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PROPOSAL FOR A MODULAR-TYPE KNEE-ASSISTIVE WEARABLE UNIT AND VERIFICATION OF ITS FEASIBILITY

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ABSTRACT

To study human locomotor adaptation and feasibility, we used a lower limb robotic exoskeleton controlled by the wearer's muscle activity. A healthy and normal subject walked while wearing an electrically powered knee exoskeleton on two knees, which effectively increased the plantar flexor strength of the knees and their neighboring muscles. We examined the capabilities and feasibility of knee assistive system (KAS) by testing the adapted motor pattern and the EMG signal variance for exoskeleton walking. It is designed for specific tasks such as level walking and step walking while the user is carrying heavy materials. Using the KAS; custom-made muscle stiffness sensors (MSS), we analyzed the muscle activity pattern which was implemented on the operating algorithm of KAS while he was walking, and examined its feasibility. The results demonstrate that robotic exoskeletons controlled by muscle activity could be useful way of assisting with human walking.

KEYWORDS

Knee-assistive system, wearable robot, exoskeleton, muscle stiffness sensor, EMG signal

1. INTRODUCTION

Powered robotic exoskeletons are currently under development for the enhancement of human locomotor performance in the military, in industry, and for patients with mobility impairments [1]. They free people from much labor and the burdens of many kinds of manual work. On the other hand, when it comes to automation in the industrial field, factory automation has made good progress. Operators (humans) can be included in a conventional manufacturing process with respect to a formal production line and uniform working conditions. Automation outside the production line, however, especially in common manufacturing stages, has several limitations and difficulties in adapting to actual conditions, as the industrial field has but a small part in the process due to its operating characteristics. There have been many approaches to the reduction of labor that do not fully but only partly assist workers, such as extremely heavy payload-oriented construction equipment, which are manipulated by humans. Manual or semi-automatic machining tools are mostly used in contemporary industries. In particular, without manpower, especially without the manipulability and mobility of the upper and lower human limbs, full automation will be incompatible with today's technologies [2]. As exoskeletons have strong advantages given their unique features such as their outstanding physical performance, which exceeds that of humans, and their agility, which is utilized by the operators' nerve system, attempts to adopt exoskeletons in the industrial field, especially in construction sites, are feasible approaches to factory automation. The strategy and the support method for exoskeletons for amplifying human muscle power can be divided into four main categories: exoskeletons that totally alternate with both the upper and lower parts of the muscle power system, those that are helpful to workers because they totally assist entire human muscle power, partly alternate with the muscle power system, and partly assist the muscle power system. The first type of exoskeleton which alternates with the full muscle power still has many limitations, as with its size and electric power supply. Due to these constraints, exoskeletons are usually bulky and cannot freely move. One of the representatives of the second type of exoskeleton--that which assists the whole body--is the HAL series. HAL utilizes the electromyogram (EMG) signal for its command signal. And it shares external loads with humans and partly assists with human loads and it is still big and bulky, and requires much patience to wear it [3]. A new product, BLEEX, can partly alternate with the human muscle power system. The BLEEX system provides a versatile load transport platform for mission-critical equipment, so it has several applications without the strain associated with demanding labor such as soldiers, disaster relief workers, fire-fighters, etc. [4]. As was taken into account in the earlier three cases, the research target for the development of exoskeletons can come under the fourth type: the partly assistive muscle power system. Therefore, in this paper, a feasible modular-type wearable robot is proposed to assist construction workers with their lower limb movements. First, for the purpose of adapting the modular-type wearable robot for lower limb assistance at construction sites, several construction work groups were defined based on specific boundaries. Second, the design process for the modular-type lower extremity focused on the knee joint movement will be presented based on the confined boundary. Third, motivation signal processing methods for actuating a proposed system were introduced, and the feasibility of the command signal was estimated. Then there were several measures to mathematically quantify the characteristics of human performance and the wearable robot platform, through an EMG signal.

