

Design and Feasibility Verification of a Knee Assistive Exoskeleton System for Construction Workers

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1. Introduction

Robotic-powered exoskeletons and body joint-adapted assistive units are currently under development for the enhancement of human locomotor performance in the military, in industries, and in patients and the elderly with mobility impairments [1]. They free people from much labor and the burdens of many kinds of manual work. For example, 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 because 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 only fully assist but also partly aid workers, such as in the use of extremely heavy payload-oriented construction equipment, which are manipulated by humans. Manual or semi-automatic machine 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]. Exoskeletons have strong advantages given their unique features such as their outstanding physical performance, exceeding that of humans, and their agility, which is utilized by operators' nerve systems. As a result, attempts to adopt exoskeletons in the industrial field, especially at construction sites, indicate the use of feasible approaches to factory automation. The strategy and support method for exoskeletons that amplify human muscle power can be divided into four main categories: (1) exoskeletons that totally alternate with both the upper and lower parts of the muscle power system, (2) assist the all extremities not alternate (here, assist means the human share the load with the exoskeleton and alternate means the human just input operation command using his own motion into exoskeleton system and it totally handles the load), (3) alternate with the part of all extremities (4) assist the part of all extremities of muscle power system. The first type of exoskeleton which alternates with the entire 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 out of the range of the power source line. One of the representative studies of the second type which assists the whole body is the HAL series.

HAL utilizes the EMG signal for its command signal [3]. Moreover it shares external loads with humans, that is partly assists the human's loads but it is still requires much patience to wear and difficult to maintain the quality of EMG signal for every wearing.



(a) The Exoskeleton Design Concept Introduced in the Movie Clip ('Alien II' and 'Matrix Revolution')



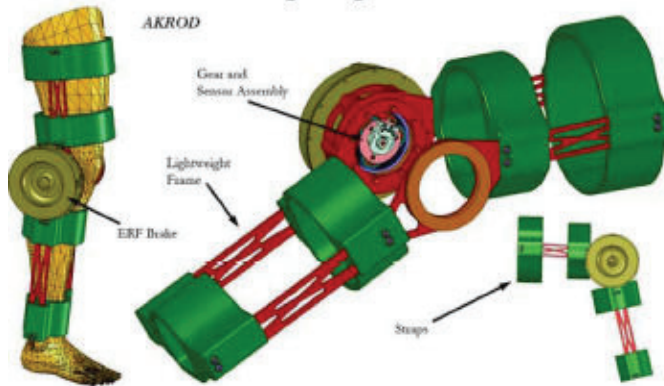
(b) Exoskeleton System for Whole Body Support ('XOS' of SARCOS and 'HAL' of Cyberdyne Inc.)

Fig.1. Developed Exoskeleton Systems to Support the Whole Body

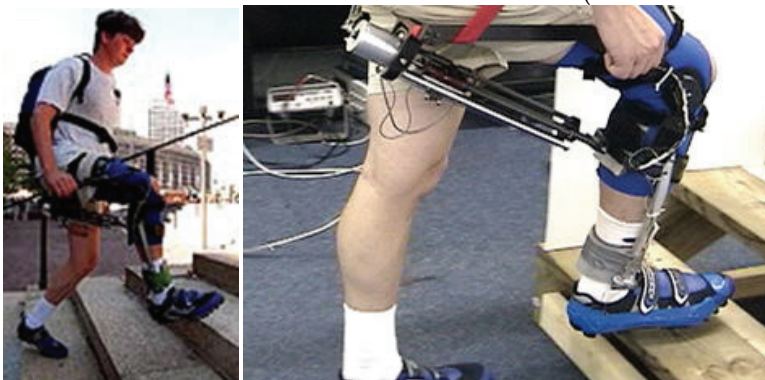
As taken into account in the earlier three cases, the research target for the development of exoskeletons can fall under the fourth type: the partly assistive muscle power system, especially the leg assistive system. Many institutions around the world have carried out research and development on exoskeletons and assistive devices in order to empower or aid human lower limbs. A well-known system, BLEEX, can partly alternate with the human muscle power system. This 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 that of soldiers, disaster relief workers, fire-fighters, and so on [4]. Northeastern University's Active Knee Rehabilitation Device (AKROD), Yobotics Incorporation's RoboKnee, and the NTU-LEE rehabilitation prototype are some of the state-of-the-art developments in the area of assistive devices to aid the human limb [5, 6, 7].



(a) BLEEX (U.C. Berkeley)



(b) Active Knee Rehabilitation Orthotic Device-'AKROD' (Northeastern Univ.)

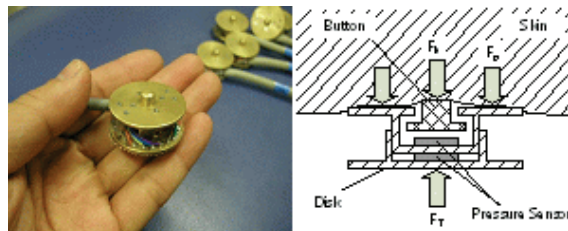


(c) 'RobotKnee' (Yobotics)

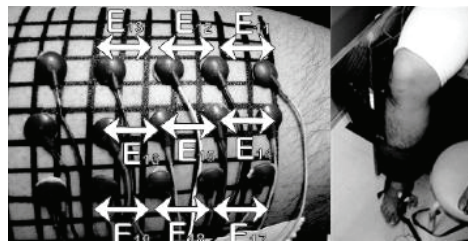
Fig. 2. Leg Assistive Exoskeletons

In addition to the systems in Fig.2, many kinds of knee assistive robots are focused on medical service or rehabilitation. The purpose of this device is to share the load or pressure acting on the knee in order 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 number of sports-related injuries and the increasingly aging world population [8]. Obviously, this concept can be applied to assist in daily life walking and laborious work in the industrial area. For the purpose of industrial usages, however, operational convenience and compactness of the system is strongly considered. This means that the system has to be designed as wieldy and can easily be synchronized with a human.

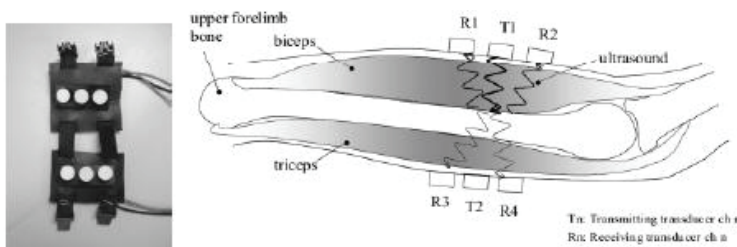
To solve this problem, innovative sensor suits have been developed, which can be put on by an operator to detect his or her motion intention by monitoring his or her muscle conditions such as shape, stiffness, and density. As shown in Fig.3, these sensors are made of soft and elastic fabric embedded with arrays of MEMS sensors such as muscle stiffness sensor (MSS), ultrasonic sensors, accelerometers, and optical fiber sensors to measure different kinds of human muscle conditions [9]. The developers of these sensor systems emphasized its



(a) Muscle stiffness sensor (Takakazu Ishimatsu)



(b) Auto-calibration system for EMG sensor suit (Maria Q. Feng)



(c) Ultrasonic muscle activity sensor (S. Moromugi)

Fig. 3. Various Sensor Systems for Human Motion Detection

convenience and ease to adapt to humans. These sensors, however, are too complicated to manufacture or are only verified to perform on a certain part of the human body. The EMG sensor is one of the most accurate measurement tools to determine human motion intensity. The approach using this sensor, however, is not considered in this study because of its inconvenient preparation to assess the signals and its inappropriateness for the working conditions at a construction site.

