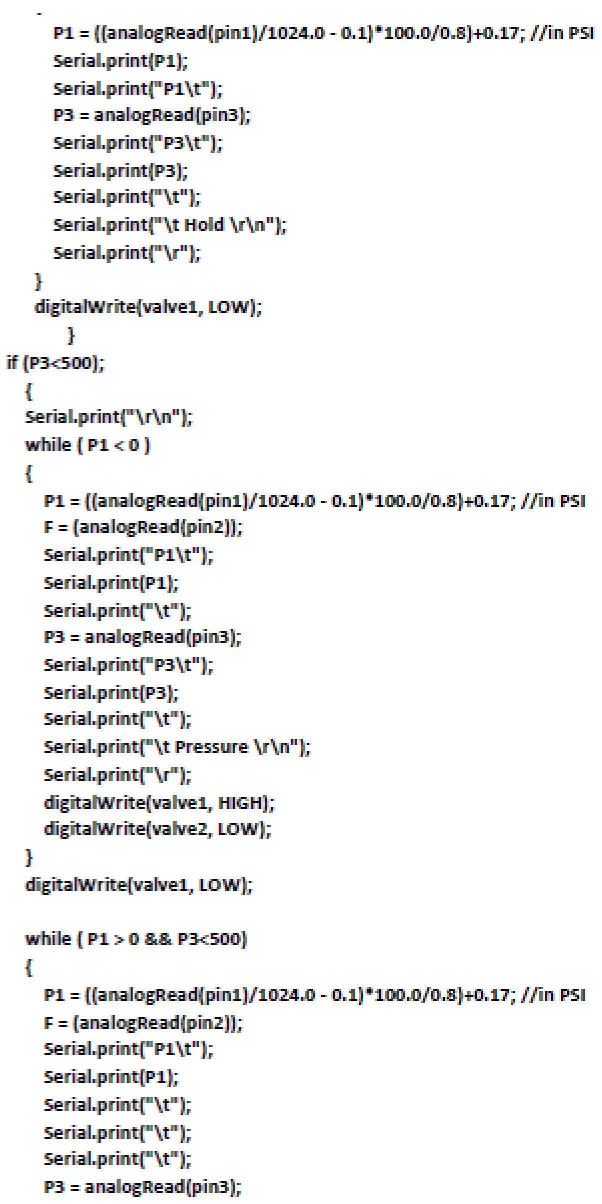
APPENDIX C

GAIT DETECTION AND ACTUATOR CONTROL CODE



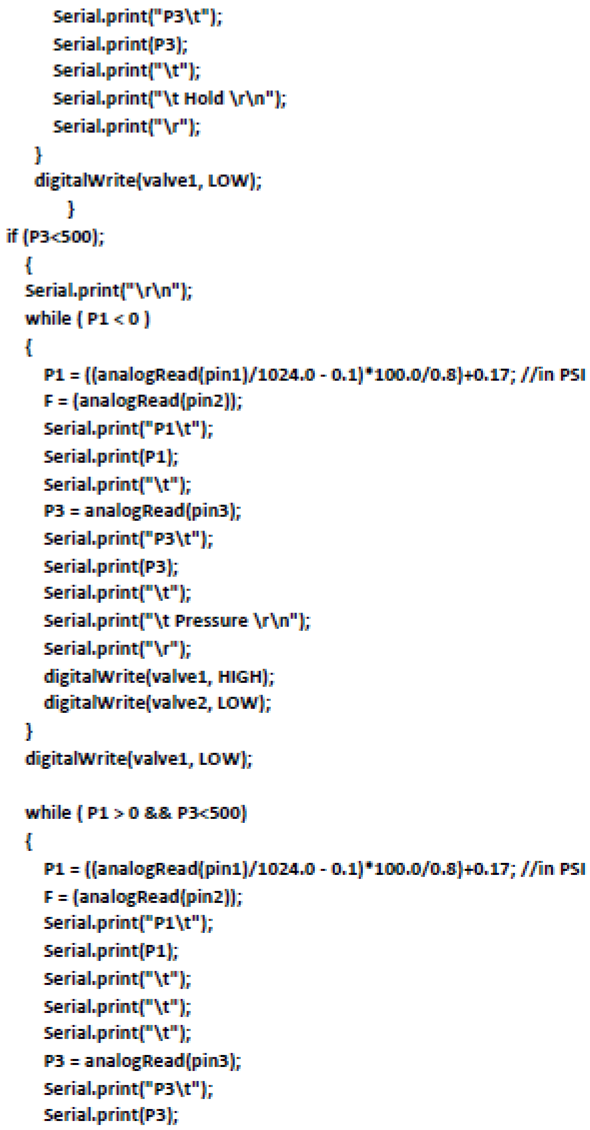
```
float pin1 = A4;
float pin2 = A1;
float pin3 = A2;
float valve1 = 8;
float valve2 = 9;
float set = 4.0; //CHANGE PRESSURE HERE in Psi
float u = set + 0.1;
float l = set - 0.1;
float P1,P2,P3;
float F;
int flag = 0;
int k = 0;
void setup() {
 // put your setup code here, to run once:
 Serial.begin(9600);
 pinMode(pin1, INPUT);
 pinMode(pin2, INPUT);
 pinMode(pin3, INPUT);
 pinMode(valve1, OUTPUT);
 pinMode(valve2, OUTPUT);
}
void loop() {
    P3 = analogRead(pin3);
    P1 = ((analogRead(pin1)/1024.0 - 0.1)*100.0/0.8)+0.17; //in PSI
    Serial.print(P1);
    Serial.print("P1\t");
    Serial.print(P3);
    Serial.print("P3\t");
    Serial.print(F);
    Serial.print("F\t");

    if (P3>=500)
     {
     Serial.print("\r\n");
     while ( P1 < set && P3>=600)
     {
```