2. ANALYSIS FOR DESIGNING SYSTEM

2.1. Occupational Analysis

In the next step, the research target was brought into the part it would assist. For the sake of embodiment, we first defined the target task at a usual construction site through a work pattern analysis, which is strongly related to occupational disorders. V. Arnd et al. (2008) conducted a 10-year follow-up research on 14,474 male construction workers. He reported that musculoskeletal diseases led to an increased proportion of occupational disability [5]. Fatal injuries of the construction workers-musculoskeletal diseases-were mainly divided into two dominant disabilities: dorsopathies and arthropathies. According to his statistical reports and the annual reports of NIOSH, it is easy to have a primary disability at a construction site. The reports classified the standard incidents into all causes and specific disabilities. Dorsopathies, arthropathies, and knee joint disorders accounted for 21.2%, 10.5%, and 8.7%. They occurred most frequently in the site (Fig. 1). The

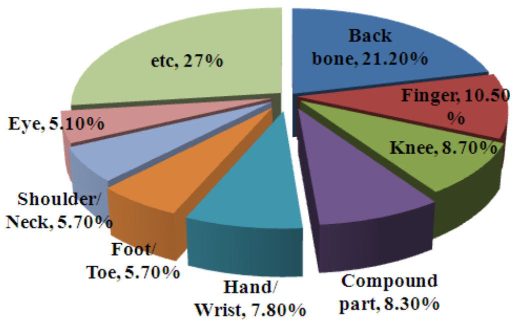

Figure 1. Construction worker' disability ratio (NIOSH)

research target and its direction were derived by disintegrating the workload, thereby improving the work space of the workers with dorsopathies and knee joint disorders. The spine movements can either translate back and forth along a straight line or rotate around a particular axis [6].

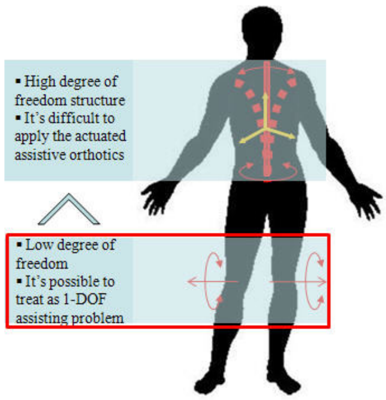

Figure 2. Decision of target region of two dominant causes of disability of construction workers.

Figure 3. Work Group Analysis

Moreover, the working index of NIOSH recommends that construction workers' spinal columns should not be rapidly bent and their posture should be kept perpendicular to the ground during manual construction work (Fig. 2). Therefore, this paper designed this specific part of the body-knee joint of the type that partly assists the knee joint (Fig. 4). The following are the specifications of the system in this research.

• Occupational target: Construction worker

• Target region: Knees (The weight of the system is borne by the combined shank-ankle orthotics)

• Target motions: Kneeling, lifting objects, climbing a staircase or a slope.

2.2. Definition of the Target Task

As shown in Fig. 3, deviating from a target task at a construction site follows the following process. First, we looked at an overview of working patterns and types at construction sites. The overview was sourced from NIOSH (National Institute of Occupational Safety & Health). In the second step, the construction workers--especially the general labourers--were divided into four major groups. As shown in step 2 under Fig. 3, sheet metal workers, electricians, labourers, and cement masons were put in charge of each group. Finally, in the third step, overlapping common works were selected to choose the target tasks. The target tasks are shown at the bottom of Fig. 3. In the first target task, the construction workers did their jobs with heavy tools on ceilings and walls. The second target task was the construction of an iterative ceiling with unstable postures. The third and fourth target tasks were the construction workers' handling of heavy materials, which only slightly differs from their work. The third target task was on level ground, and the fourth, on a stairway. Finally, we noted the target tasks throughout the entire procedure--steps 1, 2, and 3. Among the four target tasks, we focused only on two main tasks--the third and fourth.

As earlier mentioned, we developed a modular-type wearable robot to assist the lower limb, and we applied this mechanism in a real construction site. Thus, the target mission-oriented wearable robot system, which highlights handling of heavy materials and loads on level ground and on a stairway, was designed step by step.