In this study, a feasible modular-type exoskeleton system and corresponding sensor systems are newly proposed to assist construction workers with their lower limb movements. First, for the purpose of adapting the modular-type exoskeleton system 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, intent signal processing methods for actuating a proposed system were introduced, and the feasibility of the command signal was estimated. There were then several measures to quantify the characteristics of human performance and the exoskeleton platform through an EMG signal (This sensor is used as a measurement tool of muscle activity only to verify the feasibility of the proposed system).

2. Analysis for designing the 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. Arndt 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 [10].

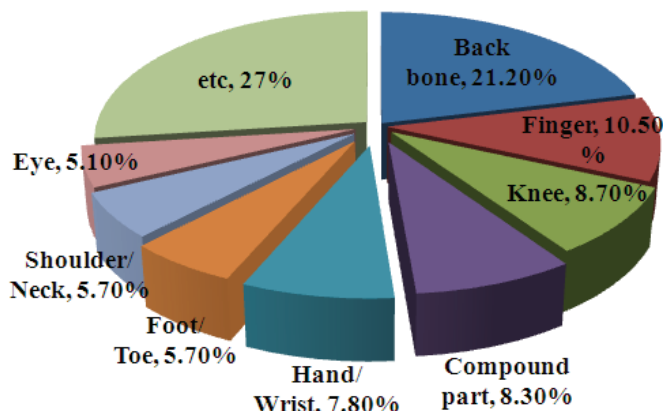


Fig. 4. Construction Workers' Disability Ratio (NIOSH)

The fatal injuries of construction workers-musculoskeletal diseases-were mainly divided into two dominant disabilities: dorsopathies and arthropathies. According to statistical and the annual reports of the National Institute of Occupational Safety and Health (NIOSH), it is

easy to have 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% respectively, and occurred most frequently at the site (Fig.4). Considering the priority of development and convenience of real adaptation, we choose the knee assistive wearable system firstly not spine assist one. 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. That means a spine support system has to be considered as support system not assist one. Therefore, this paper designed this specific part of the body-knee joint of the type that partly assists the knee joint (Fig.5).

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, and climbing a staircase or a slope

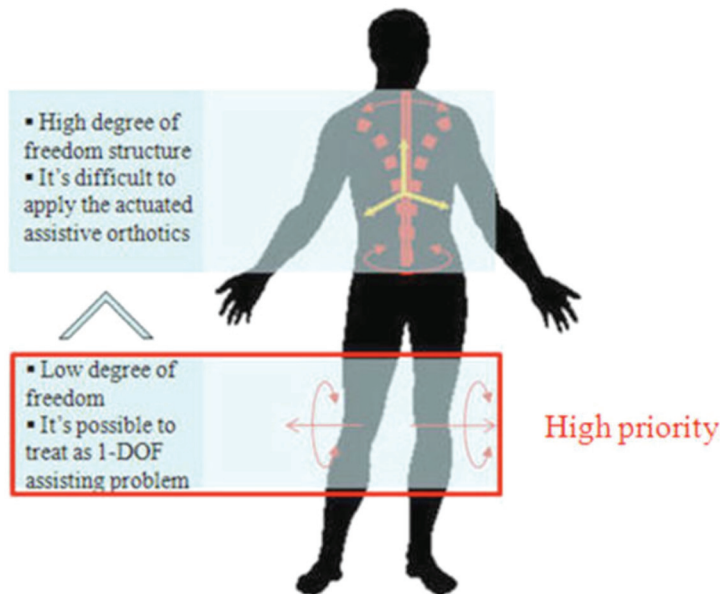


Fig. 5. Decision of Assistant Position Considering Two Dominant Causes of Disability of Construction Workers

2.2 Definition of the target task

To specify the target tasks at a construction, we follow these process steps. First, we looked at an overview of working patterns and types at construction sites. The overview was sourced from NIOSH. In the second step, construction workers-especially the general laborers-were classified into four major groups. As shown in step 2 under Fig.6, sheet metal workers, electricians, laborers, and cement masons were put in charge of each group. Finally, in the third step, based on the occupational common task of upper groups, target

tasks were selected which included heavy material handling using knee, loaded level walking, loaded ascent walking, and loaded descent walking.

As earlier mentioned, we developed a modular-type exoskeleton system to assist the lower limb, and we applied this mechanism in a real construction site. Thus, the target mission to handle heavy materials and loads at ground level and on a stairway, which is described in the following images, is critically considered.

