DESIGN OF A S ON (HARDWARE)

MOHD YASHIM WONG PAUL TZE

Report submitted in partial fulfillment of the requirements for the award of the degree of Bachelor of Manufacturing Engineering

Faculty of Manufacturing Engineering

UNIVERSITI MALAYSIA PAHANG

SEPTEMBER 2013

ABSTRACT

The Powered Exoskeleton is an electromechanical structure worn by an operator, matching the shape and functions of the human body. Exoskeletons supplements the function of the human limb by augmenting its strength, agility and endurance or at least by supplying the activation energy required to initiate the limb's movements. This project provides the detailed steps on the design of powered exoskeleton structures and considerations involved when designing it. Considerations such as ergonomics, loadings and actuator capabilities, costs and manufacturability were taken into consideration during the early steps. To be kinematically compatible with human walking motion, gait analysis or the study of human walking have been performed. Kinovea which is a video motion analysis was used to capture all the walking data. For actuation, two actuators; Pneumatic Muscle Actuator and Pneumatic Cylinders were tested for compliant actuation. Solidworks is used to design the frame and to perform Finite Element Analysis as well as a motion simulator to check compatibility with human motion. All data were compared taking actual gait data as benchmark.

ABSTRAK

Exoskeleton berkuasa adalah sejenis struktur elektromekanikal yang di pakai oleh seorang operator. Ia mempunyai ciri-ciri yang mirip bentuk dan fungsi badan manusia. Exoskeleton membantu pergerakan manusia dengan meningkatkan kekuatan, kelajuan dan ketangkasan atau dengan sekurang-kurangnya menyumbangkan tenaga pengaktifan bagi satu gerakan. Projek ini membentangkan fasa-fasa secara terperinci mengenai proses reka bentuk struktur exoskeleton berkuasa dan pertimbangan yang di buat ketika proses tersebut di buat. Pertimbangan seperti ergonomika, bebanan kebolehan actuator, kos serta kebolehmesinan di ambil kira pada peringkat pengkonsepan. Untuk menjadi serasi dari segi kinematic dengan pergerakan manusia, analisa gait atau analisa pergerakan kaki manusia ketika berjalan di buat. Kinovea di gunakan untuk merekod segala data daripada video. Dari segi aktuator, dua aktuator telah di kaji iaitu Aktuator Otot Pneumatik dan Omboh Pneumatik. Solidworks di gunakan untuk mereka bentuk rangka exoskeleton dan juga untuk menjalankan Analisa Unsur Terhingga serta untuk simulasi pergerakan untuk membandingkan keserasian dengan gerak geri berjalan manusia. Kesemua data yang di peroleh daripada simulasi pergerakan dibandingkan dengan data sebenar gerakan jalan kaki sebenar.

TABLE OF CONTENTS

APPENDICES

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

F_{a1}	Actuator force at location 1
F_{a2}	Actuator force at location 2
F_{a3}	Actuator force at location 3
m_1	Combined mass at thighs
m_2	Combined mass at leg
m_3	Combined mass at feet
l_1	Thigh length
l_2	Leg length
l_3	Feet length
θ	Angular displacement
$\dot{\theta}$	Angular velocity
$\ddot{\theta}$	Angular acceleration
g	Gravitational acceleration
τ	Torque
I	Moment of Inertia

CHAPTER 1

INTRODUCTION

1.1 Background

The powered exoskeleton is an electromechanical structure worn by an operator, matching the shape and functions of human body (Anam, K., & Al-Jumaily, A. A., 2012). Exoskeletons supplements the function of the human limbs by augmenting its strength, agility and endurance or at least by supplying the activation energy required to initiate the limb's movements. Different from conventional robotics, there is a close physical interaction between the exoskeleton and the human wearer. Close interaction means the wearer controls the exoskeleton via physical contact with sensors. This is the reverse of master-slave configurations, where there is no physical contact between the slave and the human operator, which are remote from one another (Pons, J. L., 2008). According to this concept, the exoskeleton functions as both an input device (by obtaining signals from wearer and moving to desired location) as well as a force feedback device (by providing haptic interactions between the exoskeleton and its environment).

The application of exoskeleton ranges from military use to rehabilitative use. In military applications, Matthias, H., (2007) states that exoskeletons increases the performance of soldiers through:

- Increasing payload: ability to carry or fire power, supplies, ammunition and heavier armour increasing the survival chance of a soldier after a direct hit or explosion
- Increasing speed and range: enhance ground reconnaissance and battle space coverage
- Increasing strength: ability to operate larger calibre weapons and withstand recoil as well as better obstacle clearance

Exoskeletons in this field are built with high power and efficiency as focus. Notable exoskeletons which are built for military applications are Berkeley's Lower Extremity Exoskeleton (BLEEX), Lockheed's Human Universal Load Carrier (HULC) and Raytheon XOS exoskeleton.

