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研究課題名（和文）Development of the Body Weight Support system using Pneumatic Artificial Actuators

研究課題名（英文）Development of the Body Weight Support system using Pneumatic Artificial Actuators

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研究成果の概要（和文）：免荷装置は，下肢負荷を軽減し歩行動作を支援する．滑車と重りを用いた従来の免荷装置は，振子効果を発生させ歩容に影響を与える．新しく開発した免荷装置は，空気圧制御を使用し柔軟な免荷力を提供することができる．足圧中心(COP)軌跡をフィードバックすることでリアルタイムに制御された免荷力を生成することに成功した．
擬似的に再現した異常歩行での実験結果は，新しい免荷装置の潜在的な利点を示す．歩行機能の改善は，身体重心(COM)，COP，安定限界(MOS)，及びステップ動作で確認された．本研究は，新しい免荷装置が歩行障害者の歩行機能を改善できる可能性を示唆する．

研究成果の学術的意義や社会的意義
新たに開発された免荷装置は低コストで容易に製作が可能であり、また免荷に必要な力をアクティブに生成することができる。本システムは歩行パターンとパラメータをリアルタイムに修正しながら歩行アシストを行うことで、歩行機能の改善を図っている。本システムのこの新しい免荷方法は患者の感覚フィードバックに良好な影響を与えることから、臨床的な導入を検討できると考えられる。
運動障害と歩行障害は、患者の日常生活の質に悪影響を及ぼし、医療費として数十億ドルにのぼる。 製作コストが非常に低い、新型免荷装置は歩行機能を早期に回復するだけでなく、経済的負担を軽減することができると考えられる。

研究成果の概要（英文）：The new BWS system succeeded generated the modulated unloading force that follows the COP movement. These results turned out the flexible unloading force by the new BWS system. The results from the validation experiment show the advantages of the new BWS system, such that, it could prevent the pendulum effect during walking.
The results from the experiments on the abnormal walking show the potential applications of the new BWS system in clinical to improve the gait performance of the hemiplegia and the spinal cord injury patient. The modification and improvement of the abnormal walking under the new BWS system can be found in terms of COM, COP, MOS, and step parameters.

研究分野：Rehabilitation and Health Care

キーワード：BWS　PAM　Gait training　Center of mass　Center of Pressure　Step Length

様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９（共通）

１．研究開始当初の背景

Hemiparesis and impaired ambulation are commonly resultant of spinal cord injury and stroke. In Japan, the number of the number of incidents per million people has been estimated up to 27 in each year. According Japan Time, the government statistics showed that some 3.5 million are physically disabled in 2006. Locomotor disability, and impaired ambulation made an adverse impact on the daily life quality of the patient and cost up to billions of dollars for health care expenditures. Currently, the development of the gait rehabilitation has played an important role for locomotor functionality recovering.

In recent studies, the Body Weight Support (BWS) system has been considered as an indispensable component in gait training systems that have been used to improve the ability to walk of hemiplegic, stroke, and spinal cord injury patients. The BWS system has been used in many locomotion rehabilitation systems regardless of whether treadmill-based systems or ground-based systems. The evolution of the BWS system for gait training was based on the observation of the recovery of spinal cord cutting cats when implementation gait training for them with weight-support and full weight. The application of the treadmill BWS system was then extended for human gait training. Finch et al. investigated the influence of BWS on human gait. Their findings showed that the Treadmill BWS system expressed the advantaged behaviors in every examined aspect and had potential extensive applicability in clinical gait training. The application of Martha Visintin et al. examined the differences between BWS and full weight-bearing in locomotor rehabilitation with 100 stroke-patient participation. The results confirmed that gait training for a patient who was supported by bodyweight provided walking ability better than the patient training with bearing full weight. The BWS system, then, is widely applied in locomotor rehabilitation from the laboratory to clinical for both over-ground walking training and treadmill walking training. In recent years, the Treadmill BWS system in conjugation with orthosis robots was applied for many gait training systems to reduce the therapy cost and labor.

