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무릎근력 지원용 모듈식 웨어러블 시스템 개발

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Development of a Modular-type Knee-assistive Wearable System

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ABSTRACT

This study proposes a lower-limb exoskeleton system that is controlled by a wearer's muscle activity. This system is designed by following procedure. First, analyze the muscle activation patterns of human leg while walking. Second, select the adequate actuator to support the human walking based on calculation of required force of knee joint for step walking. Third, unit type knee and ankle orthotics are integrated with selected actuator. Finally, using this knee-assistive system (KAS) and developed muscle stiffness sensors (MSS), the muscle activity pattern of the subject is analyzed while he is walking on the stair. This study proposes an operating algorithm of KAS based on command signal of MSS which is generated by motion intent of human. A healthy and normal subject walked while wearing the developed powered-knee exoskeleton on his/her knees, and measured effectively assisted plantar flexor strength of the subject's knees and those neighboring muscles. Finally, capabilities and feasibility of the KAS are evaluated by testing the adapted motor pattern and the EMG signal variance while walking with exoskeleton. These results shows that developed exoskeleton which controlled by muscle activity could help human's walking acceptably.

Keyword: Knee-assistive System, Exoskeleton, Muscle stiffness sensor, EMG (Electromyography) signal

1. Introduction

Exoskeleton−type robot which integrated with human supports and improves limited human's physical ability. This system can be operated by wear's motion intention intuitively and because of this intrinsic advantage, many researchers attempt to apply these kinds of systems into the industry, military, rescue and medical areas. Generally, the strategy and operation method for exoskeletons to amplify human muscle power can be divided into four main categories: 1. exoskeleton which alternates with whole body, 2. exoskeleton which alternates with muscle groups of partial body, 3. exoskeleton which assists all extremities and do not alternate but assist the human's muscle power partially, 4. exoskeleton that assists with part of body. Here, "assist" means the human shares the load with the

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exoskeleton and "alternate" means the human just inputs the operation command using his own motion into the exoskeleton system, and that system fully handles a load. The first type of abovementioned exoskeletons, which alternates with all extremities, has many limitations as with its size and power source such as XOS of SARCOS (http://www.raytheon.com/newsroom/technology/rtn08_exoskeleton/). This kind of system usually bulky and cannot move out of the range of power source line freely. Second case is force alternative system for a wearer's partial body, and one of the most famous systems of this category is BLEEX (Kazerooni, 2005). User did not feel the weight of backpack because it is connected through a spine and leg exoskeleton and user just operates that leg exoskeleton using his own small force. Unlike with first case, newly developed lightweight slim system which belongs to second cases is introduced recently (http://www.lockheedmartin.com/products/hulc/index.html). One of the representatives of third type of exoskeleton that assists a whole body is the HAL (Hybrid Assistive Limb) series. HAL uses the EMG signal as its command signal and shares external loads with humans and assists the wearer's force with their load (Yoshiyuki, 2000). This system however, still requires much patience to wear and it is difficult to maintain the quality of the EMG signal while wearing it. Well known system included in the fourth case of wearable system is Walking Assist Device developed by Honda Co (http://corporate.honda.com/innovation/walk-assist). Many institutions around the world have carried out research and development on exoskeletons as assistive devices. There are many other studies are exist including abovementioned cases. Yobotics Incorporated's RoboKnee, and NTU-LEE's rehabilitation prototype are some of the state-of-art developments in this area of assistive devices to aid the human limb (Weinberg, 2007; Yobotics, 2005; and Low, 2005). In addition to these systems, many kinds of leg assistive robots are focused on medical services and rehabilitation. The purpose of these device are to share the load or pressure which are exerted on the knee so as to relieve pain or speed up the healing process without disrupting normal daily activities. This is likely to be a potentially useful research area due to the rising cases of musculoskeletal injuries caused by daily activities and the increased elderly and handicapped people (Paluska, 2000). Obviously, this concept can be used to assist human with daily walking and laborious work in the industrial area. For industrial usage, however, the operational convenience and compactness of the system are strongly considered. This means the system has to be designed to be flexible and synchronize with humans easily. In this context, an innovative sensor suit has been developed that an operator can put on it to detect his or her motion intention by monitoring his or her muscle conditions such as their shape, stiffness, and density. These sensors are made of soft and elastic fabrics into which are embedded arrays of MEMS sensors such as a muscle stiffness sensor, ultrasonic sensors, accelerometers, and optical fiber sensors, to measure different kinds of human muscle conditions (Feng, 2006). The developers of these sensor systems emphasize their convenience in terms of the ease with which they adapt to humans. These sensors, however, are not suitable to manufacture easily and have been verified its performance for a restricted part of the human body. The EMG sensor is one of the wide-spread means to sense the intention of motion of human by measuring an activity of his/her muscle. However, the approach of using this sensor is not considered in this study because of its inconvenient preparation procedure for measuring signals and its incongruence to daily working conditions.