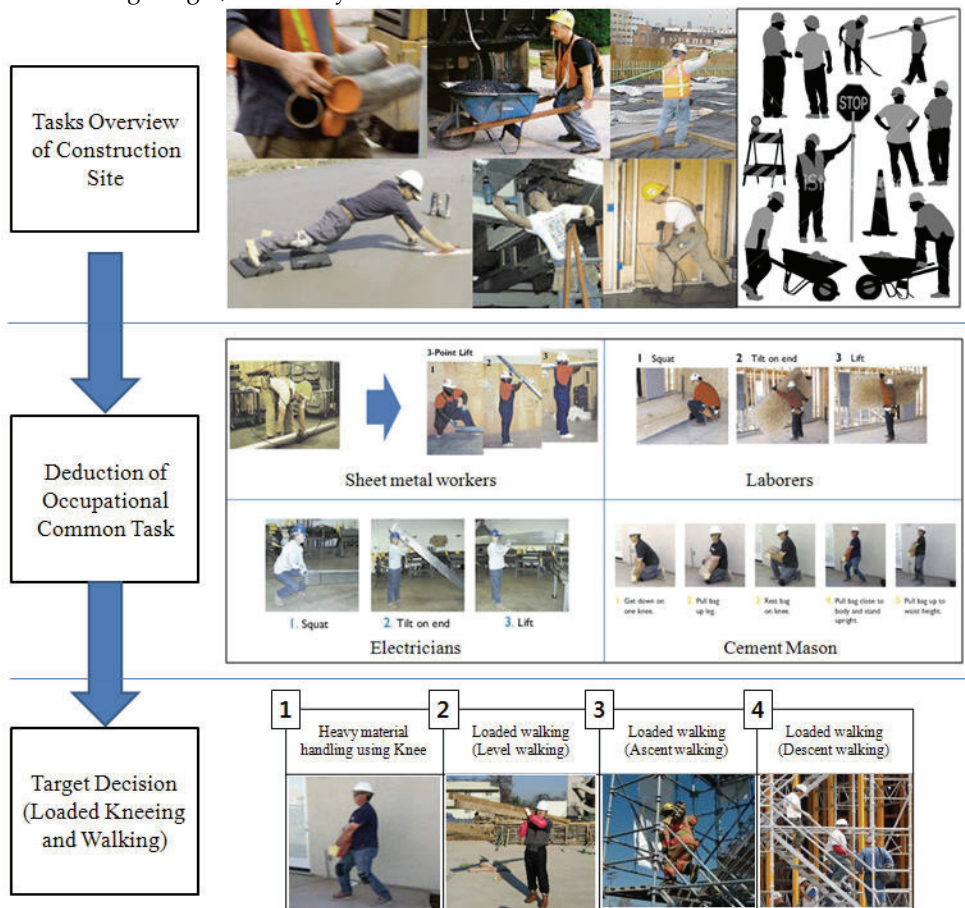


Fig. 6. Work group analysis for construction workers

3. Mechanics of muscle activity at the knee

3.1 Extensors of the knee

Rectus femoris functions as an extensor of knee extension, hip flexion, lateral rotation of the hip, and abduction of the hip [12,13]. Regarding the effect of its weaknesses, direct measurements of the contribution made by the rectus femoris to knee extension strength are not available. However, the physiological cross-sectional area of the rectus femoris is approximately 15% of the total quadriceps femoris muscle mass. Therefore, its negative

effect on a knee is as much as this contribution [14]. Vastus intermedius functions as an extensor of knee extension and prevents impingement of the pouch in the patellofemoral joint. It is based on the physiological cross-sectional area range from approximately 15~40% of the total muscle bulk [14]. Vastus lateralis is a large pinnate muscle, and its uncontested action is knee extension. The amount of its recruitment is proportional to the amount of resistance to extension [15]. If its activity is diminished, knee extension strength is reduced. Its physiological cross-sectional area suggests that in some individuals, the vastus lateralis may contribute 40% of the extension strength of the knee [16]. Vastus medialis is the most studied among the four heads of the quadriceps femoris muscle [15]. It is divided into two sections, VML (Longus) and VMO (Oblique), based on both anatomical and mechanical analysis. It is approximately 20 to 35% of the overall cross-sectional area of quadriceps femoris. It functions as an extensor of knee extension and for the stabilization of the patella during knee extension [16,17,18].

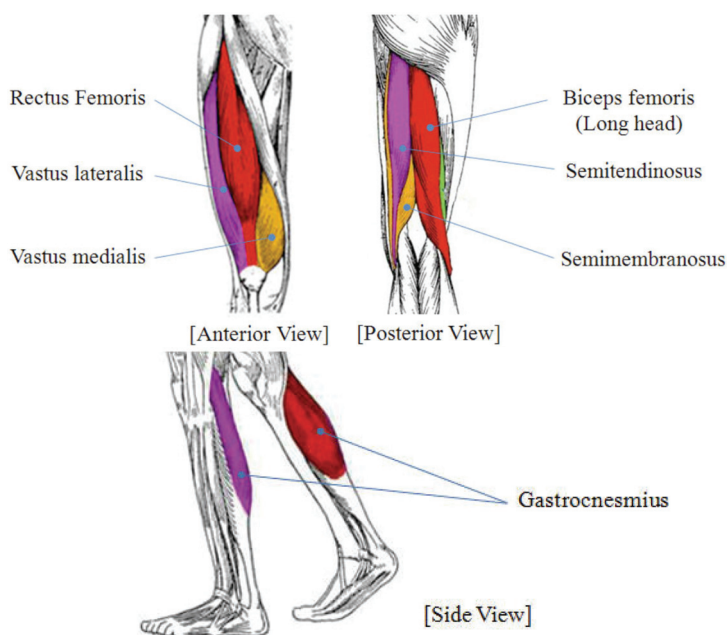


Fig. 7. Primary Knee Extensors, Flexors, and Plantar Flexor Muscles Focused in this Study

3.2 Flexors of the knee

The hamstring muscles represent the primary flexors of the knee. Hamstrings comprise of the biceps femoris longus and brevis, which form the lateral mass of the hamstrings, and the semimembranosus and semitendinosus, which make up the medial mass. The major functions of the hamstring are knee flexion, hip extension, medial rotation, lateral rotation of the knee, medial rotation of the hip, lateral rotation of the hip, and adduction of the hip. Hamstrings provide between 30 and 50% of hip extension strength and are active during normal locomotion. The most prominent period of activity is during the transition between the swing and stance periods of the gait cycle. During locomotion, the role of hamstrings'

activity is to slow down the extension of the knee during late swing, and to help extend the hip in the stance phase.

3.3 Mechanics of the two-joint muscles in the knee

The knee is controlled mostly by two-joint muscles that cross either the hip and knee, or the knee and ankle. Contraction of one of these muscles alone produces movement in all of the joints that the muscle crosses. To isolate movement at a single joint, the two-joint muscles cross or they must contract with other muscles. The iliopsoas and the hamstrings, as an example, together produce isolated knee flexion by canceling each other's effect at the hip. Similarly, simultaneous contraction of the gluteus maximus and quadriceps femoris produces knee extension without hip flexion. However, the knee more frequently displays simultaneous contraction of the quadriceps and hamstrings. This unusual pattern of simultaneous contraction of two-joint muscles appears to increase the ability of the knee and hip to generate the large moments needed during many activities [14].

4. System operation method – trial (1)

4.1 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 exoskeleton system for lower limb assistance, that is, for handling heavy materials during level walks and on stairways. To gather adequate motivation signals when the construction workers do their jobs at the site, first, an analysis of knee joint movements was needed. Fundamentally, the muscle activation status is completely different during level walks and on stairways. Figure.8 and Figure.9 show which parts of the muscle groups are mainly related to knee joint movement during level walks. Thus, a different type of gait pattern is created 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.