In the rehabilitative and assistive field, the exoskeleton provides muscular augmentation as well as structural support as functional replacements for weak limbs. The functional requirements in this field differs from military use as exoskeletons in this field places safety and ergonomic in the highest priority.

The most notable exoskeleton in the rehabilitative and assistive field is the Hybrid Assistive Limb (HAL) developed by Japan's Tsukuba University and the robotics company Cyberdyne.

HAL is a full-body exoskeleton designed to aid people who have degenerated muscles or paralyzed due to brain or spinal injuries (Guizzo and Goldstein, 2005). In HAL-5, the structure consist of nickel molybdenum and aluminium alloy which is further strengthened by plastic casing. Power assistance is provided by electric motors which helps aid the wearer in standing up, walking, climbing stairs and perform a range of other leg movements.

Regardless of application focus of exoskeleton, the limitations and problems of this technology remains the same, which are:

- Need for lighter, longer lasting and faster recharging portable power
- High complexity, technology, cost and size of system limits the ability to mass manufacture exoskeletons
- Requirement of high strength to weight materials to support the wearer as well as the exoskeleton components

1.2 Aims and Objectives

The objective of this project is to design and fabricate efficient, cost-effective, ergonomic and reproducible hardware components for a walking exoskeleton which functions as a walking assistive device for individuals with walking impairments.

1.3 Problem Statement

In the 1950s, only 4.9% of the world's population was over the age of 65. In the present date, almost 20% is over the age of 65 due to increase in quality of living and better healthcare. In Malaysia, the number of population above the age of 65 is steadily increasing from 3.99% in 2002 to 4.92% in 2012 (Trading Economics, 2012). This trend shift in population demographics demands more care towards health risk associated with aging. Among the common health risk is loss of muscle strength which leads to walking impairments.

The elderly with walking impairments have troubles moving about in their daily life. Often, they rely on using wheelchairs as a mean of locomotion. Although the performance of wheeled assistive devices is acceptable for a large portion of daily activities, the user of these devices will face difficulty in traversing through uneven terrain and manoeuvring through obstacles.

In terms of rehabilitation, overdependence on wheelchairs will cause the following:

i. Causes secondary problems; formation of contractures in the lower limbs, pressure sores, bowl infections, lower limb spasticity, osteoporosis and kidney/urinary tract infections.
ii. Reduces cardiopulmonary functions
iii. Negative psychological effects

1.4 Project Scopes

This project is focused on the design and fabrication of a wearable exoskeleton mechanical components as well as hardware selection based on human biomechanics data. The project scope is broken down into the following:

- **a.** Clinical Gait Analysis
- **b.** Design and motion simulation of exoskeleton frame
- **c.** Selection and assembly of mechanical elements
- **d.** Fabrication of frame and mechanical elements
- **e.** Live test run of exoskeleton
- **f.** Performance evaluation

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter, general concepts and terminology of walking will be introduced. This includes discussion on previous works comprising the analysis, mechanics and description of stages involved in walking. Methods employed during the design phase of various previous works on exoskeleton will be reviewed and adapted to this project. In the analysis part of this chapter, torque, power, velocity and angle of normal walking, walking with load and walking with exoskeletons designed by previous papers will be reviewed and be used as a benchmark to this project's findings.

2.2 Human Gait Analysis

Human gait analysis is defined as the systematic study of human walking. Understanding the human gait is not just important for deciding the kinematic and dynamic architecture but also for the proper selection of powered joints and exoskeleton ergonomics as well as specification for actuation components and its placement. It is important that the design of the exoskeleton mimics the kinematics and dynamics of walking so that it does not cause the walker to alter their gait. This is because gait changes have been shown to increase energy expended during locomotion (T. A. McMahon, G. Valiant, E. C. Frederick, 1987).

