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<tr>
<td>学位授与大学</td>
<td>筑波大学 モダル・ハサン博士 ( \text{Ph.D.} )</td>
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<tr>
<td>学位授与年度</td>
<td>2016年</td>
</tr>
<tr>
<td>報告番号</td>
<td>東京甲第 0000号</td>
</tr>
<tr>
<td>年月</td>
<td>公開日付未定</td>
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<tr>
<td>URL</td>
<td><a href="http://hdl.handle.net/2241/00151524">http://hdl.handle.net/2241/00151524</a></td>
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Body Synergy Approach of Exoskeleton Robot Control for Hemiplegia

Graduate School of Systems and Information Engineering, Department of Intelligent Interaction Technologies
Modar HASSAN (201330222)

I. INTRODUCTION

A. Background

Locomotion deficits are fatal to human well being, self dependence, work and social activities. According to the World Health Organization (WHO) there are annually 5 million people who suffer from permanent disability after stroke, being the biggest cause of major disability in the United Kingdom, for example. Technology of wearable exoskeleton robots offer great potential to assist the locomotion of people with deficiency in gait function due to neuronal injuries, such as hemiplegia and paraplegia [1]–[7]. Providing assist with an exoskeleton robot to compensate for lost / deficient gait function requires estimation of motion intention [7], and proper operation of the robot in coordination with the remaining gait function of the user [8].

Several methods of human motion intention estimation have been investigated and realized for operation of human assistive exoskeleton robots [3], [7], [9], [10]. These methods vary according to the intended assistance level (complete reproduction of movement, support of movement etc.), the level of injury or dysfunction of the patient (muscle weakness, partial or complete paralysis etc.), and the structure of the assistive robot itself. The biological signals are reliable information to estimate human motion intention [9]. However, in the case of neuronal injury / dysfunction such as stroke related hemiplegia or spinal cord injury, biological signals are different from those of healthy subjects, or even not available. Therefore, reference trajectory for the assisted limb(s) needs to be computed, and the motion intention is required to be estimated in different ways [2], [3]. Kawamoto et al. [2] developed a control system for single leg version of HAL [1] by using FRF (Floor Reaction Force) sensors to detect the gait phase shifting intended by the patient. The robot is then operated by assembling segments of reference trajectories to restitute the motion of the impaired limb. And more extended work has been realized for paraplegia patients in [3] with the use of body posture information to convey the motion intention of paraplegic patients. For another exoskeleton robot, eLEGS, Krausser and Kazerooni [7] developed a Human Machine Interface for SCI patients with two crutches. The patient convey his/her intention to the robot using the two crutches to perform Four-Point walking gait with assistance from the robot and the crutches. The sensor suit comprises load measurement mechanism on the crutches, inertial sensors on the arms, force sensors in the shoe insole, and angle sensors on the robots actuators. The robot uses hip and knee angle measurements, foot pressure, arm angle, and crutch load to determine the current state and state transition in a state machine controller customized for Four-Point gait.

The mentioned paradigms do not consider human inter-limb synergies in gait. Human gait is not only a function of the lower limbs, but also a coordination between upper and lower limbs [11]–[13], adding to balance and cognitive functions as well. Research on human locomotion have shown evidence for the existence of a task-dependent neuronal coupling of upper and lower limbs [14], [15]. Also, research on inter-limb coordination after stroke [16] indicated that stroke patients in acute stage have close to normal synergies in the unaffected side, and that synergies in the chronic stage depend on the level of recovery. It was also demonstrated that high functioning stroke patients preserve the ability to coordinate arm and leg movement during walking [17]. In regard to rehabilitation, Ferris et al. [18] suggested using the arms’ swing to facilitate lower limb muscle activation because of the neuronal coupling between upper and lower limbs in rhythmic locomotion tasks. Behrman and Harkema [19] have also shown that reciprocating arm swing in a natural and coordinated form facilitates stepping.