The primary motion is 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 from the work of Spivak and Zuckerman (1998). The following table shows the range of normal values of normal adult gaits at a free walking velocity. These values were used as reference values while we performed the experiments.

| <i>Contents</i> | <i>Values</i> |
|------------------------|---------------------|
| 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 |

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

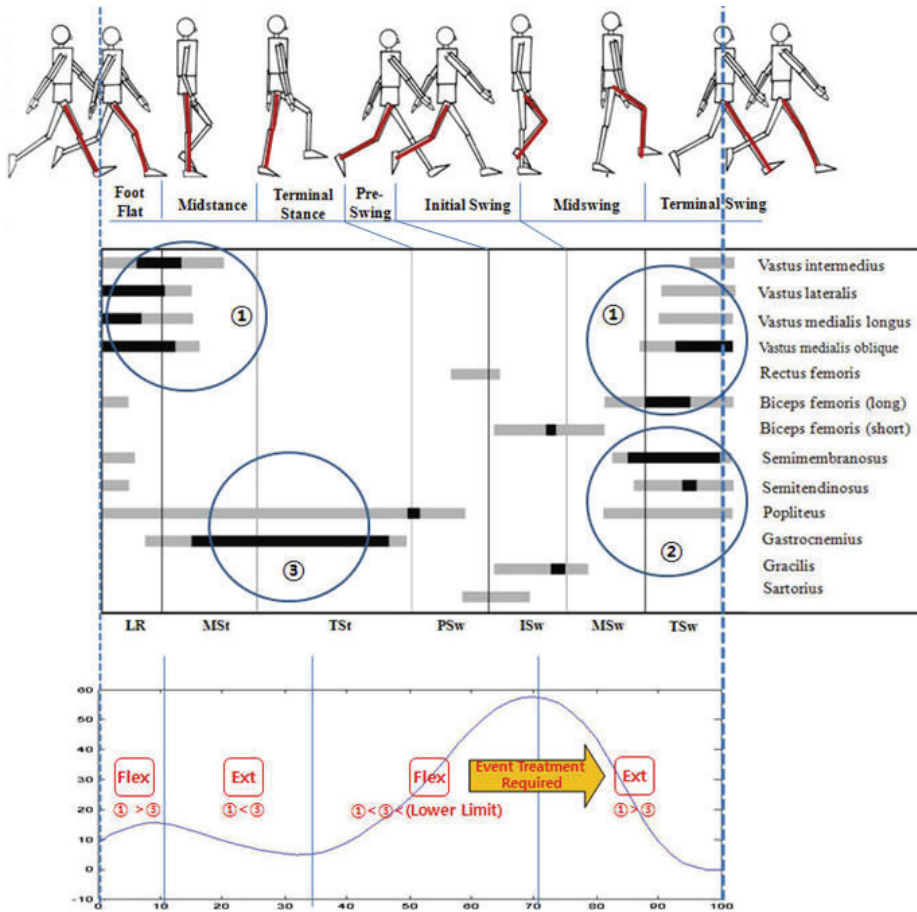
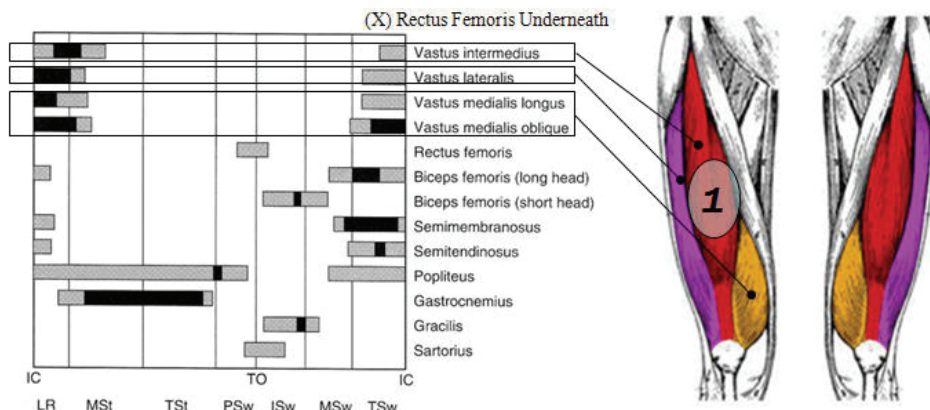


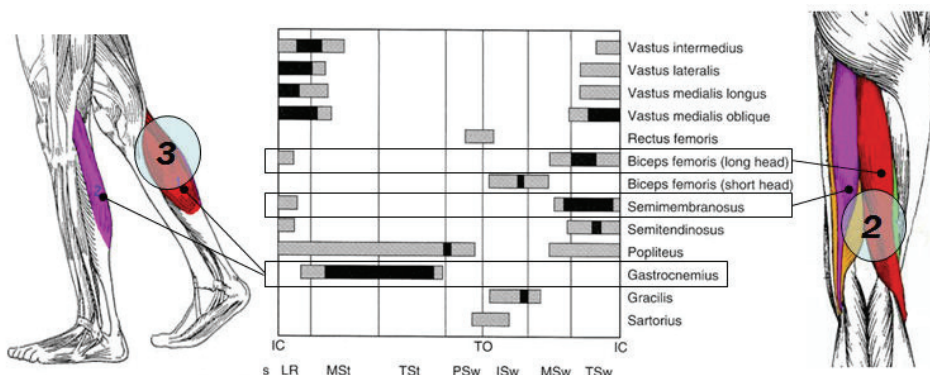
Fig. 8. Phasic Pattern of the EMG Activity of the Muscle and the Angular Displacement of the Knee during Level Walking by Healthy Adults

4.2 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 during 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 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.



(a) Muscle Activity Pattern of Anterior Side of the Leg during Walking and Proposed Sensor Position '1'



(b) Muscle Activity Pattern of Posterior Side of the Leg during Walking and Proposed Sensor Position '2' and '3' (Position '2' is discarded finally)

Fig. 9. Muscle Activity Pattern of Leg and Proposed Sensor Position for Exoskeleton

The gracilis and sartorius muscles may also contribute to swing-phase knee flexion when they are activated during late pre-swing, initial swing, and early mid-swing. These muscles, however, may very well be acting as primary hip flexors during this period [19]. Based on Fig.8, we analyze that to explain or measure the gait pattern using the muscle activity pattern, we must consider three positions of the muscle groups.

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). Fig.9 describes the sensor position of the anterior side (1) and the posterior side (3) 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 Knee Assistive System (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 be comprised of only one event, without intermission. Therefore, these successive movements could be organized into a single case. As shown in Fig.6, the proposed algorithm was gradually adjusted to the wearers, such as by calibrating the sensor system and regulating the velocity as with fine-tuning before starting the machinery, in order to develop a handy prototype of the system that is easy to wear. However, the trial of event treatment using a two-sensor set and its customized limit value was not easy to apply to various users because the acquired values for each person were inconsistent in every experiment. Therefore, the more convenient approach of using the restricted number of sensors and minimizing the calibration process is required. The results of the verification of the effects of 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