By definition, walking is an alternating repetitive sequence of limb motion to move forward while simultaneously maintaining stance stability (C.J Walsh, 2003). The cyclical process of events during gait is known as the gait cycle. It starts and ends the moment when one foot comes into contact with the ground, usually termed heel strike (Perry, 1992). The analysis of walking is three dimensional but in this final year project, the focus is on the sagittal plane as the largest motions, torques and powers are in this plane. (H. Kazeeroni, 2005)

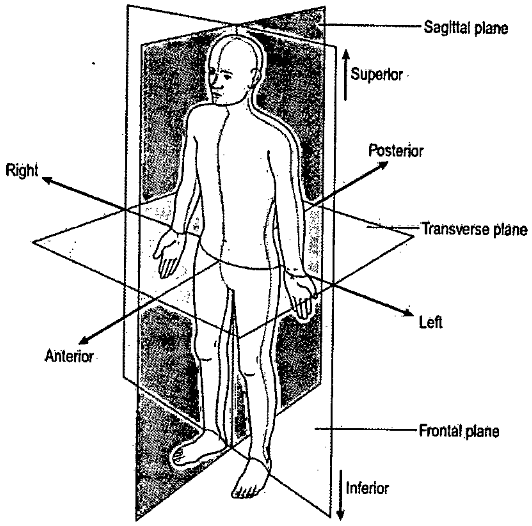

Figure 2.1: Reference planes of body in standard anatomic position (Michael, W. Whittle., 2007)

Since the key focus is on the Sagittal Plane, the motions that will be discussed throughout this thesis are Extension (positive direction) and Flexion (negative direction).

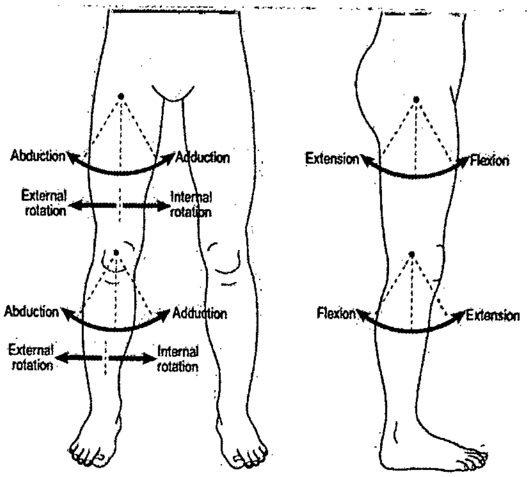

Figure 2.2: Description of direction of joint motions (Michael, W. Whittle., 2007).

For motion of ankles, the nomenclature varies slightly. Dorsiflexion is named for the upwards flexion while Planar flexion is for the downward extension of the ankle.

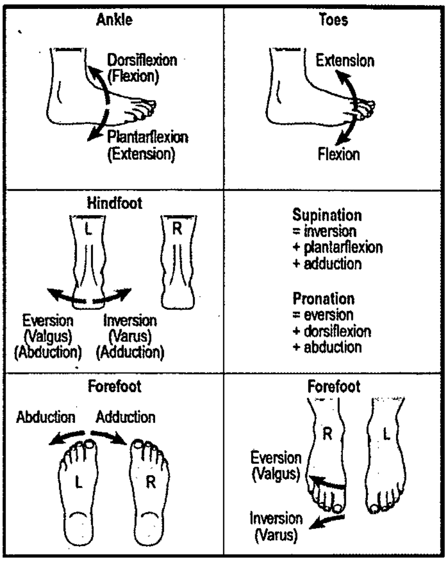

Figure 2.3: Nomenclature for Movements of the ankle, toes, hindfoot and forefoot (Michael, W. Whittle., 2007).

The sign convention for joint angle measured is referenced as positive counter clockwise displacement of the distal link from the proximal link (set to zero degrees in standing position) with the person oriented as shown in Figure 2.2. In the figure shown, the hip angle is positive whereas both knee and ankle angles are negative.

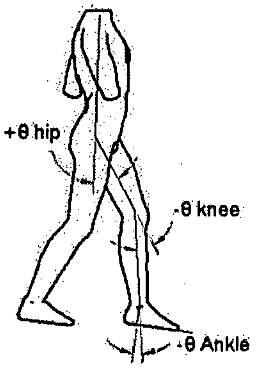

Figure 2.4: Sign convention used for joint angles (Chu *et al.*, 2005).

The following terms are used to identify major events in the gait cycle; Initial Contact, Opposite Toe Off, Heel rise, Opposite Initial Contact, Toe off, Feet Adjacent and Tibia Vertical.