B. Purpose of this Research

The field of robot assisted locomotion is yet to explore the concept of synergies in the control strategy. In this work we investigate the use of synergies in robot control for robot assisted locomotion. We define the case of hemiparesis as a target of this research for the following reasons; First, hemiparesis is one of the prevailing causes of physical disability. Second, persons with hemiparesis have an affected side, and a less-affected side, which adds extra value to consideration of synergies in assisted locomotion, to keep coordination between healthy and assisted limbs. Third, there are several reports that indicate the preservation of inter-limb coordination ability in persons with hemiparesis, which makes them good candidates to use and benefit from prospect synergy based systems. Last, persons with hemiparesis usually use a walking aid cane to help maintain balance and support body weight. Which represents a valuable resource to be harvested, in terms of human robot interface, to instrument the cane with sensors and use it as a device to capture upper limbs motion, and to control the assistive robot.

For this purpose we set to explore the concept of body synergies in robot assisted locomotion in a series of investigations.
First, we investigate the inter-limb synergies of walking with a walking aid cane to verify our initial hypothesis, and acquire the healthy body synergies required for development of a synergy based robot control system. We then formulate a body synergy based motion intention estimation and robot control method considering the case of hemiparesis. Second, We develop a wearable gait measurement and robot control system, a system calibration method to integrate motion sensors with the user’s body, and a control logic for the system. Finally, we devise and conduct a series of experiments to: (i) Verify the proposed method and developed hardware with healthy subjects. (ii) Conduct pilot trials with persons with hemiparesis and the developed system to verify their ability to use the system. Here we measure improvements in gait variables while using the robot, and compare the synergy based method to an alternative autonomous robot control method. (ii) Conduct synergy analysis of robot assisted locomotion on the trials with hemiparetic subjects. Here we measure and quantify kinematic (body joints) synergies and muscle synergies, in order to investigate differences between the two systems and infer human-robot interactions in robot assisted locomotion. In the following sections we present each of these steps. Then we discuss the obtained results, and conclude with a summary of this work’s novelty and impacts, and future directions.

II. METHODS

In this section we describe the methods used in this research. The methods include definition and analysis of synergies in gait, the formulation of a human motion intention method based on synergistic characteristics, and how it could be applied to exoskeleton robot control. The technical implementation - development of hardware and software to implement these methods - is presented in a following chapter.

A. Body Synergies

Synergies in human gait are the manifestation of Central Nervous System (CNS) control of body limbs (muscles) to achieve locomotor tasks. In related literature, synergies are investigated in terms of kinematics of lower (and upper) limbs [16], [20], or as muscle synergies extracted from muscle activation signals, EMG, to describe coordination of limbs (muscles) in locomotion [21].

1) Kinematic Synergies: We use the term Kinematic Synergies to refer to body synergies extracted from kinesiological information of gait. More precisely, angles and angular velocities of body joints (Hip, knee, shoulder, etc.) are used in the literature to quantify kinematic synergies in motion / locomotion tasks [20]. Recorded joint angle trajectories are usually recorded with a motion capture system, and then statistical methods such as Principal Component Analysis (PCA) or Factor Analysis is used to extract synergies from the observed variables. Since forward gait has the most pronounced joints’ range of motion in the sagittal plane, most research suffices by using sagittal plane trajectories.

2) Muscle synergies: Muscle Synergies is the widely used term for body synergies extracted from muscle activation signals, measured by means of Electromyography (EMG). EMG signals of several muscles are recorded in the studied motion / locomotion task, and statistical methods are used to extract synergies between EMG signals. In recent literature muscle synergies were used to measure and quantify deviations in CNS motor control brought upon by disability. By comparison of the number and structure of synergies between paretic and non-paretic limbs of hemiparetic subjects, the number and structure of synergies were found to be a good indicator of the impairment level [21].

3) Synergies in Robot Assisted Locomotion: Muscle synergies provide a deep insight into the operation of CNS in locomotion since they represent the direct activation signals on muscle surfaces. Kinematic synergies, on the other hand, are the outcome of muscle activation, passive dynamics, and mechanical constraints of gait. For the purpose of exoskeleton robot control, we consider kinematic synergies to be an appropriate bases for the following reasons:

1) Current exoskeleton robot technologies mostly rely on actuators fitted on limb joints that only provide assist in the sagittal plane.
2) It is possible to make direct mapping from the motion intention estimation algorithm to the robot’s actuators if both are in joint-angle coordinates.
3) It is feasible to measure joint angles on body limbs by using inertial motion sensors.