There are some reasons so that the Body Weight unloading system plays an important role in the gait training system. The first reason is by reducing the gravitational forces acting on the legs by the BWS system would reduce the load that needs to be overcome by the patient and then the patient could be stepping movements. The other reason is the use of the BWS system may be beneficial, because of its dynamic characteristic and special task activity which allow the patient to initiate gait training activities early after injury. Finally, the BWS system also provided the safety conditions and stability for the gait training process.

The gait training processing for incomplete patients may undergo many periods depending on the situation of the patient. In the beginning of gait training, the BWS system would carry out the high level of unloading force during training which reduces the gravitational force act on the legs of the patient during gait training. The level of unloading force would be up to 80% support for bodyweight because of the weakness of ability bearing for the patient’s body. The level of unloading force is reduced following the improvement of the mobility of the patient. The amount of unloading force can be adjusted depending on the clinical processing of the therapist. In general, the amount of supported weight will be gradually reduced, when the afferent signals to the brain would be increased. In this way, the sensory receptors will be activated and improved patients’ walking functions.

The BWS system normally consists of a harness, cables pulleys, frame, and the actuators that carry a percentage of the bodyweight of the patient. The actuators for the BWS system have been developing in more than two decades and extremely generous. Base on the implementation of the actuator, the BWS systems for human gait training can be classified into three types: static, passive, and active systems. Static systems often consist of a winch system that is connected to a harness through the rope-pulley. Winch systems, attached to a hard frame, can be driven to adjust the unloading force using a manually wound winch crank or using an electric motor with manually controlled speed. Static systems are considered to provide a constant weight support level; however, due to the vertical movement of the COM, this feature cannot be fit. Passive systems can be applied with some types of actuators, for example, counterweights, extension springs, and pneumatic cylinders. In these systems, the structures are like the static system, but the actuators to adjust the unloading force are changed. For a counterweight system, the unloading force depends on the gravitation and inertia of the counterweights. In the system using an extension spring, the actuator comprises several springs connected in series. Passive systems also maintain a constant unloading force; their characteristics are superior to those of static systems in that the suspension force is passively adapted but is uncontrollable with a moving COM during walking. The adapted suspension force is a potential force, such as gravitation, elastic force, and displacement of the cart in the case of using a pneumatic cylinder. Limitations of passive systems are that they could not guarantee a constant force, and using a rope-pulley system, the subject can be swung during walking. Recently, the development of active systems can overcome almost all the limitations of passive systems. They ensure constant weight support by combining a closed-loop control system with a dynamic roller or electromagnetic motor. However, almost all active systems, which apply the inherent structure in which very complex and cumbrous actuators are connected to the subject's trunk through a pulley-rope mechanism, have the disadvantage of potentially swinging the subject using these systems. In contrast, the pneumatic muscle actuator (PMA) has many advantages that could be applied to the BWS system such as simple structure, low cost, high power-to-weight ratio, and especially the capacity to generate force actively. Even though the PMA has some inherent limitations such as nonlinear and hysteresis behavior, it still is very attractive to the researcher to put more attention to apply PMA in therapy medical devices and rehabilitation. In addition, Franz et al. suggested that the unloading force, which varies with gait pattern, is more efficient than a constantly supported force. Using the PMA directly connects to the subject's trunk during gait training, we can adjust the unloading force actively. Moreover, the critical point of gait training is that the center of the human body always changes in three-dimensional space. Franz et al. suggested that synchronizing between gait and force modulation during the stance phase could provide more effective gait training. However, no study successfully modulates the support force in the other dimensions of the COM's movement as well as considers a moving center of pressure (COP).