To solve the abovementioned problems of wearable robot and its corresponding sensor system, a feasible modular-type exoskeleton system based on easy-to-use sensor systems which is based on the scheme of muscle stiffness sensing are proposed. To do this, the design process of the modular-type knee-assistive type exoskeleton is introduced, and developed system is represented based on the confined system requirements. Using this system, human intention signal acquisition and processing methods for actuating the developed system are proposed. Finally, a feasibility of designed MSS and exoskeleton system is evaluated based on the several kinds of walking motion, and its degree of assistance is also tested through the measuring of EMG signal while walking with it.

2. Motion Analysis of Human Leg

2.1 General Analysis of Knee Muscle Group

One of the important issue for a development of exoskeleton system is to gather adequate motivation signals from a motion intent detector when user wears the system and conduct the movements of the leg. Figure 1 shows which parts of the muscle groups are mainly related to the knee joint movement during level walks. Considered mucle part of this research is located in a knee and its related muscle groups

As shown in this Figure 1, phase pattern of EMG signal of the muscles of the leg during walking in healthy adults. Gray parts show the activation of muscle below 20% of maximum voluntary contraction and black parts represent activation above 20% of maximum voluntary contraction. Fundamentally, the muscle activation status is completely different during level walks and on stairways. Thus, a different type of gait pattern results in a dissimilar muscle activation phase. In the case of the knee joint movement, three DOFs with angular rotations are possible during a level walk. The primary motion is the knee flexion-extension with respect to a mediolateral axis. Internal/external knee rotation and adduction/abduction (valgus/varus) also occur among healthy individuals, but with less consistency and amplitude, due to their soft tissue and bony constraints to these motions.

2.2 Extraction of the Knee muscle activity pattern

During the stance phase, the quadriceps muscle group relies on the control of its tendency towards knee flexion collapse with weight acceptance and single-limb support. This muscle group is activated during terminal swinging, and then acts eccentrically during weight acceptance, as the knee rotates from the fully extended position at the initial contact to its peak support phase flexion of approximately 20 degrees during the loading