In the case of Hemiparesis, patients usually uses a cane in the healthy arm (contralateral to the affected leg) to support their body weight and balance [22], and the cane’s motion is in phase with the affected leg. The role of cane as an orientation and sensory input [23] motivated us to investigate its role in the synergistic coordination of limbs in gait. Having a cane, the arm is more significantly incorporated in the coordination of gait, and the movement of cane can be expected to be naturally a part of the upper-lower limb synergies. For this purpose we proposed to conduct gait analysis with walking aid cane.

4) Body Synergy Analysis of Gait with Walking Aid Cane: We designed an experiment to investigate the kinematic body
synergies of gait with a walking aid cane. We recorded gait patterns of seven healthy subjects of walking with / without a cane using a motion capture system (Motion Analysis .co). The joint angles and angular velocities of the shoulder, elbow, hip and knee joints for the right and left side limbs, as well as the tilting angle and angular velocity of the cane were computed. Three cases were inspected: (i) Joint coupling of the lower limbs. (ii) Joint coupling of the upper and lower limbs. (iii) Coupling of the cane and the lower limbs.

In this investigation we used Principal Component Analysis to investigate the lower limbs’ inter-joint and cane synergies. PCA was performed on three sets of variables. Two sets of variables are the joint angles of lower limbs with their derived angular velocities, and the joint angles of upper and lower limbs with their derived velocities. The other set of variables is the joint angles of the lower limbs and the tilting angle of the cane with their derived angular velocities. We investigated the number of Principal Components (PCs) explaining the major percentage of data variation for each set of variables among the subjects. The accumulated proportion of the first Principal Components (PCs) that exceeds 95% was considered in this study. The first 4 PCs accounted for more than 95% of the data variation for all the three sets of variables (Fig.1), except for subjects 5 and 7 while walking with cane, where the percentage of their first 4 PCs was 94.48% and 94.67% respectively, which still represents the major percentage of data variation. This result supports our hypothesis that cane’s motion is part of the upper-lower limb synergies, and thus can be used in a synergy based system for motion intention estimation and robot control.

B. Body Synergy based Exoskeleton Robot Control

We propose a method for exoskeleton robot control based on synergetic relationship between body limbs. The method can be devised for exoskeleton control in hemiplegia, paraplegia, and healthy people. Here we describe the algorithm developed for hemiparesis. The method uses kinesiological information from the walking aid cane and the less affected side’s leg to estimate the intended motion on the affected side’s leg. Estimation is performed based on inter-limb gait synergies extracted from healthy people in real time. Figure 2 shows the concept of the proposed method and measured joint angles, and an illustrative diagram of signal flow in the proposed method.

Using the synergies extracted from walking with cane of the healthy subjects, in the form of principal components, we formulated the method for control using the cane for hemiparetic people [24]. We adapted a method for limb motion estimation called Complementary Limb Motion Estimation (CLME) [8], [10] in which trajectories for affected limbs can be estimated in real time from other less affected limbs. We use the synergies of walking with cane from healthy people as means for estimation of motion on the affected side, from voluntary input in the form of motion information of the cane and the less affected side, as in the following equation:

\[ A = \Gamma \begin{bmatrix} U \\ C \end{bmatrix} \]

All motions described here are in the sagittal plane. \( A \) is the motion of the affected side to be estimated: hip and knee joints’ angles and angular velocities, \( U \) is the motion of the unaffected side: hip and knee joint’s angles and angular velocities and \( C \) is the cane’s motion: tilting angle and angular velocity. The principal components matrix \( \Gamma \) is matrix of principal components used for estimation, which is already extracted from the gait of 7 healthy subjects. This matrix, \( \Gamma \), provides linear mapping from unaffected side and cane motion to the affected side’s motion. \( \Gamma \) was also calculated from motion data in the sagittal plane. In this sense the developed method is semi-autonomous. Compared to other control methods of lower limbs exoskeleton robots based on kinesiological information [2], [3], [7], this method captures input from both the lower limbs (unaffected leg motion) and the upper limb (cane motion). Using input from the cane represents a direct voluntary channel to control the assisted motion on the affected side. And the use of motion information from the less affected side helps generating assisted motion in coherence with the user’s remaining gait function as well. Therefore, the proposed system is theoretically expected to be able to adapt to the user’s gait pattern due to the nature of synergy based control, while offering a voluntary input channel to modify the assisted motion according to the user’s intention as well.