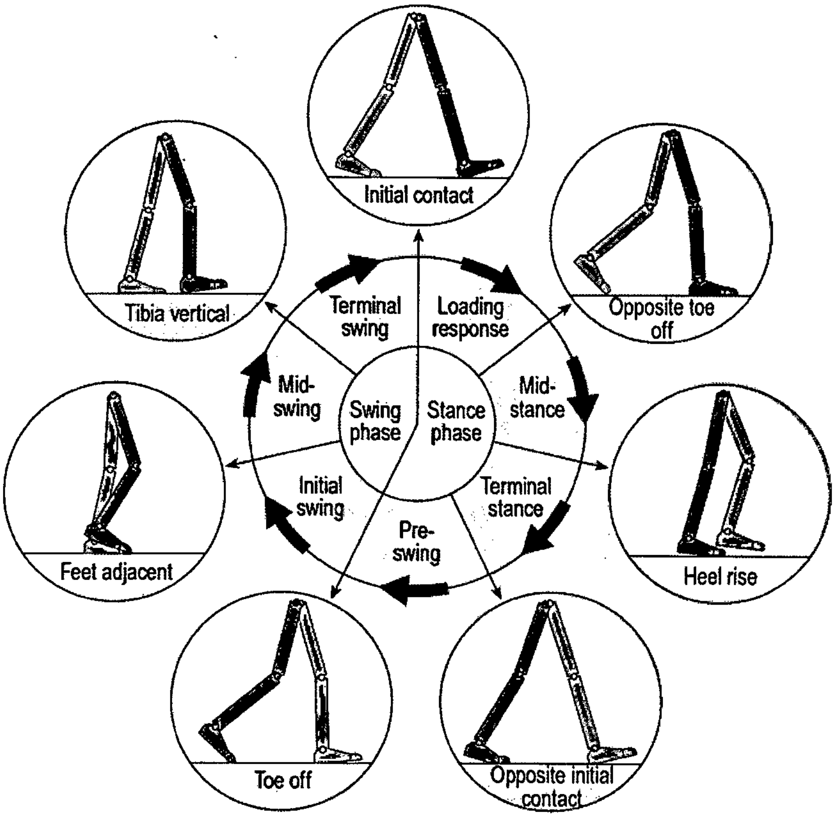

Figure 2.5: Phases and position of legs in Gait Cycle (Michael, W. Whittle., 2007)

These events are divided into two phases; the stance phase and the swing phase. During the stance phase muscles at the hip, knee and ankle functions as stabilizers of the body by decelerating forward motion. At the end of stance phase, the ankle is powered by planar flexion movement providing forward thrust. During the swing phase, the foot moves forward through air with no ground contact or support. The hip during this phase provides energy to raise the leg and swing it forward.

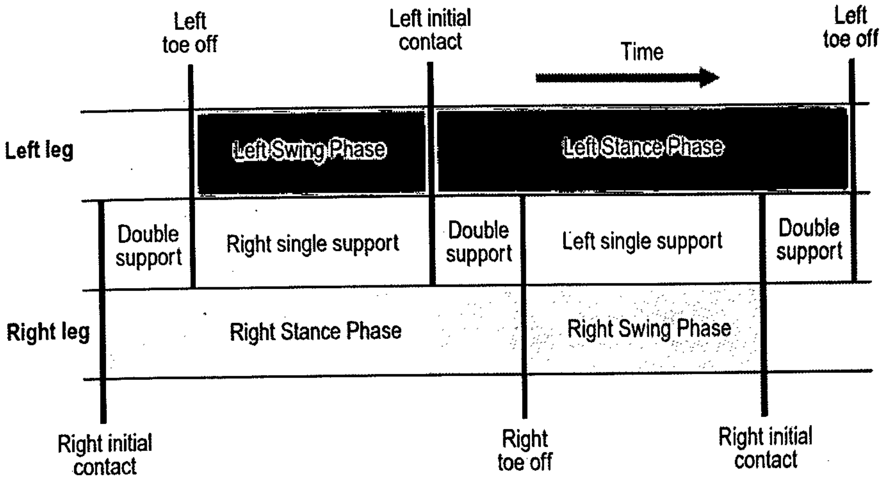

Figure 2.6: Timings of double and single support during gait cycle (Michael, W. Whittle., 2007)

During each gait cycle, there are two single support and two double support periods. The stance phase at average takes up 60% of the total cycle while the swing phase takes about 40%. The double support phase only takes up 10% each during gait cycle. This diagram is only valid for slow walking and is inaccurate at higher walking speeds. As velocity is increased, stance phase duration is reduced, whereas swing phase duration increases. (Sheila A. Dugan, Krishna P. Bhat, 2005)

2.3 Power Requirements during Walking

In the human body, muscles contracts to provide locomotion or force. Voluntary muscular contractions can be categorized into the followings based on their length changes or force level:

1. Concentric Contractions

   Force generated by muscle is sufficient to overcome resistance, and muscle shortens as it contracts. Positive work is performed during this type of motion movement which provides limb acceleration and powers such as hip flexion during pre-swing.