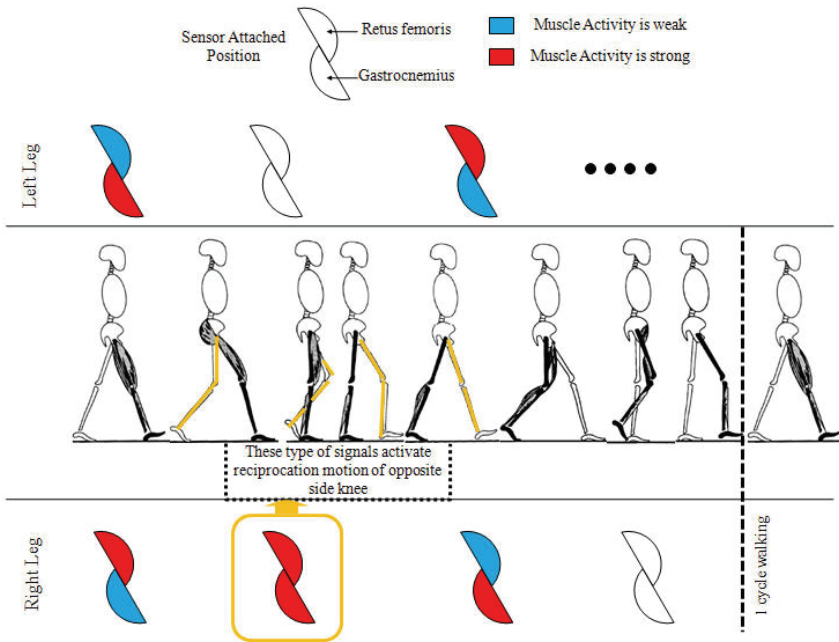
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Fig. 10. Operation Algorithm of KAS using MSS

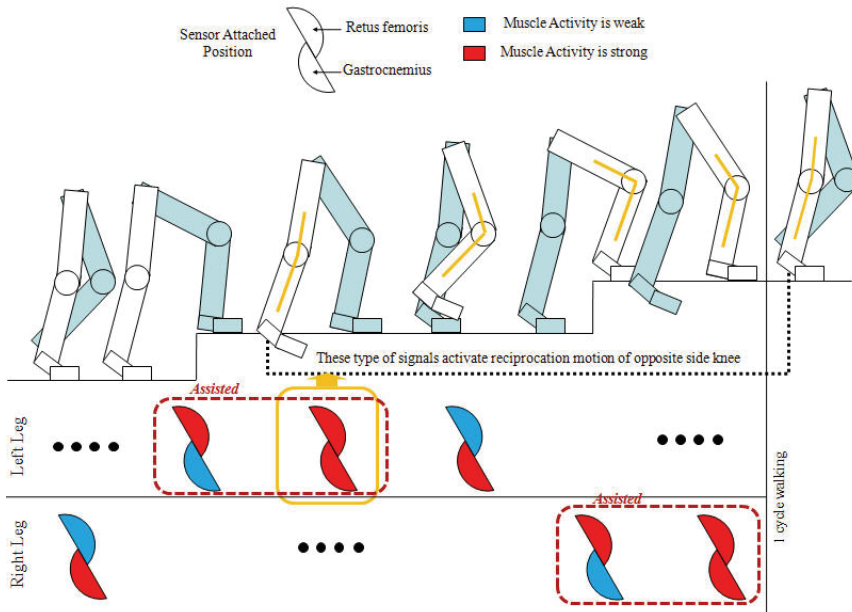
5. System operation method – trial (2)

To cope the above-mentioned problem, we newly designed the activation algorithm as a second trial. To explain the second trial of the activation algorithm for KAS, a simplified muscle activation pattern of two muscles is introduced. The positions of these muscles are exactly the same as with the sensor attached one.

To activate a KAS, a cross-activation algorithm is designed to use the event of simultaneous contraction of two-joint muscles (which appears to increase the ability of the knee and hip) as an activating signal of reciprocation motion of opposite side knee exoskeleton.



(a) Newly Designed Operation Algorithm for Level Walking



(b) Newly Designed Operation Algorithm for Step Walking

Fig. 11. Operation Algorithm of KAS - Trial (2)

An important thing of this algorithm is activation timing of the exoskeleton. Though this algorithm uses the event of simultaneous contraction to activate the opposite side, in the meantime, the two simultaneous contracting muscles are assisted by their own exoskeleton. As described in Chapter 6, this algorithm brings three effects for the wearer's muscle activation pattern. First is the reduction of required strength for simultaneous contracting, second is pattern shifting of sequential muscle activation, and the last is, as shown in Fig.11(b), the possibility to use this directly as an ascent walking algorithm. Consequently, the performance of the second trial algorithm is better than the first one and is thus selected as an operation algorithm of KAS.

6. System development

6.1 Exoskeleton unit

As mentioned earlier in this chapter, we analyzed the gait pattern based on the muscle activity pattern and the angular displacement of the knee joint. Finally, we deduced the proper sensor position (using only two MSS groups) and the basic operating algorithm. In this chapter, we briefly introduce our experimental exoskeleton system. Fig.12 shows the user-convenient knee movement assistive system that was devised by applying commercial

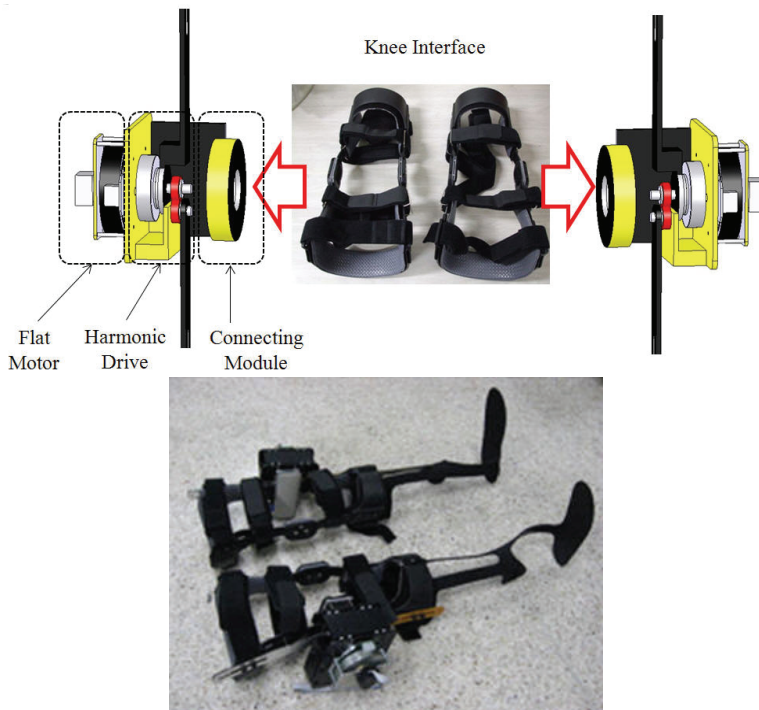


Fig. 12. Exoskeleton Unit of the KAS

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 muscle force, the joint reaction force, and so on. Reilly and Martens (1972) found the highest value for the quadriceps muscle force during level walking, which is 804 N (180.7 lbs) [20]. Considering both the maximum required force value on the quadriceps and the type of system—which partly assists 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 4,670mNm, 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 human motion, the proposed system feasibly accomplishes the goal of this research. Moreover, it can theoretically add approximately 45kg more payload to construction workers.