III. System Overview

In this section we describe the hardware development and implementation of the proposed synergy based robot control method. This includes the development of a wearable system for gait measurement and robot control, system calibration, and the logic for robot control.
A. Wearable System

We developed a wearable gait measurement system based on inertial sensors, force sensors and embedded microprocessors to control exoskeleton robot [25]. The system consists of three IMU modules: two modules fitted on the thigh and shank of the unaffected leg to acquire its motion (Figure 3.a), and a main unit fixed on the cane (Figure 3.b). Modules on the thigh and the shank acquire the motion (angle and angular velocity) of the hip and knee joints of the unaffected leg. The shank module is connected to the thigh module with wired serial communication, while the thigh module streams motion data from both thigh and shank modules to the main unit on the cane (Figure 3.a,b). The module on the cane is the main unit (Figure 3.c). It receives motion data via Bluetooth from the thigh module, acquires the cane’s motion (angle and angular velocity) from its own IMU, acquire the ground contact information from force sensors in the shoes of the robot through wireless communication, acquire the cane’s ground contact information from FSR sensors, compute the control commands for the robot according to the current status, and stream those commands to the robot via WIFI communication. The force sensors embedded in the shoes consist of floor reaction force sensors under the heel and forefoot of each foot. The sensors provide continuous measurement of the floor reaction forces, and are used together with the FSR sensors on the tip of the cane to monitor the ground contact patterns for start-walk-stop support as well as for modification of control parameters in stance and swing phases.

B. System Calibration

The sensor fusion algorithm for each IMU takes readings from 3-axis Gyroscope, 3-axis Accelerometer and 3-axis Magnetometer, and outputs the coordinates of sensor frame relative to reference frame (earth frame) in quaternion form. Performance of the algorithm is described in [26], accuracy: $<0.8^\circ$ static RMS error, $<1.7^\circ$ dynamic RMS error. In order to find the joint coordinates from the sensor coordinates a transformation is needed from the sensor frame to the joint frame. For performing this transformation we followed a procedure similar to that in recent methods [27], [28]. The transformation from sensor frame to joint frame is given by Equation (6)

$$q^J = q^E_S \otimes q^J_S$$  \hspace{1cm} (6)

The quaternions $q^E_J$, $q^E_S$ and $q^J_S$ represent the orientation of joint frame relative to earth frame, sensor frame relative to earth frame, and joint frame relative to sensor frame, respectively. And operator $\otimes$ is the quaternion multiplication. Therefore, to transform the sensor frame to joint frame we need to find the orientation of joint frame relative to sensor frame $q^J_S$. To do this we assume an initial position where the joint frame is known relative to earth frame. In our system we consider the initial position as quiet standing with the leg fully extended (leg completely vertical) and the person is roughly facing north. In this pose we assume that the joint frame for both hip and knee joints is identical to earth frame. From this position we can extract the quaternion of joint frame relative to sensor frame as in Equation (7)

$$q^E_J = (q^E_S)^{-1} \otimes q^J_S$$  \hspace{1cm} (7)

After calculating $q^E_J$ from the initial position we can use it to find the joint coordinates from the sensors coordinates assuming that the sensor mounting on the limb segment will not change while walking (sensor is attached firmly on the limb segment). We find the knee joint coordinates from the sensor fixed on the shank, and the hip joint coordinates from the sensor fixed on the thigh. Then we extract the joint angles in the sagittal plane since only motion in the sagittal plane is required in our system (the robot only provides assistance in the sagittal plane).

For the cane module this procedure was not required since the module is permanently fixed to the cane and well aligned to its axis. Therefore, just extracting the angle in the sagittal plane from the sensor’s frame is adequate to produce the required cane’s tilting angle.

C. Robot Control

In our work we use the single leg version of Robot Suit HAL. The hybrid control algorithm of Robot Suit HAL [1] consists of a human voluntary control and an autonomous control. The wearer’s voluntary muscle activity is obtained from the bioelectrical signals, detected at the surface of the muscles, and then the required assist torque of the actuators is computed from the estimated joint torque. An autonomous control is also implemented based on the pre-determined motion primitives, together with the voluntary control method. In this work we provide the control reference to the robot from the developed wearable measurement system, and the robot’s embedded motor control algorithm handles the execution. This modular approach for robot control allows for stacking additional modules of control in the future, allowing the capacity for further considerations (e.g. balance monitoring and head orientation).