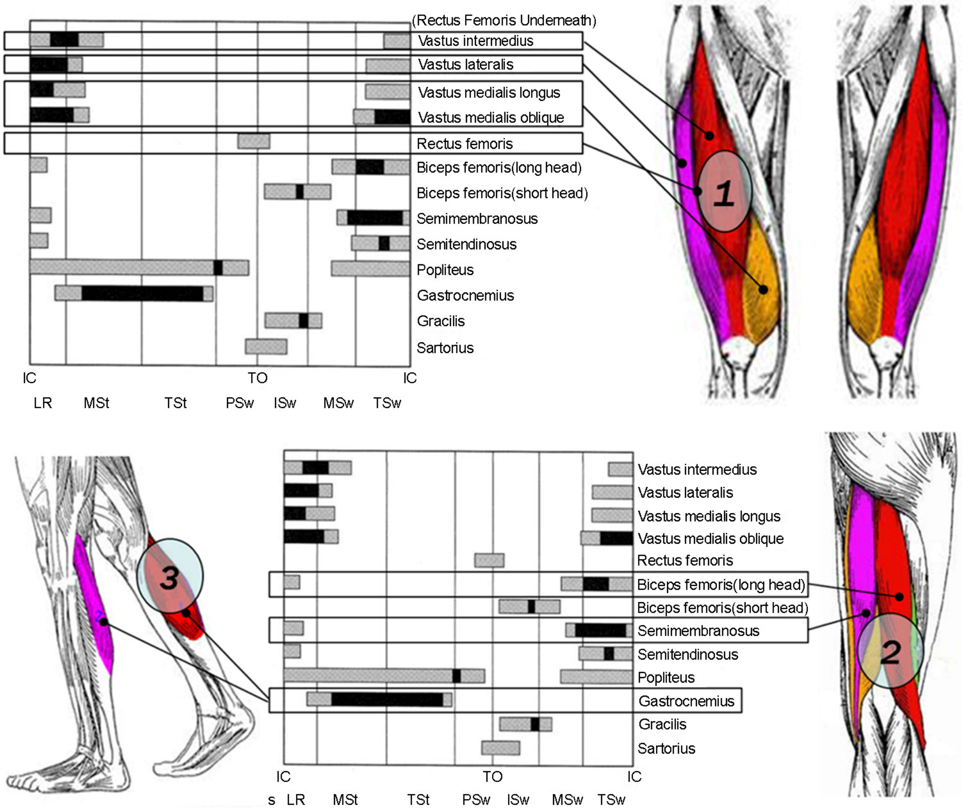

Figure 1. Muscle Activity Pattern of Leg and Proposed Sensor Position for Exoskeleton

response. Thereafter, the quadriceps act concentrically to extend the knee through an early mid-stance, as the center of the body's extremity mass is raised vertically over the supporting limb and the anterior orientation of the ground reaction force vector precludes the need for further muscular control of the knee flexion. Most hamstring muscles are activated in the late mid-swing or the terminal swing. Their function with respect to the knee is probably to control the angular acceleration of the knee extension. The short head of the biceps femoris is activated earlier and probably assists in the flexion of the knee for foot clearance. The Gracilis and Sartorius muscles may also contribute to the swing-phase knee flexion when they are activated during the late pre-swing, initial swing, and early mid-swing. These muscles may very well be acting as primary hip flexors during this period, though (Nordin, 2001).

3. System Development

3.1 Required torque consideration

One of the most power intensive maneuvers with published biomechanical data is climbing stairs. Kazerooni and Zoss calculated required torque of their own lower limb exoskeleton system using clinical gait analysis data (2005). Figure 2 shows the Clinical Gait Analysis (CGA) of knee flexion/extension joint powers for a human ascending various stair inclinations. The data presented here are from Riener et al. (2002), but more detailed three-dimensional CGA for stair ascent can be found from Duncan et al. (1997). During stair ascent, the ankle Dorsi/plantar flexion has no function of absorbing much power during the early stance, and it still has a large power requirement during the late stance. Thus, the average ankle Dorsi/plantar flexion power is slightly larger during stair ascent than during level walking. The knee flexion/extension joint shows the largest change from level walking to ascending stairs. The maximum instantaneous power requirement during stair ascent is 200W, much higher than 30W for level walking. Also, very little energy is absorbed at the knee during stair ascent. Thus, the average knee power is no longer negative, so the knee dynamics cannot be imitated by a controlled damper, but must be actuated to stair ascent. During the stance phase of stair ascent, the instantaneous powers of the hip flexion/extension joint are significantly more positive than during level walking (Zoss, 2006). The peak power requirement for stair ascent is the same as that for level walking, however, and still occurs during the swing phase.

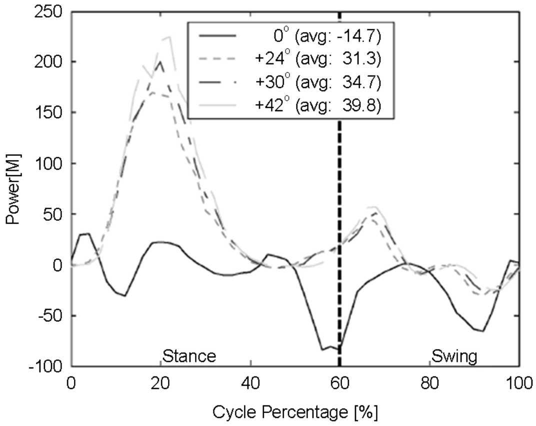

Figure 2. Knee flexion/extension powers during stair ascent

3.2 Actuator selection

As mentioned earlier, the gait pattern is analyzed based on the muscle activity pattern and the angular displacement of the knee joint. The proper sensor position is decided using only two MSS (Muscle Stiffness Sensors) groups and the basic operation algorithm. In this chapter, the experimental exoskeleton system is briefly introduced. Figure 3 shows the developed knee-movement-assistive system which is composed of knee joint orthotics and minimized number of actuating systems. Because of safety is most important issue of this kind of system, harmonic drive which prevents a backlash of the motor shaft and the link unit is applied. During the stance phase, the flexion is less than 20 degrees, and the quadriceps muscle force during level walking depended on the body weight, the magnitude of the muscle force and a joint reaction force. Reilly and Martens (1972) found the largest value of the quadriceps muscle force during level walking is 804N. Many researchers throughout the world have also introduced the analytical or experimental value of each joint of the lower limb, especially the joint torque (Paluska, 2000;