3. SYSTEM OPERATION METHOD

3.1 Angular Displacement of the Knee Joint

Following the steps shown in the previous chapter, the final target task was defined more specifically. We decided to devise a modular-type wearable robot for lower limb assistance, i.e., for handling heavy materials at level walks and on stairways. To gather adequate motivation signals when the construction workers do their jobs at the site, first, an analysis of the movements of the knee joints was needed. Fundamentally, the muscle activation status is completely different during level walks and on stairways. Fig. 4 (Appendix) shows which parts of the muscle groups are mainly related to the knee joint movement during level walks. Thus, a different type of gait pattern makes for a dissimilar muscle activation phase. In the case of the knee joint movement, three DOFs with angular rotations are possible during the level walk (Table 1). The primary motion is the knee flexion-extension with respect to a mediolateral axis. Knee internal-external rotation and adduction-abduction (varus-valgus) also occur among healthy individuals, but with less consistency and amplitude, due to their soft tissue and bony constraints to these motions. The information presented in this chapter was gathered by J. Spivak and J. Zuckerman (1998) from their research.

Table 1. Range of Normal Values for the Time-Distance Parameters of Adult Gaits at a Free Walking Velocity

Contents	*Values*
Stride or cycle time	1.0 to 1.2 m/sec
Stride or cycle length	1.2 to 1.9 m
Step length	0.56 to 1.1 m
Step width	7.7 to 9.6 cm
Cadence	90 to 140 steps/min
Velocity	0.9 to 1.8 m/sec

3.2. Extraction of the Muscle Activity Pattern

During the stance phase, the quadriceps muscle group is relied on to control 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 response. Thereafter, the quadriceps act concentrically to extend the knee through an early mid-stance, as the body's center of 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 flexing 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 the early mid-swing. These muscles, however, may very well be acting as primary hip flexors during this period [7]. Based on Fig. 4, we analogize that to explain or measure the gait pattern using the muscle activity pattern, we must consider three positions of the muscle groups (Fig. 5 and Fig. 6 in Appendix). In this study, however, we propose a method that uses only two muscle sensing groups. Although this approach is not perfect, it reduced the MSS module in the proposed system and minimized the loads in the processing system. We decided to disregard the sensor position ②, because we could explain the muscle activity pattern during the entire cycle using only ① and ③. Figs. 5 and 6 describe the sensor position of the anterior side (□) and the posterior side (□) of the sensor position we chose. The gray areas represent activation below 20% of the maximum voluntary contraction, and black areas represent activation above 20% of the maximum voluntary contraction. Muscle activation means KAS is inflated at the moment when the foot of the user touches the ground; the flexion/extension movement occurs in succession and cross-happens within one gait cycle. It seemed to comprise only one event, without intermission. Therefore, these successive movements could be organized into a single case. The algorithm was gradually adjusted to the wearers, such as by calibrating the sensor system