Robot control with the developed wearable system will be explained here in detail. The system monitors the status of a start-stop button fitted on the handle of the cane and the ground contact patterns of the feet and the cane to detect start, walk, and stop conditions (Figure 7). We figured the start and stop conditions for this particular version considering the case of left side hemiplegia, where the user would be holding the cane with the right arm (unaffected side), and the robot would be fitted on the left leg (affected side). In this case we consider that the user would typically start with the left leg and the cane, since the right (unaffected) leg is more capable of supporting the body weight and balance requirements for starting. Accordingly, the start assist is triggered when the button is on, the right foot ground contact force is large, and the left foot and cane ground contact forces are small (Figure 7). Transmission to the continuous walking mode is made at the next heel strike of the assisted leg, a state at which the unaffected leg is near to toe-off, and the cane is at contact with ground or close to it (Figure 7). From this point assistance would be based on synergies based motion
estimation from the cane and unaffected leg, as explained in the previous section. The estimated trajectories are streamed to the robot, and tracked with the actuators on the robot’s hip and knee joints with PD controllers. The ground contact information from the robot’s feet are used to modify control parameters in different conditions (Stance, Swing). To stop walking the user pushes the handle button again to release, then at the next heel contact of the unaffected leg (Figure 7), toe-off of the affected leg, the stop motion would start, leading to quiet standing condition (Figure 7). This pattern is also based on the stopping motion being supported by the unaffected leg.

IV. Experiments

We devised and conducted a series of experiments to verify and evaluate the function of the proposed method and developed system in healthy and hemiparetic subjects. Here we present these experiments with their goals and outcomes.

A. Verification Experiment with Healthy People

Objective: We devised this experiment to verify function of the developed method with healthy people, and to test the function of the developed wearable gait measurement and robot control system against a motion capture system.

Setup: We implemented the proposed synergy based control method using two systems, one is implemented with a 3D-Motion Capture System (MOCAP), and one with the developed wearable systems based on IMU’s. We asked four healthy subjects to walk on a treadmill with the MOCAP and wearable systems. Experiments were done with a left leg version of Robot Suit HAL, with the cane being used in the right arm (Figure 4.a). We only used the continuous walk support, to avoid any fall risks that could result from using the start and stop support on a treadmill. We evaluated the resulting gait variables for both cases and compared the results among the two.

Results

We extracted and compared the trajectories and step related gait variables from the walking trials. For each subject we extracted 10 consequent gait cycles from a trial of walking with the wearable system and 10 consequent gait cycles from a trial with the MOCAP system.

The joint angle trajectories show close to normal assisted motion trajectory on the robot’s hip and knee joints, compared to that of the unassisted motion on the right leg’s hip and knee trajectories (figure 4.b). However, the range of motion on the robot’s knee was smaller than that on the other side. This observation has several possible underlying causes. One is imperfections in the motion estimation algorithm, another is the change in balance and gait dynamics resulting from wearing a robot on one side of the body. From the cane’s trajectory we note some variation in range between the subjects, as we
encouraged subjects to adjust the motion of the cane to reach more comfortable gait.

Though subjects walked at the same speed on the treadmill, they had different body constitutions and walked at their own preferred cadence (figure 5). Subjects had slightly varying step length between the right and left sides (figure 6). Which reflected on the symmetry ratio (considered here as the ratio of right step to left step). Subjects 1 and 2 achieved close to 1 (more symmetrical gait) ratios for both the wearable system and MOCAP trials, while subjects 3 and 4 had more varying symmetry ratios, closest to 1 is the wearable system trial of 4.

B. On-ground start and stop experiment

Objective & Setup: We conducted this experiment to verify the usability of the start and stop functions in the developed system. We asked one healthy subject to walk on ground with the robot and developed wearable system. Function of the system and start stop function were explained to the subject. The subject performed 7 steps of walking on ground including start and stop steps.

Result: The subject was able to successfully walk with the robot, and transitions from start to continues gait to stop were performed successfully as shown in trajectories and transition moments in figure 7.