6.2 Muscle Stiffness Sensor (MSS) and control system

We designed MSS to acquire the signal for the degree of expansion of the muscle and to use this signal as a human intensity signal to operate the proposed KAS (Fig.13). 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.

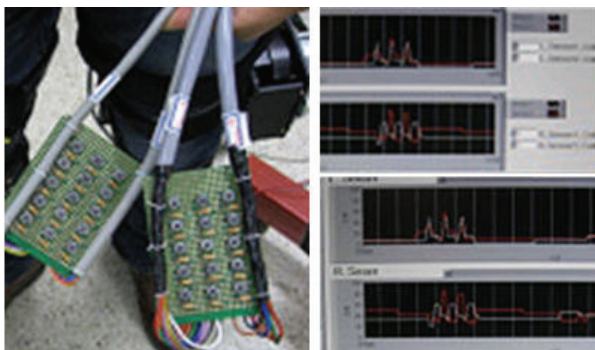


Fig. 13. Custom-Made MSS and Its Performance Test

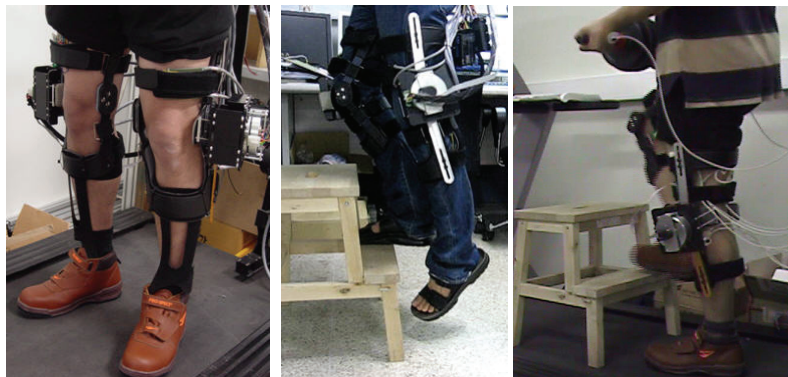


Fig. 14. Walking Experiments Using KAS

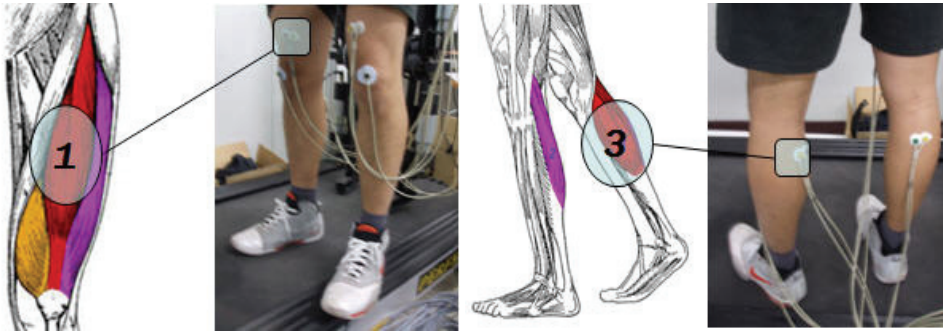


Fig. 15. Performance Verification of KAS using EMG Sensor

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

7. Experiments and conclusions

Experiments are set up with two topics: with payloads (10kg) and without KAS and with payloads and with KAS. During each experiment, EMG signals are gathered by four channels, and their sampling frequency and gain value was 1024Hz and 1126.7uV, respectively. These channels are attached on the upper and lower parts of quadriceps and gastrocnemius muscle groups. Every signal has a tendency to be assisted as shown in the figures below. All magnitudes of the EMG signals have an approximately 20% smaller value using KAS than before. This means that the required muscle strength to accompany the same task is reduced. Through this research, we discovered that partly assisting or supporting the muscle power could be useful for the users' safety and freedom from labor. Even though it was done in a specific and confined condition, that is, minimizing system weights and solving independent electrical power system, KAS is going to be a useful powered harness for construction workers.

As mentioned above, this result shows the characteristics of KAS. First, the muscle activity of quadriceps femoris is larger than that when not wearing KAS (2~3sec) because of the initial state of KAS, which is not activated yet. Second, the signal strength of the simultaneous contraction area of quadriceps femoris and the gastrocnemius muscle is reduced (4~6sec). Third, in the area of 5~6sec, only the signal of gastrocnemius muscle is retained. These changes of EMG pattern can be explained as a continuous change of muscle activity pattern which described in Fig.11. As a result, proposed system leads to the intentional changes of muscle activity pattern but it is helpful entirely for loaded ascent walking.