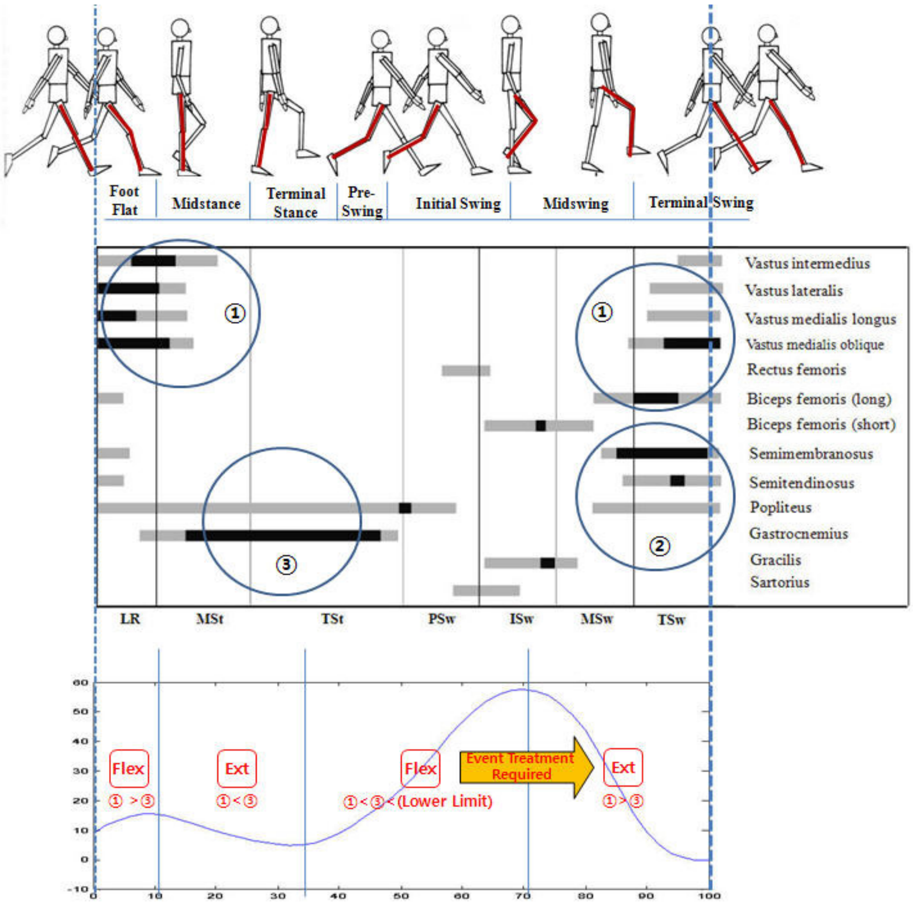

Figure 4. Phasic pattern of the electromyography (EMG) activity of the muscle and the angular displacement of the knee during level walking by healthy adults.

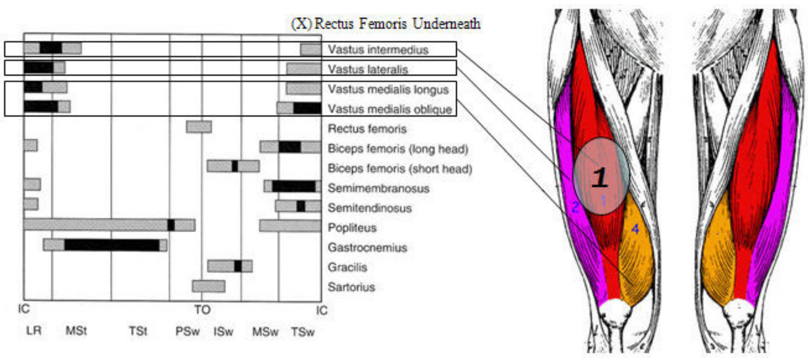

Figure 5. Sensor position (Anterior side of the leg)

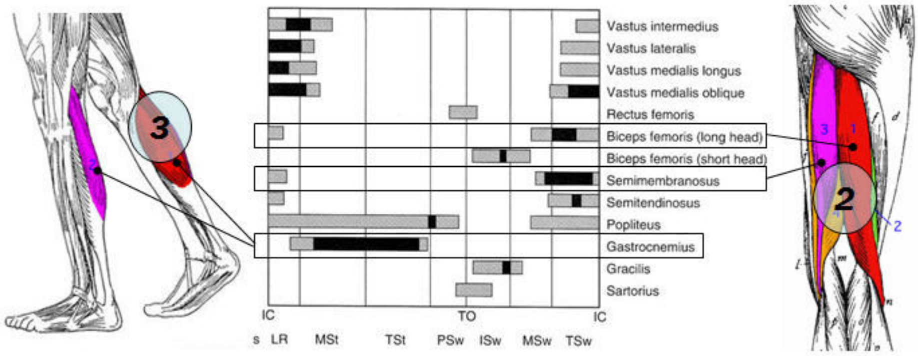

Figure 6. Sensor position (Posterior side of the leg)

and regulating the velocity as with fine-tuning before starting the machinery, to develop a handy prototype of the system that is easy to wear. The results of the verification of the effects of the muscle power assistance through repeated experiments with KAS and an EMG signal sensing device will be introduced in the last chapter.

```
##mfg_i= ith motor sensing group
##Counter clock wise rotation of motor : Positive and
Extension motion of knee
##lim=Lower Limit (User-define value)
If (min(mfg_03, mfg_01)>lim) then,
        If (Knee_theta>50) then,
        Knee_dtheta=0
        else if (mfg_03>=mfg_01) then,
        Knee_dtheta=motor velocity
        else
        Knee_dtheta=-(motor velocity)
Else if (max(mfg_03, mfg_01)<lim) then,
        If (Knee_theta>50) then,
        Knee_dtheta=0
        else if (mfg_03<mfg_01) then,
        Knee_dtheta=motor velocity
        else
        Knee_dtheta=-(motor velocity)
       End
End
```