C. Pilot Study with Hemiparetic Subjects

Objective: In this investigation we set to verify the clinical applicability of the developed exoskeleton control method with hemiparetic persons. The objective of this experiment is not to use the method in a clinical application such as rehabilitation, rather to verify the applicability of the proposed method and developed system in such a clinical environment. Also, the objective is to compare the performance of developed method relative to an alternative autonomous method based on pre-recorded gait trajectories, and detection of intended phase shift from shoe insole sensors. The outcomes assessed in this experiment are:

1) The subject being able to walk with the system (control the robot with the wearable sensors and cane).
2) The step length of right and left legs when walking with / without the robot (symmetry ratio).
3) The joints’ range of motion when walking with / without the robot (hip and knee joints on both sides in the sagittal plane).
4) The cadence and time for 10 meters when walking with / without the robot.

Subjects: In collaboration with the Physical Rehabilitation Department in the University of Tsukuba Hospital we recruited five hemiparetic persons as test-pilot volunteers to evaluate the clinical applicability of the proposed method. The subjects were all left side hemiparetic who are using a walking aid cane, or have used a cane at some point after acquiring the hemiparetic condition. All subjects signed an informed consent, and all procedures were approved for by the ethics committee in the University of Tsukuba. The subjects’ clinical condition and locomotion ability are shown in Table ??.

Setup: We asked the subjects to walk on flat ground in a 16-camera motion capture room. Each subject walked the 10 meters pathway two times without the robot. Those who were able to use the robot walked with the developed system, and then with the autonomous control system. There was no training sessions prior to the experiments, and all subjects
TABLE I. TABLE OF SUBJECTS AND THEIR RESPECTIVE CLINICAL CONDITION / LOCOMOTION ABILITY.

<table>
<thead>
<tr>
<th>Subject (SEX:AGE)</th>
<th>Stroke Type</th>
<th>Affected Brain Side</th>
<th>Stroke Location</th>
<th>Duration from Stroke</th>
<th>Brunnstrom Stage</th>
<th>Barthel Index</th>
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<tr>
<td>M:58</td>
<td>Cerebral Hemorrhage</td>
<td>Right</td>
<td>Putamen</td>
<td>5 years</td>
<td>IV</td>
<td>75</td>
</tr>
<tr>
<td>M:44</td>
<td>Subarachnoid Hemorrhage</td>
<td>Right</td>
<td>Middle Cerebral Artery</td>
<td>4 years</td>
<td>IV</td>
<td>95</td>
</tr>
<tr>
<td>M:46</td>
<td>Cerebral Infarction</td>
<td>Right</td>
<td>BrainStem</td>
<td>8 years</td>
<td>V</td>
<td>95</td>
</tr>
<tr>
<td>F:62</td>
<td>Cerebral Hemorrhage</td>
<td>Right</td>
<td>Thalamus</td>
<td>8 years</td>
<td>IV</td>
<td>85</td>
</tr>
<tr>
<td>M:52</td>
<td>Cerebral Hemorrhage</td>
<td>Right</td>
<td>Putamen</td>
<td>18 years</td>
<td>III</td>
<td>95</td>
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Results: Three participants were able to walk with the robot (M:58, M:44, M:46). Following data analysis and results are only for the three subjects who were able to walk with the robot. The first trial, 10 meters, of each condition was considered as a familiarizing phase and was not used in the analysis. Only data from the second trial of each condition was used to create the results.

Joint range of motion: When walking without the robot, subjects had similar range of motion on the hip joint between right and left legs, but the left side’s (affected side) knee suffered a pronounced decrease in range of motion compared to the less-affected side (Figure 9). When walking with the robot, with both the autonomous system and the synergy based system, there was an increased range of motion on the affected side’s knee joint compared to walking without the robot, while the affected side’s hip joint range of motion varied in decrease or increase compared to walking without the robot. It can be noted that there was also a difference in joints’ range of motion on the less-affected side as well, though not directly acted on by the robot, which was in general a decrease in range of motion of these joints.

Step length: There was no obvious trend in the increase or decrease of the step length of either legs among the subjects (Figure 10). As for the symmetry ratio (right leg step length to left leg step length), subjects had better symmetry ratio (value closer to 1) without the robot and with the synergy based system compared to that with the autonomous system. By comparison of the synergy based system and no-robot conditions, we found that two out of the three subjects had better symmetry ration with the synergy based system, while one had better symmetry ration without the robot.

Cadence and speed: Subjects were instructed to walk at their preferred speed in all trials. All subjects walked slower (time for 10 meters) and at a lower cadence (steps per minute) with the robot compared to walking without the robot (Table II).