２．研究の目的

This research introduces the novel development of a BWS system using pneumatic actuators for a gait training system. Based on the assessments and its evaluations, the novel BWS system exhibits the characteristics of being simple, low cost, able to maintain a constant unloading force, and the unloading force generated by the new system can be adjusted actively. An especially important capability of the novel BWS system is to generate the unloading forces that track the COP since it switches from left to right and vice versa.

Furthermore, we investigate the influence of the unmodulated BWS system based on the Counter weight (CW) system and modulated BWS system power by the Pneumatic Muscle Actuator (called the new BWS system) on the gait characteristics of abnormal gait during walking on the treadmill. The abnormal gait was generated by a healthy subject walking on the treadmill; however, the knee motion on one side was restricted. We hypothesis that the new BWS system may improve the gait characteristics and provide better behavior in comparison with the CW system.

３．研究の方法

Figure 1 shows an overview of the schematic diagram of the new BWS system. Currently, the BWS system employs the National Instrument device–NI cRIO-9176–that utilizes the NI Control and LabVIEW My Rio software as the operating system. A real-time control program was developed to drive the pneumatic muscle actuators. The signals from load cells are used to calculate the center of pressure (COP) tracking model and generate the reference signals. The control signals are output from the NI output module to operate the electro-pneumatic regulators (ITV 2050 by SMC). In this system, a regulator implements each muscle. The measurements by the system (i.e. force (N)) provide the feedback signal to the controller through analog/digital (A/D) input modules from National Instrument. The force sensors are provided by KYOWA (LUR-A-2KNSA1). The motion capture system with six cameras (from Motion Analysis Corporation) was also used to collect data from 16 markers positioned at the ends of the bones of the lower limbs, pelvis, and the shoulder of the trunk. The data collected from

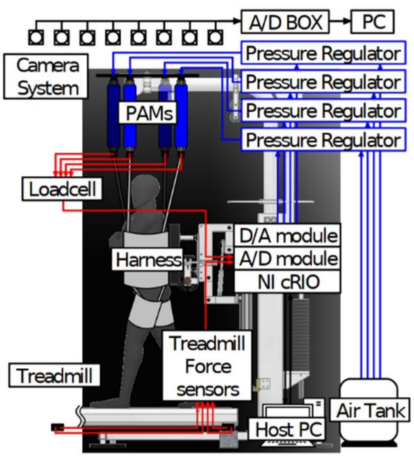

Figure 1. The principle scheme of the Body Weight Support system power by the pneumatic muscle actuators.

the motion capture system was used to calculate the center of mass (COM), Margin of stability (MOS), step parameters...

The COP tracking model is ideally based on the moving COP of the subject while walking. In Figure 2, the COP trajectory of a human in one gait cycle is represented. Particularly, the COP of a human, for example, is located at the left leg of the subject; when the left leg enters into a swing state, the COP switches to the right leg. The subject ' s COP will travel along the stance phase on the right leg until the right leg enters into the swing state, and at the same time, the left leg enters into a stance state. The COP will again switch to the left leg and the process is repeated in every gait cycle during human walking.

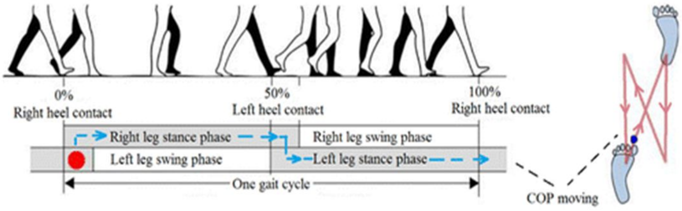

Figure 2. Demonstration of COP movement in force plate.

Two experiments were conducted basing on the novel BWS system power by the pneumatic muscle actuators. Furthermore, the experiment results based on the CW system were used for comparison with the novel BWS system. The first experiment was implemented on three healthy subjects with the novel BWS system and CW system. The main purpose of this experiment was for validation the new BWS system. The second experiment focused on the changes in gait performance of the abnormal gait under the BWS system and the CW system. The abnormal gait was generated by a healthy subject walking on the treadmill; however, the knee motion on one side was restricted. The active Body Weight Support (ABWS) system was hypothesized that it would improve the gait characteristics and provide better behavior in comparison with the CW system.