Figure 7. Operation algorithm of KAS using MSS

4. SYSTEM DEVELOPMENT

4.1. Exoskeleton Unit

As mentioned earlier in this chapter, we analyzed the gait pattern based on the muscle activity pattern and

Figure 8. Exoskeleton unit of the KAS

the angular displacement of the knee joint. Finally, we deduced the proper sensor position (using only two MSS groups) and the basic operating algorithm (Fig. 7). In this chapter, we briefly introduce our experimental exoskeleton system. Fig. 8 shows the user- convenient knee movement assistive system that was devised by applying commercial knee joint orthotics and minimizing the number of actuating systems. Using a harmonic drive especially prevents a backlash of the motor shaft and the link unit. The system was devised using the following biomechanical and statistical approach. For most of the stance phase, the flexion was less than 20 degrees and the quadriceps muscle force during level walking depended on the body weight, the magnitude of the muscle force, the joint reaction force, etc. Reilly and Martens (1972) found the highest value for the quadriceps muscle force during level walking, 804 N (180.7 lbs) [8]. Considering both the maximum required force value on the quadriceps and the type of system – that which partly assists with the lower human limb motion, the specifications of the flat motor (Maxon®) and the harmonic drive (THK™) are enough to cover the requirements. The stall torque, gear ratio, and gear efficiency were 4,670 mNm, 100:1, and approximately 70%. Therefore, the motor output torque was estimated as 1.63 times more than the requirement. When it comes to the research target of partly assisting with human motion, the proposed system feasibly accomplishes the goal of this research. Moreover, it can theoretically add approximately 45 kg more payload to construction workers.

4.2. Muscle Stiffness Sensor and Control System

We designed MSS to acquire the signal for the degree of expansion of the muscle and to use that signal as a motivation to operate the proposed KAS (Fig. 9 and Fig. 10). EMG is typically combined with stride or angular kinematic analysis to provide information on phasic muscle activation patterns. EMG helps explain the motor performance underlying the kinematic and kinetic characteristics of gaits. In this paper, we tried to prove the efficiency of KAS using the EMG test. First, we examined the

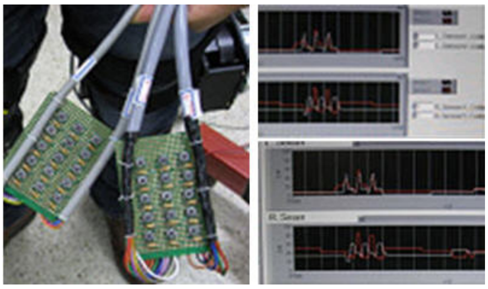

Figure 9. MSS and its test

Figure 10. Wearing the KAS

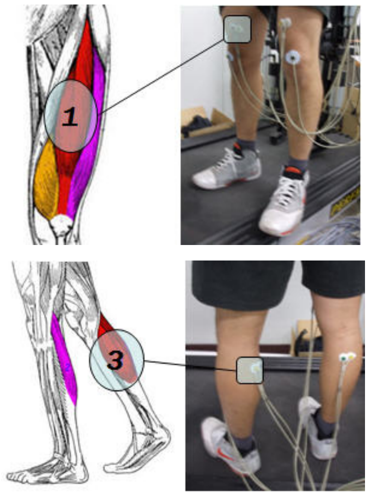

Figure 11. EMG sensing test during level walking

EMG signal of healthy subjects while they walked normally on a treadmill and a step, after which we asked them to wear the exoskeleton system we developed. Then we repeated the procedure. Finally, we gathered the EMG signal history and verified its feasibility adapted by the industrial fields.