TABLE II. CADENCE AND TIME FOR 10 METERS FOR ALL SUBJECTS.

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<thead>
<tr>
<th></th>
<th>Cadence</th>
<th>10 Meters Time</th>
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<tr>
<td>S1 No Robot</td>
<td>35 (step/minute)</td>
<td>20.32 (Sec)</td>
</tr>
<tr>
<td>S1 Robot (autonomous system)</td>
<td>29.52</td>
<td>22.22</td>
</tr>
<tr>
<td>S2 Robot (synergy based system)</td>
<td>26.75</td>
<td>22.43</td>
</tr>
<tr>
<td>S3 Robot (autonomous system)</td>
<td>34.03</td>
<td>16.96</td>
</tr>
<tr>
<td>S2 Robot (synergy based system)</td>
<td>33.5</td>
<td>15.64</td>
</tr>
<tr>
<td>S3 NG Robot</td>
<td>36.75</td>
<td>18.32</td>
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<tr>
<td>S3 Robot (autonomous system)</td>
<td>25.94</td>
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<tr>
<td>S3 Robot (synergy based system)</td>
<td>26.75</td>
<td>22.43</td>
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D. Synergy Analysis in Assisted Locomotion

Objective: The concept of synergy analysis has surfaced in recent literature of motion analysis [21], [29]. In assisted locomotion, kinematics synergies are a result of the final outcome of robot assisted gait captured by the motion capture system, while the muscle synergies are a direct result of the user’s intended motion. Therefore, by comparing the kinematic synergies with corresponding muscle synergies under different control systems, we can infer the interaction between the user...
and the robot. We propose such synergy comparison as a criteria to evaluate the function of different exoskeleton robot control system in regard to synergic cohesion with the user’s gait.

Method: EMG recordings were acquired from the pilot study, as explained in the previous section, of the three hemiparetic subjects walking without the robot, with the robot using the developed control method, and with the robot using an autonomous control method. Recordings were acquired from the motion capture data for joint angles, and from wireless EMG sensors for iliopsoas, gluteus maximus, rectus femoris and biceps femoris muscles of both legs. EMG signals were down-sampled to 1 Khz, smoothed with a butterworth band-pass filter (40 400 Hz, 3rd order), rectified, integrated and variance normalized.

Synergies were extracted using Non-Negative Matrix Factorization (NMF). This method represents target variables as a linear combination of time-invariant synergies and time-varying activation coefficient. To calculate the kinematic synergies we used NMF with the joint angle trajectories in the sagittal plane of right and left legs’ hip and knee joints. As for muscle synergies, due to difficulties in fitting the EMG sensors together with the robot and other wearable motion sensors, some EMG signals were corrupted. Therefore we excluded the two EMG signals that were most affected on each leg, leaving 4 signals for the analysis, two from each side for each subject.

Results: We calculated the correlation coefficients (Figure 11.c) between synergies of walking without the robot and walking with the robot under autonomous control and synergy based control respectively. The results for muscle synergies (Figure 11.a) show very little difference between the No robot and autonomous control correlation coefficient, and the No robot and Synergy based control correlation coefficient (difference $< 0.06$), for all subjects. On the other hand, the same investigation on kinematic synergies (Figure 11.b) showed bigger differences, 0.2 for first subject, 0.15 for second subject, and 0.34 for the third subject. The results also show that the synergy based system had higher correlation coefficients with walking without the robot in terms of kinematic synergies, than the autonomous system did, even though the muscle activation did not differ as significantly.

V. Discussion

In the body synergy analysis of gait with walking aid we revealed an important observation, that a walking aid in gait is used in coordination with other body limbs, or in other words, the falls within the inter-limb synergies of gait. This result is of importance for engineering applications since it provides the background to instrument and utilize a walking aid cane as part of an interface with exoskeleton robot. It is also of importance from a physiological aspect, as in the theory of tool use, and tool representation in the body schema.
In the verification experiment with healthy people, we inspected the function of the developed wearable gait measurement and robot control system compared to an optical motion capture system. We found the function of the wearable system to be comparable to that of the MOCAP system, which means it can be used for robot control without serious deterioration in performance or accuracy. The wearable system also have the advantage of being much more compact and portable, thus possible to implement and use in various environments and scenarios. An important observation of this experiment is that all subjects were able to walk the developed synergy based system at different cadence and step lengths. This outcome reflects the flexible nature of the synergy based system, since it generates assisted motion based on motion of the user’s contralateral leg and cane, and thus inherently adapts with the user’s gait pattern.