４．研究成果

The new BWS system succeeded generated the modulated unloading force which follows the COP movement. In Figures 3, the adaptation of the unloading force is represented for the left side. From Figure 3 **a**, as the COP changes to the left side, left leg changes to the stance phase, and the unloading force also rises to the peak. When the left leg is on the stance phase, the COP takes time to travel along the sole from the heel to the toe, and therefore, the unloading force is kept at a constant. When the COP switches to the right, the locomotion posture changes the left leg to the swing phase and the unloading force on the left side quickly decreases. We may see that the actual force from the new BWS system tries to follow the desired unloading force. From Figure 3 **b**, the actual force from the CW system does not follow the desired unloading force; instead, it tries to stay constant.

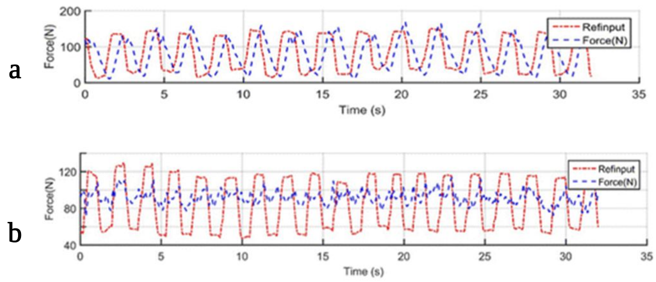

Figure 3. The adaptation of the unloading force on the left side. The red line represents the desired unloading force (named Refinput), while the blue line represents the actual force. (**a**) represents the unloading force by the new BWS system, (**b**) represents the unloading force by the CW system.

The results from the experiment validation show the potential advantages of the new BWS system, such that, the new system prevents the pendulum effect during walking that often happens when using conventional BWS systems that use cable-pulley apparatuses. The Figure 4 shows the variance of the differences in the COM trajectories in the vertical direction when applying the weight support systems to the COM trajectory in normal walking. The COM patterns using the BWS system were also stable and were less variable than the CWS system. On the contrary, the COM paths using the CW system greatly changed and varied, especially at the higher levels of weight support. For the high variance of the COM applying to the CW system, this variance happened due to the

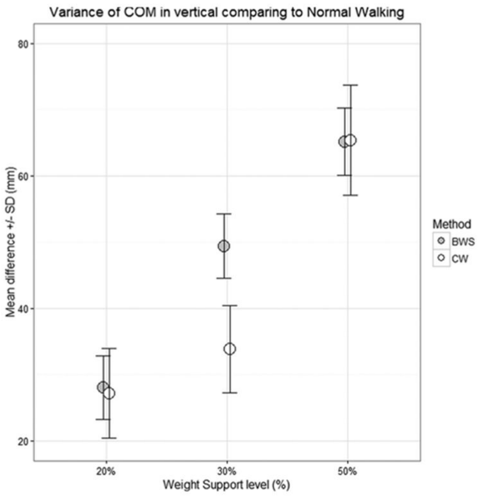

Figure 4. Demonstration of the variance of differences in COM trajectories in the vertical direction (difference = COM by weight support system − COM of normal walking).

dynamic character of the counterweight. This counterweight used for the unloading system was always moving like an oscillation during walking. This oscillation added a bit more force to the unloading force, therefore affecting the COM movement. In the new BWS system using PMs, this effect is removed such that the gait training is totally more comfortable for the subject. The other advantage of the BWS system using PMAs is that the unloading force directly acts on the subjects and does not use any intermediary apparatus. This makes the system very simple and easy to develop, improve, and it is also easy to apply the suitable therapy strategy based on weight support.