Kuster, 1997; Umberger, 2002; and Townsend, 1978) and the muscle activation pattern (Ivaeneko, 2004 and Lee, 2007). The results of the abovementioned studies are used to determine the specifications of the flat motor (Maxon®) and the harmonic drive (THK™), which can sufficiently cover the requirements. These selected motors have relatively large diameters and small widths, and have separate rotor and stator components instead of being preassembled to minimize the joint width that heavily guides the motor and the gearing selection. With just the bare rotor and stator, the motor can be tightly integrated into the mechanical structure of the joint; but the design must meet the required mounting tolerance values, provide the necessary bearings, and sufficiently extract the heat from the motor. The large torques seen at the joints and the large desired gear ratios eliminated some gear options. Other options are eliminated because they would create too large joints. Harmonic drives are selected because of their large torque capacities, high gear ratios, and small sizes. They are available as components that can be closely integrated into the mechanical structure (Zoss, 2006).

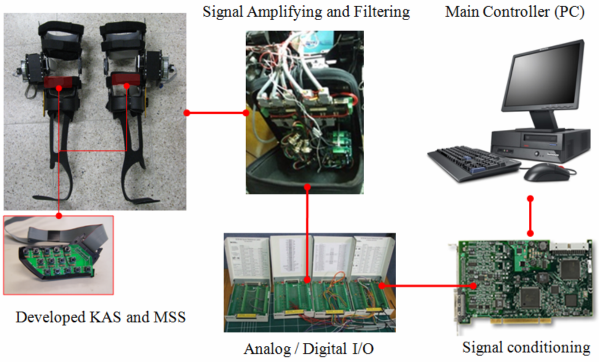

Figure 3. Developed Knee Assistive System (KAS)

3.3 System integration with MSS

MSS is designed to acquire the signal for the degree of expansion of the muscle to use that signal as a motivation to operate the proposed KAS (knee–assistive system) (Figure 4). Before these sensor systems are synchronized with KAS, a calibration process had to be performed. An embedded computer is applied as the main controller and the signal analyzer for this system, and the external Data Acquisition system and MSS sensor system are composed.

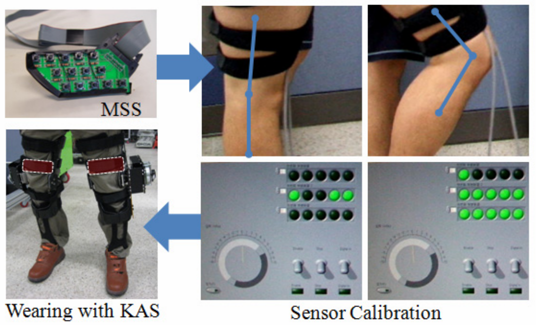

Figure 4. MSS and its performance test

The reference muscle power that each user needed to operate this system is determined based on the following procedure. After the installation of MSS into the operator's body, the stiffness parameter below the maximum activity and above the minimum activity for each muscle is measured. Using these data acquired under the maximum and minimum conditions, the stiffness parameters are normalized using following equations.

$$S_{NR} = \frac{S_R - \min(S_R)}{\max(S_R) - \min(S_R)}$$

$$S_{NG} = \frac{S_G - \min(S_G)}{\max(S_G) - \min(S_G)}$$

S_{NR} : Normalized muscle stiffness of Rectus Femoris
S_{NG} : Normalized muscle stiffness of Gastrocnemius
S_R : Measured muscle stiffness of Rectus Femoris (left and right sides)
S_G : Measured muscle stiffness of Gastrocnemius (left and right sides)

4. System Operation Method

The proposed system uses two MSS units. One unit is attached to a Rectus femoris, and the other is attached to a Gastrocnemius muscle. Under the condition of these restricted numbers of sensors, considered sensor