In the pilot study with hemiparetic subjects, we verified the feasibility of the proposed method and developed system with hemiparetic persons. Three out of five participants were able to walk with the system. Although gait speed and cadence decreased from those of walking without the robot, that is to be expected from first time users of an exoskeleton robot due to problems of habituation and altered dynamics due to wearing the robot on one side of the body. On the other hand, walking with the robot and the developed synergy based system lead to noticeable improvement in some other gait variables such as range of motion on the affected side’s knee joint, and step-length symmetry ratio in two out of the three subjects. From the results of joints’ range of motion we observe a general trend that the autonomous system provided a high increase in joints’ range of motion on the affected side that they surpassed the range of motion on the unaffected side. On the other hand, with the synergy based system, the joints’ range of motion increase on the affected side was present but lesser than the range on the unaffected side. The percentage difference between right and left sides’ hip joint was lesser with the synergy based system, and higher with the autonomous system, and vice versa for the knee joint. These results are probably due to the functional difference between the two systems. The autonomous system provides assist based on the detected phase shift on the foot sensors solely, and does not take into consideration the joints’ motion of the unaffected side. The synergy based system, on the other hand, generates assisted motion based on direct mapping from the unaffected leg and cane motion, and thus has the inherent ability of adapt to the user’s gait.

In the synergy analysis in robot assisted locomotion, we explored a novel method of gait analysis during robot assisted locomotion. Depending on the difference between kinematic and muscle synergies in robot assisted locomotion, the earlier being a direct result of robot actuation and later being the actual commands of the user’s CNS. We were able to find a simple holistic variable that quantifies consistency between the robot action and the wearer’s action. The two control systems behaved differently in terms of synergetic relationships between the limbs, even though the muscle activation did not differ as significantly. The synergy based system had higher correlation coefficients with walking without the robot in terms of kinematic synergies, than the autonomous system did. This indicates that the synergy based system had higher ability of operating in cohesion with the user’s body synergies, yet it was able to produce enhancements in some gait parameters such as range of motion on the assisted knee joint and symmetry ratio for two out of the three subjects.

We suggest that the proposed method of synergy analysis in assisted locomotion can be used as a holistic criteria for user-robot interaction in robot assisted locomotion. We also suggest that synergy based robot control / synergy based analysis of assisted locomotion, can be used in rehabilitation programs to provide assist in cohesion with users’ body synergies, and to quantify human-robot interaction, and adaption (change) of user’s body synergies during and after rehabilitation.

### VI. Conclusions and Future Directions

In this research we explored and realized an approach for the use of body synergies in gait analysis and exoskeleton control for robot assisted locomotion.

We formulated an online motion intention estimation algorithm using motion of healthy limbs, and an instrumented cane, to estimate the motion of affected limbs. We then developed a sophisticated robot control system with wearable sensors, implemented with the single leg version of Robot Suit HAL.

The main contribution of this research is in introducing the concept of synergy to the field of exoskeleton robot control and gait analysis in assisted locomotion. This approach helps bridge the gap between human motor control and robot
control, to bring assistive technologies closer to practical implementation in rehabilitation and assisted life styles. While the concept of synergies have been investigated in fields such as physiology, neuro-science, and brain science for over a decade, this research is one of the first real attempts to import this knowledge into implementation in engineering field.

Traditional gait variables such as gait speed, cadence, step length and symmetry ratio are the main criteria used in characterization of gait. But these criteria are becoming insufficient of describing the interaction during robot assisted locomotion. New exoskeleton robots and control methods are constantly being developed. Many of which are based on motion intention estimation, and aim at a user cooperative scheme. Thus, finding new criteria to evaluate human-robot interaction in assisted locomotion, such as the one we suggested in the synergy paradigm of describing the interaction during robot assisted locomotion, will be of great help in evaluating different robot control methods. Although the analysis of data acquired in the pilot study was not fully comprehensive, it paves the way for future extended studies to evaluate and apprehend body synergies in robot assisted locomotion.

REFERENCES