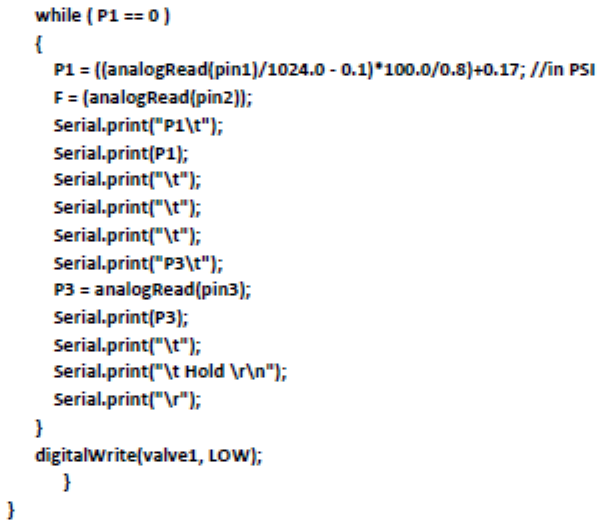
```
     P1 = ((analogRead(pin1)/1024.0 - 0.1)*100.0/0.8)+0.17; //in PSI
     Serial.print(P1);
     Serial.print("P1\t");
     P3 = analogRead(pin3);
     Serial.print("P3\t");
     Serial.print(P3);
     Serial.print("\t");
     Serial.print("\t Hold \r\n");
     Serial.print("\r");
   }
   digitalWrite(valve1, LOW);
       }
if (P3<500);
  {
  Serial.print("\r\n");
  while ( P1 < 0 )
  {
    P1 = ((analogRead(pin1)/1024.0 - 0.1)*100.0/0.8)+0.17; //in PSI
    F = (analogRead(pin2));
    Serial.print("P1\t");
    Serial.print(P1);
    Serial.print("\t");
    P3 = analogRead(pin3);
    Serial.print("P3\t");
    Serial.print(P3);
    Serial.print("\t");
    Serial.print("\t Pressure \r\n");
    Serial.print("\r");
    digitalWrite(valve1, HIGH);
    digitalWrite(valve2, LOW);
  }
  digitalWrite(valve1, LOW);

  while ( P1 > 0 && P3<500)
  {
    P1 = ((analogRead(pin1)/1024.0 - 0.1)*100.0/0.8)+0.17; //in PSI
    F = (analogRead(pin2));
    Serial.print("P1\t");
    Serial.print(P1);
    Serial.print("\t");
    Serial.print("\t");
    Serial.print("\t");
    P3 = analogRead(pin3);
```



```
     Serial.print("P3\t");
     Serial.print(P3);
     Serial.print("\t");
     Serial.print("\t Hold \r\n");
     Serial.print("\r");
   }
   digitalWrite(valve1, LOW);
      }
if (P3<500);
  {
  Serial.print("\r\n");
  while ( P1 < 0 )
  {
    P1 = ((analogRead(pin1)/1024.0 - 0.1)*100.0/0.8)+0.17; //in PSI
    F = (analogRead(pin2));
    Serial.print("P1\t");
    Serial.print(P1);
    Serial.print("\t");
    P3 = analogRead(pin3);
    Serial.print("P3\t");
    Serial.print(P3);
    Serial.print("\t");
    Serial.print("\t Pressure \r\n");
    Serial.print("\r");
    digitalWrite(valve1, HIGH);
    digitalWrite(valve2, LOW);
  }
  digitalWrite(valve1, LOW);

  while ( P1 > 0 && P3<500)
  {
    P1 = ((analogRead(pin1)/1024.0 - 0.1)*100.0/0.8)+0.17; //in PSI
    F = (analogRead(pin2));
    Serial.print("P1\t");
    Serial.print(P1);
    Serial.print("\t");
    Serial.print("\t");
    Serial.print("\t");
    P3 = analogRead(pin3);
    Serial.print("P3\t");
    Serial.print(P3);
```



```
    while ( P1 == 0 )
    {
      P1 = ((analogRead(pin1)/1024.0 - 0.1)*100.0/0.8)+0.17; //in PSI
      F = (analogRead(pin2));
      Serial.print("P1\t");
      Serial.print(P1);
      Serial.print("\t");
      Serial.print("\t");
      Serial.print("\t");
      Serial.print("P3\t");
      P3 = analogRead(pin3);
      Serial.print(P3);
      Serial.print("\t");
      Serial.print("\t Hold \r\n");
      Serial.print("\r");
    }
    digitalWrite(valve1, LOW);
        }
}
```