The results from the experiments which implemented the new BWS system on the abnormal walking show the highly potential applicable of the new BWS system in clinical to improve the gait performance of the hemiplegia of the patient recovering from the spinal cord injury. In this experiment, the abnormal gait was generated by restriction movement of the knee joint and 3kg-weight on the ankle. The Figure 5 shows the comparison of the gait performance of the abnormal gait and the abnormal gait under the new BWS system and the CW system. The hypothesis assumed that the BWS system plays a role as a clinical intervention such that the BWS system would influence the gait patterns and parameters during rehabilitation. The assistance of the stepping movement by the BWS system, which changes the gait patterns and parameters of the abnormal walking, may alter and activate the sensory feedback, therefore, improve the ambulation functionality. The results confirmed that the BWS system would strongly alter the abnormal walking gait pattern and could play an important role in the clinical implementation of gait rehabilitation of the lower extremity. The new BWS and CW system generally cannot correct the extreme abnormal gait since the significant differences from the normal walking condition can be observed. However, the modification and improvement of the abnormal walking under the new BWS and CW system can be found in terms of COM, COP, MOS and step parameters.

When comparing the influence on the gait performance of the abnormal walking, the new BWS system provided better behavior than the CW system in most cases. The representative results on the Figure 5 suggested that the unloading force of the new BWS system with the COP tracking could provide better gait trajectories in comparison with the case of using the CW system with a constant counterweight. These results could be explained that the lateral force in the pendulum effect by using the CW system pulled subject COM to the vertical center axis. Consequently, the COP in the horizontal direction would distort while walking under the CW system, especially at the high level of unloading force. In contrast, the better results of the COM and COP while waking under the new BWS system suggest that the lateral force in the pendulum effect was reduced. These results confirmed the advantages of the new BWS system and the highly potential applicable of the new BWS system on the gait rehabilitation.

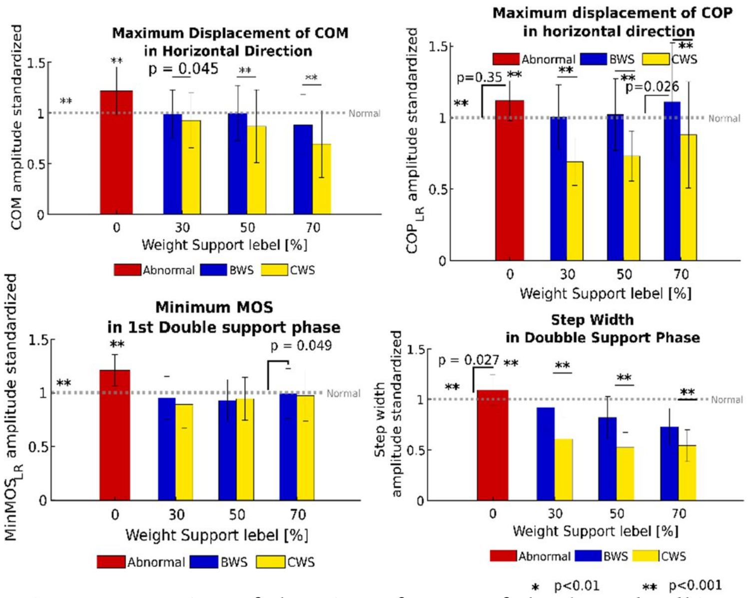

Figure 5. Comparison of the gait performance of the abnormal walking condition and the abnormal walking under the new BWS system and the CW system. The significant value (p) was selected as 0.05. * and ** show that p is less than 0.01, and 0.001, respectively.

５．主な発表論文等

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３．雑誌名 MPDI/Applied Sciences	６．最初と最後の頁 1-18
掲載論文のDOI（デジタルオブジェクト識別子） なし	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

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〔図書〕　計0件

〔産業財産権〕

〔その他〕

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6．研究組織

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