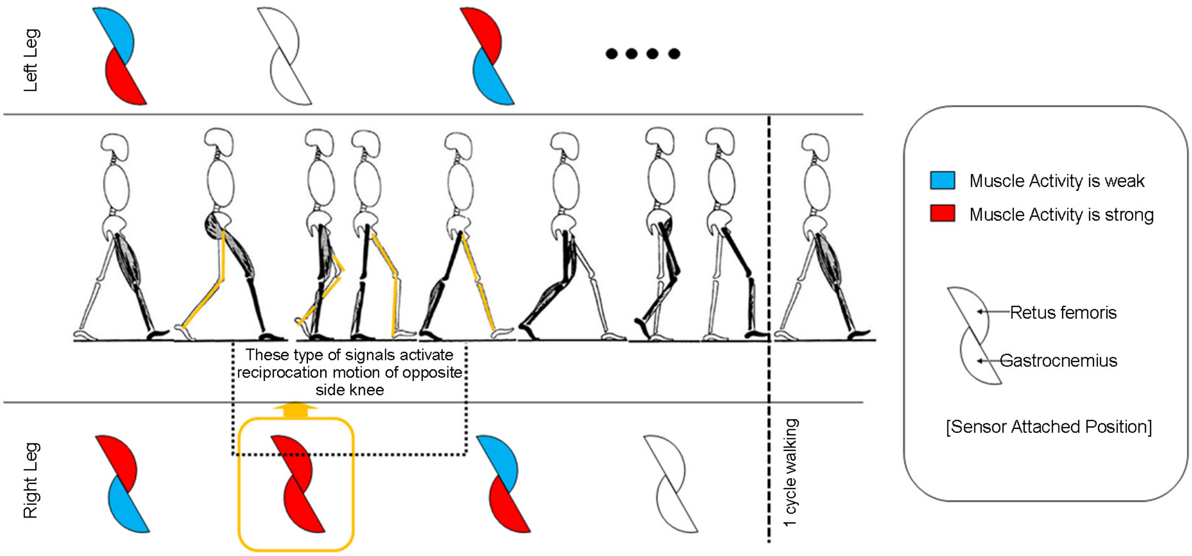

Figure 5. Operation Algorithm of KAS (Level Walking)

calibration scheme is preceded as shown in the Figure 4. The activation algorithm is based on a cross–activation algorithm which uses the event of the contraction of two–joint muscles which belongs to a knee and hip. If the two groups of muscles which are attached with MSS are activated at the same time over the calibrated minimum value, exoskeleton part of opposite side of leg is activated through the predefined motion range automatically. This algorithm is appropriate to operate the walking assistive exoskeleton only if the synchronized activation timing between one side of MSS and the other side of KAS can be realized.

5. Experiments

The experiment of developed KAS is preceded as following steps. First, we obtained the EMG signal of healthy subjects while they walked on a step and a step by carrying the 10kg weight. After that, we asked them to wear the developed exoskeleton system. The subject then repeated the procedure with the same walking speed. Finally, we gathered the EMG signal history and verified its feasibility. Figure 7 shows its illustration and experimental results.

The EMG sampling frequency and gain value is 1024Hz and 1126.7μV. Those are attached on upper and lower parts of quadriceps and gastrocnemius muscle groups (Figure 6). The experimental result of Figure 7 shows the characteristics of KAS. First, muscle activity of Quadriceps femoris is larger than without wearing KAS. (2~4sec) because of the initial state of KAS which is not activated yet. Second, the magnitude of signal of simultaneous contraction area of Quadriceps femoris and Gastrocnemius muscle are reduced (4~6sec). Third, the area of 5~6sec, only the signal of gastrocnemius muscle is remained. Most important thing is every signal has tendency to be reduced and that means each muscle is assisted by KAS.