2. Eccentric Contractions

   Force generated is insufficient to overcome external load and muscle fibres lengthens as they contract. Eccentric movements are generally for decelerating limbs for movements. Negative work is performed during this type of contraction. Energy is stored by the limb while resisting pull of gravity.

3. Isometric Contractions

   Muscle remains the same length as before contraction. The muscle force exactly matches the external load. This type of contractions occur during movements that involve holding a position without moving. In walking, many muscles contract isometrically to maintain upright posture against gravity.

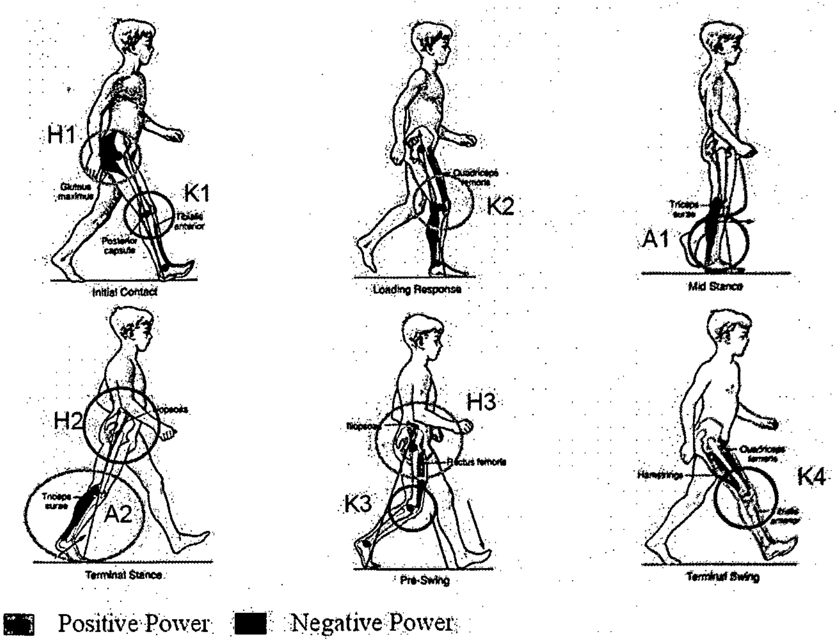

Figure 2.7 Significant regions of positive and negative work in walking (C.J. Walsh *et al.*, *2006*).

Figure 2.7 shows significant regions of positive and negative power during human gait. The red and blue circle indicates region of positive power and negative power at hip, knee and ankle during phases in the gait cycle. A large portion of positive power during gait were generated from H1 and H3 at the hip and A2 at the ankle. The knee dissipate large amounts of energy during gait except at K2 region as the body's center of mass is raised. During A1 at ankle and H2 at hip, negative power is generated to control the body's forward movement against gravity.

Power profiles of the hip, ankle and knee in the sagittal plane were plotted (C.J. Walsh *et al.*, 2006) against data obtained from previously done Clinical Gait Analysis (A.J Van den Bogert, 2004; C. Kirtley, 1998; J. Linskell, 1997). In their research (C.J. Walsh *et al.*, 2006), they estimated that the weight of the exoskeleton and the load it carries to be 60 kg and the human wearer to be of 75 kg. In estimating torque and power requirements at hip joint of the exoskeleton, the normative data were scaled to a 135 kg person. The torque vs. angle plots they used are obtained from CGA data (J. Linskell, 2006) and is for walking speed of 0.8 m/s. The assumptions that were made in applying biomechanical gait data to the exoskeleton design are:

1. The exoskeleton carries its own weight, power supply and payload.
2. Joint torques and joint powers scale linearly with mass. This assumption seems reasonable as previous research shown that increase in load being carried is proportional to increase in ground reaction forces (R. Lloyd, & C. B. Cooke, 2000)
3. Exoskeleton will not greatly affect the gait of the wearer.

1. Hip

Throughout normal gait, the human hip joint follows a roughly sinusoidal pattern with the thigh flexed forward on heel strike and the hip moves through extension during the stance as body is pivoted at the ground, over the stance leg in a reverse pendulum-like motion. Positive power is required on heel strike to raise the center of mass of the human over the stance leg.