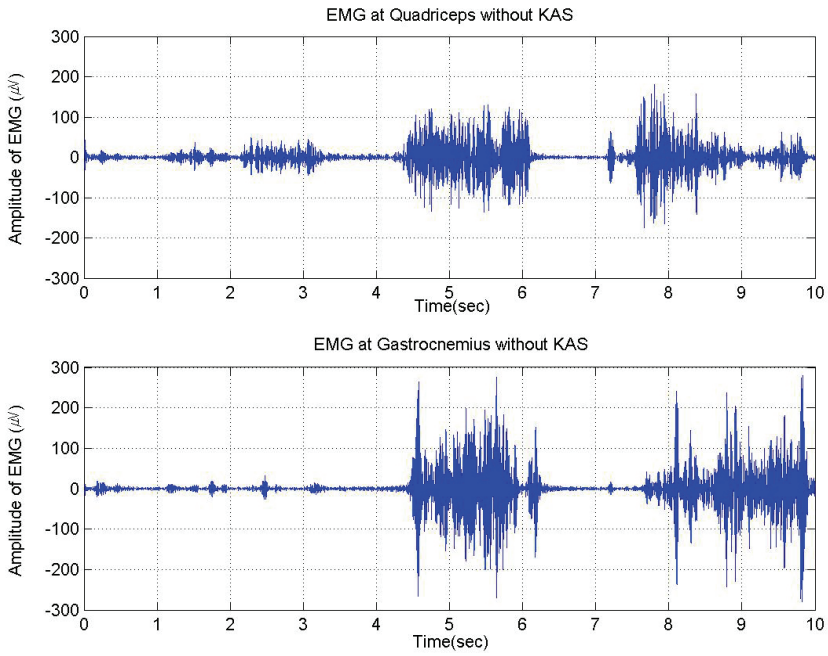


Fig. 16. Gathered EMG Signal without KAS

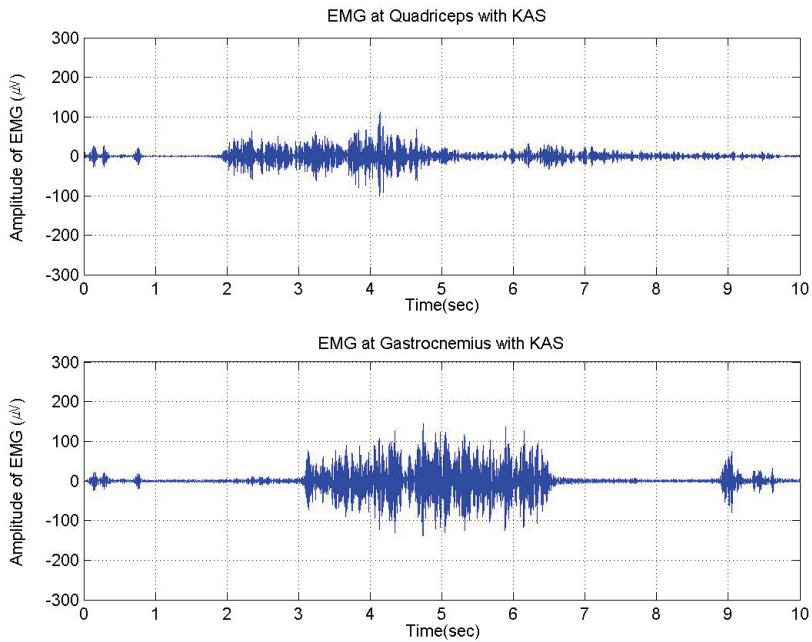


Fig. 17. Gathered EMG Signal with KAS

8. Further studies and future work

We studied and developed a force augmentation system for upper extremities [21,22]. This prototype system is fixed to compensate for self-weight and has 20kg payload per arm. To integrate this system with the knee assistive system which we developed, a weight compensation system through the spine, hip joint, knee, and ankle is obviously required. Most importantly, the actuator capacity and control performance of KAS should be increased.

As further work, we are examining two aspects: (1) improving the mechanical structure to minimize the system volume and weight, and stabilizing the system operation by human intent sensing, and (2) developing the total system which is an integrated lower limb exoskeleton with the upper one for whole body augmentation of industrial workers, especially construction laborers.

Fig.18 shows the system integration concept. To integrate the two exoskeleton systems, the most important factors to be considered are weight compensation, joint torque enlargement of lower limb exoskeleton, and its operation algorithm. To address these requirements adequately, many field tests are currently being performed.

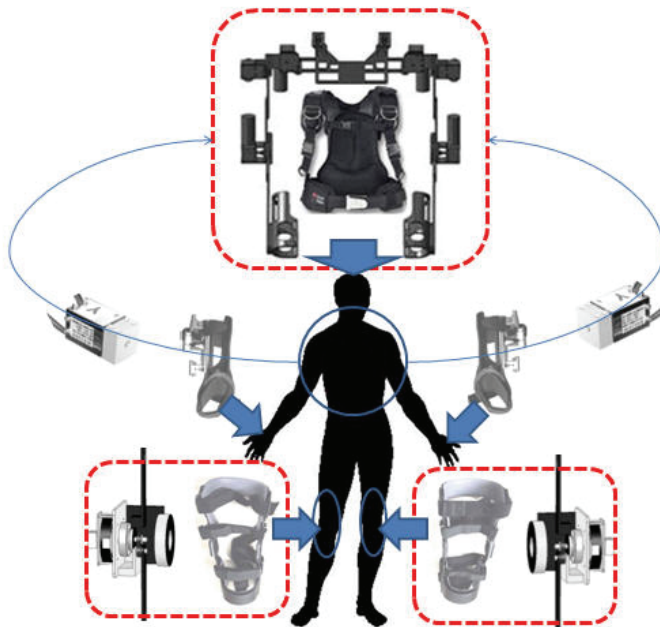


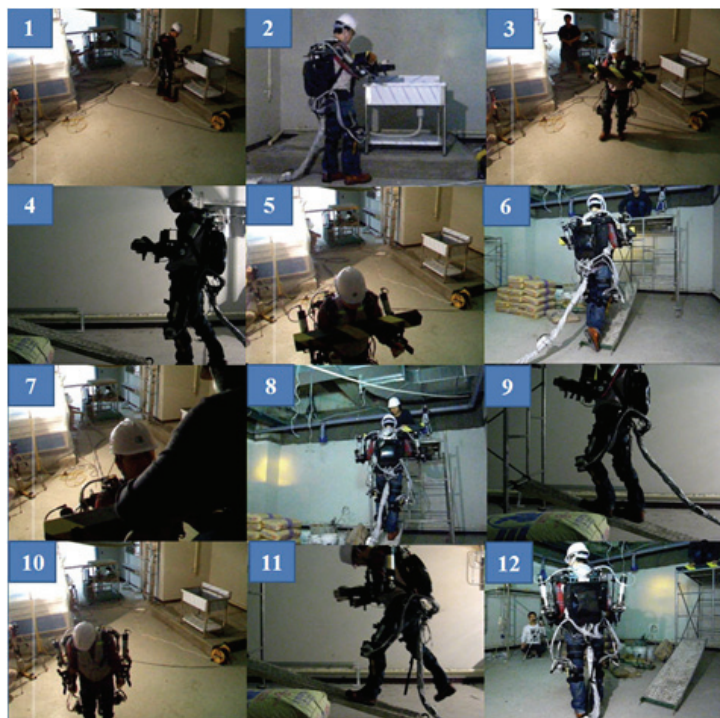
Fig. 18. System Integration Concept for Whole Body Support

Fig.19 describes several tests for a specified task using an incomplete system to gather the dominant problems for operating the newly integrated system. Case (1) is the heavy material carrying task while stepping up the stairs, and Case (2) is heavy material handling task while climbing up the slope.

Fig.20 describes the current status of the newly studied system. As shown in the colored area of the load distribution of humans, the mechanical load bearing structure has to be established before anything else.



(a) Field Test: Case (1)



(b) Field Test: Case (2)

Fig. 19. Field test using current prototype system (Proposed KAS is part of this system)

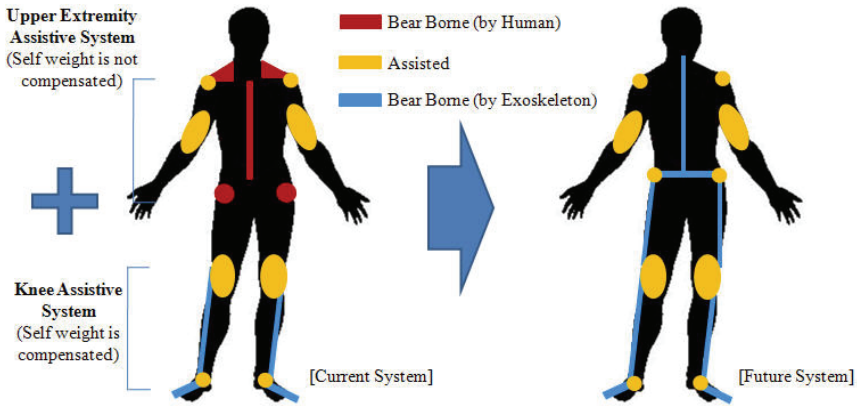


Fig. 20. Newly Proposed System in this Study and Considerations for adequate final Goal

A number of studies are performed to overcome the human performance limit. These studies, however, encountered several limitations on actuator performance, power source, system weight, convenient human-robot interface design, and so on. As described in the following diagram, for an adequate design of a force augmenting system for use in an industrial setting, we have to consider which type of system is more possible and helpful among many types of approaches.