5. EXPERIMENTS AND CONCLUSIONS

Experiments are set up by four main topics: ① with payloads (20kg) and KAS, ② without payloads and KAS, ③ with payloads and without KAS, and ④ without payloads and with KAS (Fig. 12 in Appendix). At each experiments EMG signals are gathered by four channels and its sampling frequency and gain value was 1024Hz and 1126.7uV. Those are attached on upper and lower parts of quadriceps and gastrocnemius muscle groups (Fig. 11). Every signal has tendency to be assisted as shown at the figure below. All magnitudes of EMG signals have 20% larger value using KAS than before. Though system mass is approximately 10kg, muscle activation gets the effects of assisting (Fig. 13, 14 in Appendix). Through this research, we got to know that partly assisting or supporting the muscle power could be useful for the users' safety and free from labors (Fig. 12). Even though it was in specific confined condition, minimizing system weights and solving independent electrical power system, the KAS is going to be useful powered harness for the construction workers.

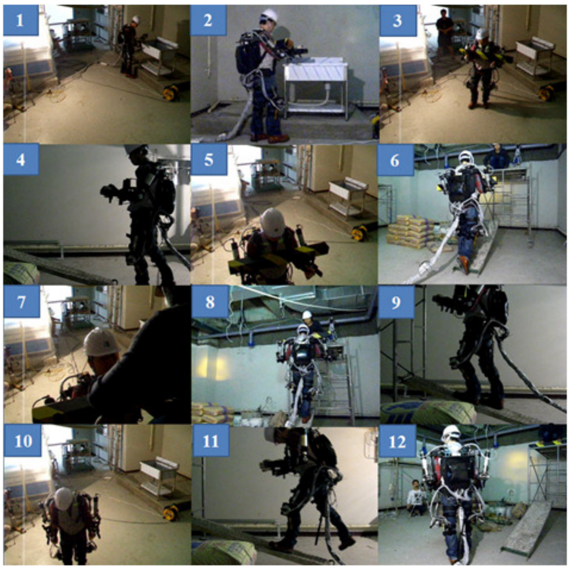

Figure 12. System demonstration of construction work

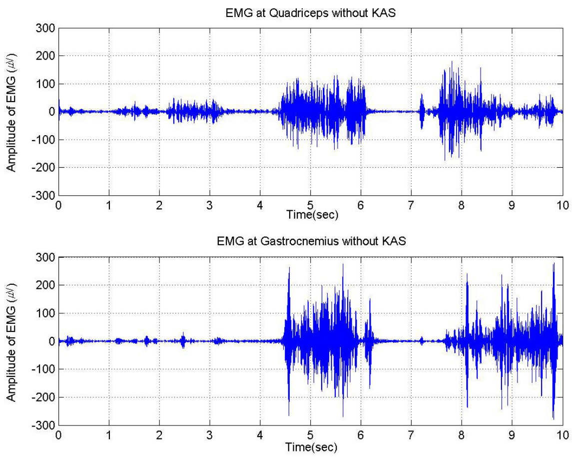

Figure 13. Gathered EMG signal without KAS

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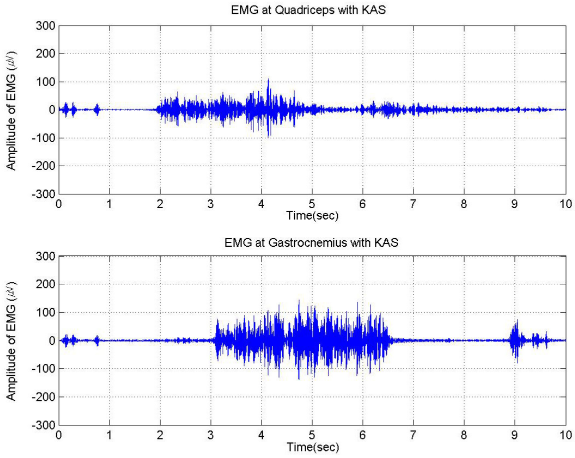

Figure. 14. Gathered EMG signal with KAS

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