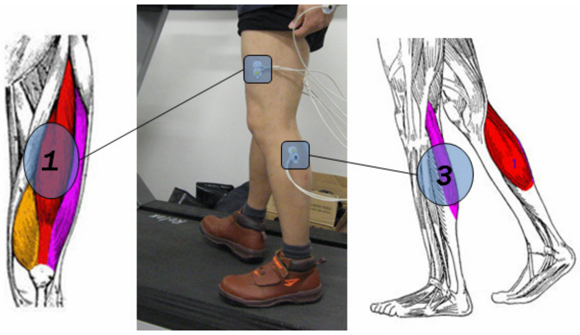

Figure 6. Experimental Setup using EMG Sensor

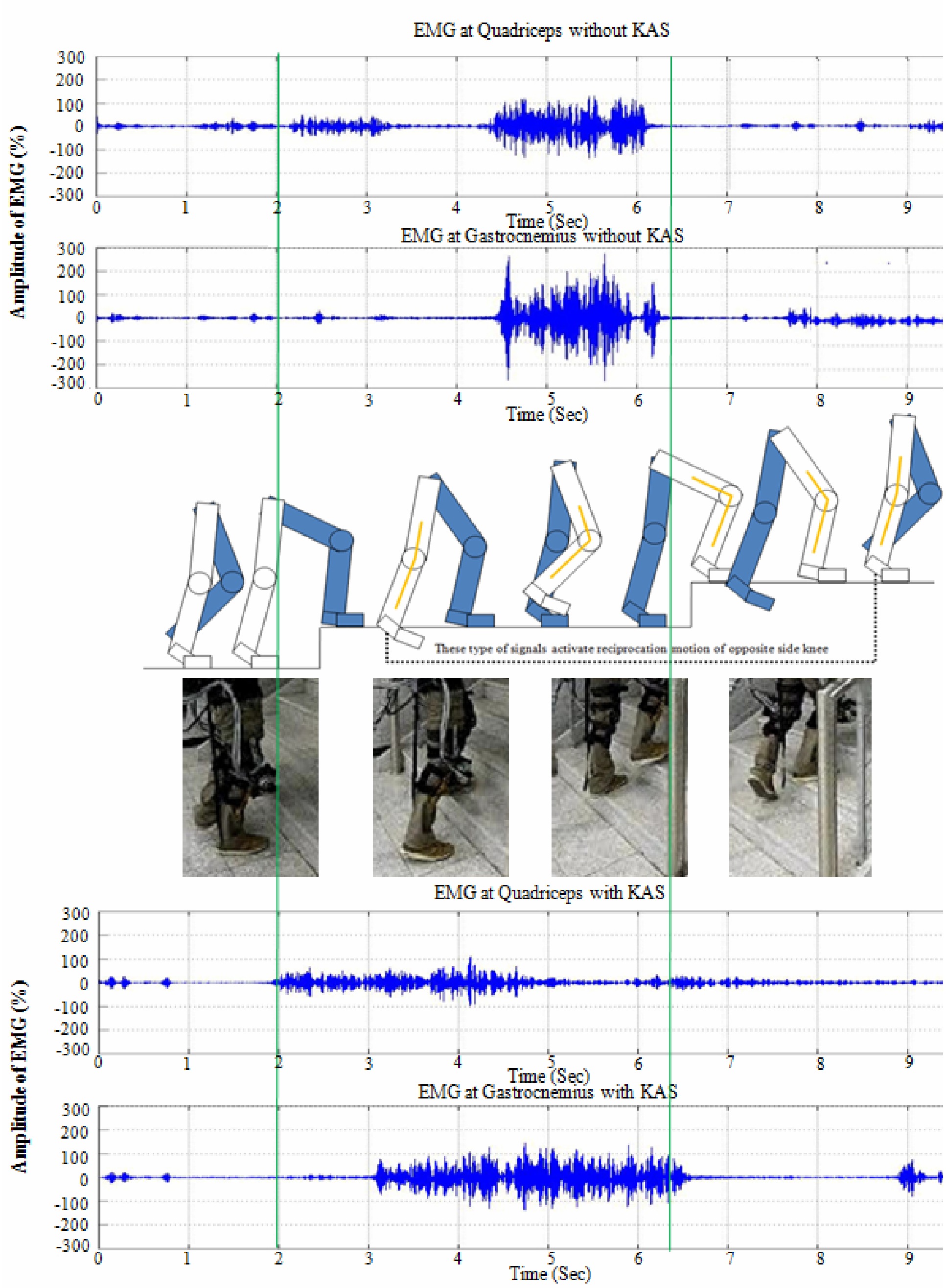

Figure 7. Gathered EMG signal from Legs with KAS (Step Ascent Walking)

6. Conclusions

In this study, the developed walking algorithm of knee-assistive exoskeleton brings following three effects of the wearer's muscle activation pattern. First effect is the reduction of the required strength for simultaneous contraction. Second one is the changing of the pattern of the sequential muscle activation. The last one is, as shown in Figure 7, the possibility of using it directly as an ascent walking algorithm. Consequently, the performance of the developed exoskeleton and its walking algorithm is verified through the walking experiment, and it is found that this kind of system based on command signal of MSS which is generated by human intent can help human's walking conditionally.

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