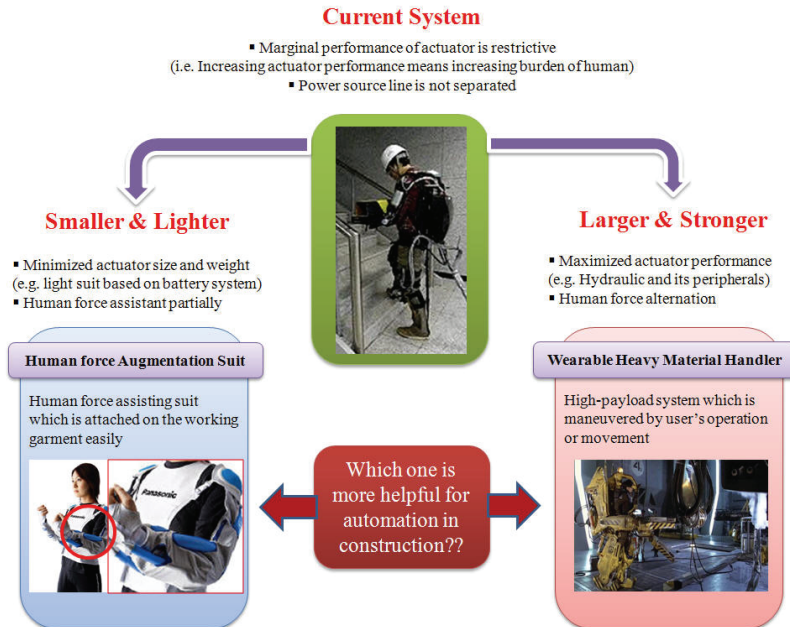


Fig. 21. Current Status of the Newly Developed System and Final Goal (REALIVE™ Power Assist Device of Matsushita Electric Industrial Co., Ltd., and Powerloader of the movie, “Alien II”)

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10. References

- Okamura, J., Tanaka, H., and Sankai, Y., "EMG-based Prototype-powered Assistive System for Walking Aids", Proceedings of the Asian Symposium on Industrial Automation and Robotics (ASIAR'99), Bangkok, Thailand, pp. 229~234, 1999
- Thring, M. W. "Robots and Telechirs." Halsted Press, a division of John Wiley & Sons, 1983
- Sankai Y., Kawamura Y., "Study on exoskeleton power assist HAL for walking aid using EMG", Nippon gakkai gakujutsu Yokoshu, Vol. 18, pp.453-454, 2000
- Kazerooni H., Chu A., Zoss A., "On the Bio-mimetic Design of the Berkeley Lower Extremity Exoskeleton (BLEEX)", 2005 IEEE International Conference on Robotics and Automation, pp. 4345-4352, 2005
- Weinberg B., Nikitczuk J., Patel S., Patrilli B. Mavroidis C., Bonato P. and Canavan P., "Design, Control and Human Testing of an Active Knee Rehabilitation Orthotic Device", 2007 IEEE International Conference on Robotics and Automation, pp.4126-4133, 2007
- Yobotics, 2005, RoboWalker, <http://yobotics.com/robowalker/robowalker.html>, 2006
- Low K. H., Liu Xiaopeng, and Yu Haoyong, "Development of NTU Wearable Exoskeleton System for Assistive Technologies," 2005 IEEE International Conference on Mechatronics and Automation, Niagara Falls, Canada, 2005
- S. A. Paluska and M. D. McKeag, "Knee Braces: Current Evidence and Clinical Recommendations for Their Use", Am Fam Physician, Vol. 61, pp.411-418, 2000
- Maria Q. Feng, "Sensor Suit for Human Motion Detection", Report Document of DTIC, ADA444285, 2006
- Arndt V., Rothernbacher D., Daniel U., Zschenderlein B., Schuberth S., Brenner H., "Construction work and Risk of Occupational Disability: A Ten Year Follow up of 14,474 Male Workers", Occup. Environ. Med., Vol.62, pp.559-566, 2005
- Jensen L., "Knee Osteoarthritis: Influence of Work Involving Heavy Lifting, Kneeling, Climbing stairs or Ladders, or Kneeling/ Squatting Combined with Heavy Lifting", OEM, Vol.65, pp.72-89, 2008
- Basmajian J.V., DeLuca C.J., "Muscles Alive: Their Function Revealed by Eletromyography", Baltimore: Williams &Wilkins, 1985
- Kendall FP, McCreary, E.K., Provance P.G., "Muscle Testing and Function", Baltimore: Williams & Wilkins, 1993
- Carol A. Oatis, "Kinesiology: The Mechanics & Patholomechanics of Human Motion", Lippincott Williams & Wilkins, 2004
- Lieb F.J., Perry J., "Quadriceps Function: An Anatomical and Mechanical Study using Amputated Limbs. J. Bone Joint Surg, Vol.50A, pp.1535-1548, 1968
- Farahmand F, Senavongse W, Amis AA, "Quantitative Study of the Quadriceps Muscles and Trochlear Groove Geometry Related to Instability of the Patellofemoral Joint", J. Orthop Res, Vol.16, pp.136-143, 1998

- Goh J.C., Lee P.Y., Bose K, "A Cadaver Study of the Function of the Oblique Part of Vastus medialis", *J. Bone Joint Surg*, 77-B, pp.225-231, 1995
- Wickiewicz T.L., Roy R.R., Powell P.L., Edgerton V.R., "Muscle Architecture of the Human Lower Limb", *Clin Orthop*, Vol.179, pp.275-283, 1983
- Margareta N., Victor H., "Basic Biomechanics of the Musculoskeletal System", Lippincott Williams & Wilkins, 2001.
- Barney, F. "Biomechanics of Human Motion." W. B. Saunders Company, pp. 266~272, ISBN 0-7216-5743-5, 1991
- Seung-Hoon Lee, Seung-Nam Yu, Hee-Don Lee ,Jung-Soo Han and Chang-Soo Han, "Development of force assistive wearable robot for the upper limb Part I. Kinematical analysis of the exoskeleton", *Proc. of Korea Society for Precision Eng.*, 2007
- Hee-Don Lee, Seung-Nam Yu, Seung-Hoon Lee ,Jung-Soo Han and Chang-Soo Han, "Development of Force Assistive Wearable Robot for the Upper Limb- Part II. Generation of Command Signal", *Proc. of Korea Society for Precision Eng.*, 2007