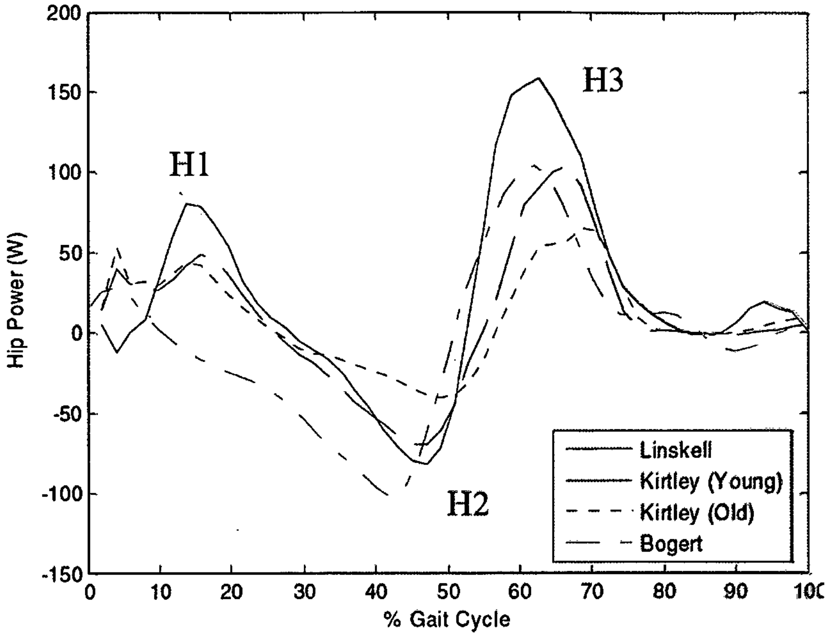

Figure 2.8: Hip joint power profile scaled for a 135kg person as a function of the gait cycle (C.J. Walsh *et al., 2006*).

H1 is a small region of positive powers which corresponds to backward movement of the leg (concentric hip extension) during loading response. H2 is a region of negative power which corresponds to eccentric hip flexion during mid-stance and H3 is a region of positive power, corresponding to concentric hip flexion during pre-swing and initial swing.

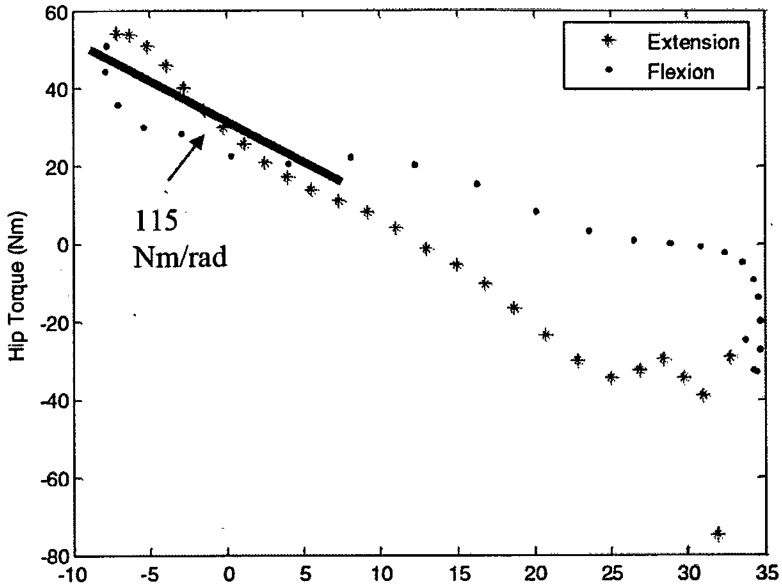

Figure 2.9: Hip angle versus hip torque for walking speed of 0.8m/s (C.J. Walsh *et al., 2006*).

Assistive power could be added in the H1 and H3 regions by using actuators. Energy storing passive elements such as springs can be placed at hip joints to absorb negative energy and H2 and release it during H3 to assist in swinging the leg forward. In Figure 2.9, a linear relationship can be observed between hip joint angle and torque. C.J Walsh *et al.* (2006) estimated that the required spring constant as 115m/rad.

Range of Motion	-20 deg to 45 deg
Max Joint Velocity	4 rad/s
Max Joint Torque	130 Nm
Max Joint Power	150 Watts
Extension Spring Constant	115 Nm/rad

Table 2.1: Specification for the hip joint of the exoskeleton that were extracted from gait data (C.J. Walsh *et al.*, 2006)