2014 IEEE International Conference on Robotics & Automation (ICRA)
Hong Kong Convention and Exhibition Center
May 31 - June 7, 2014. Hong Kong, China

A Body Weight Support System Extension to Control Lateral Forces: Realization and Validation

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Abstract— **Body weight support systems are frequently used as part of robotic gait training to provide unloading in order to help subjects perform walking, but can also induce stabilizing forces and render the task of maintaining balance less challenging. In this paper, a two-dimensional body weight support system extension is presented which reduces lateral forces induced on the subject by means of linearly translating the cable pulley according to lateral movements of the subject. It is demonstrated that the system accurately tracks lateral movements of the pelvis at different levels of vertical support load and thereby lowers the induced lateral forces. The system will be used in advanced robotic body weight supported treadmill walking incorporating a balance training element.**

I. INTRODUCTION

Regaining the ability to walk is a major focus of the rehabilitation process in stroke survivors and patients suffering from a spinal cord injury. Being ambulatory is crucial for accomplishing activities of daily living and therefore contributes essentially to quality of life [1]. Body weight supported treadmill training (BWSTT) is frequently used as part of rehabilitation for patients suffering from spinal cord injury or neurological diseases such as stroke. The body weight of the subject is partially unloaded according to their walking abilities and strength. Positive results have been shown regarding the effectiveness of body weight supported treadmill training for stroke patients [2] and for spinal cord injured patients [3].

The training is often combined with a form of supporting forces to move the neurologically impaired leg, which can be provided manually by therapists or by powered orthoses. Robotic assisted therapy can enhance the intensity and frequency of training as it reduces the physical workload of the therapists. On the other hand, a robotic device with limited degrees of freedom restricts pelvis and trunk movements and therefore can alter the gait kinematics [4]. These constraints hinder lateral movement - an important element underlying the control of balance during walking [5] - and therefore can limit the scope of and reduce the challenge of the training [6].

Most body weight support systems (BWS) are realized with a cable system which is connected to a harness worn by the subject. The cable is guided by a passive or active weight unloading system over an overhead mounted deflection pulley to the subject. An example of a commercially available body weight support system is the Lokolift [7]. The scope of body weight supported gait training has recently been expanded to large workspace overground walking with the development of the ZeroG (Bioness, Inc., Valencia, CA, U.S.), which follows the subject in the walking direction by means of a trolley that runs on a rail and contains a pulley mechanism with a series elastic actuator to unload the subject [8], and with the development of the FLOAT (Lutz Medical Engineering, Switzerland), which allows transparent 3D support during overground gait, by means of four actuators and moving deflection units on two rails [9].

Preliminary experiments [10] indicate that most of the currently available body weight support systems with a fixed pulley system impose lateral forces on the subject. These forces tend to pull the subject back towards the centerline as shown in Fig. 1 and thus cause a stabilising effect, which may reduce the challenge of the dynamic balance control task.

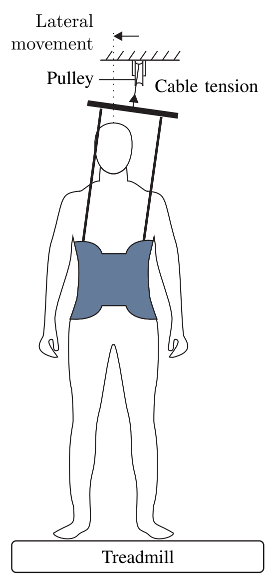

Fig. 1: Principle problem with missing lateral DoF.

This paper presents an extension to body weight support systems incorporating an additional degree of freedom (DoF) to minimize these lateral forces. The device hardware and validation of its performance is shown. Finally, a comparison between a conventional, fixed BWS system and one equipped with the new extension is made.

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II. BACKGROUND

A new treadmill-based gait rehabilitation system has been developed which focuses on balance aspects and therefore enables lateral weight shift of the subject. This modular system consists of several components with the core element of a new pelvis module, which allows for lateral displacement of the human pelvis. As described in section I, there is a need for an actuated BWS in order to avoid the stabilising effects of the induced lateral forces in the supporting cable. The main application of the new BWS will be in the context of the new gait rehabilitation device. To clarify the interaction between the two components, the pelvis module is simplified as a linear actuator to support the lateral movement of the pelvis, as depicted in Fig. 2.

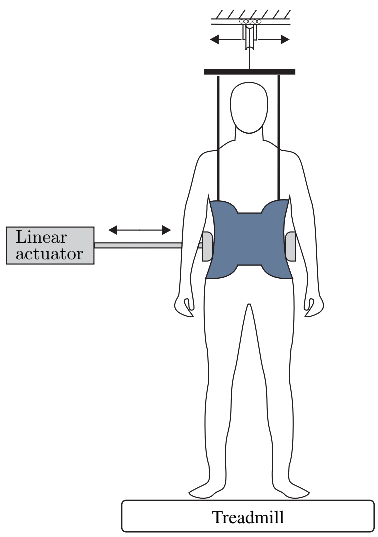


Fig. 2: The linear actuator supports the natural horizontal weight-shifting movement of the pelvis and emulates the pelvis module of the complete BWSTT platform.

III. CONCEPT AND MODEL

The main function of the body weight support extension is to laterally translate the main pulley according to pelvic movements using a linear actuator[1]. However, a lateral deviation of the pulley would alter the cable length of the main BWS which would induce large forces on the pulley. Therefore, a design is proposed that cancels out the static forces and compensates for changes in cable length. The actuator force needed is small as it only compensates for friction effects and inertia. A system of pulleys (Fig. 3) is used to ensure that changes in the overall cable length in response to lateral movements of the main pulley are kept to a minimum. Further details of the concept, including a mathematical model and a simulation study of the system, are presented in [11].

In comparable applications such as cranes with trolleys, another approach is often used, namely a free hanging pulley.

[1]Two linear actuators are used: the first mimics the pelvis module for the experiments of this study (Fig. 2, 6 and 9) while the second is a component of the presented 2D BWS (Fig. 3 and 4).

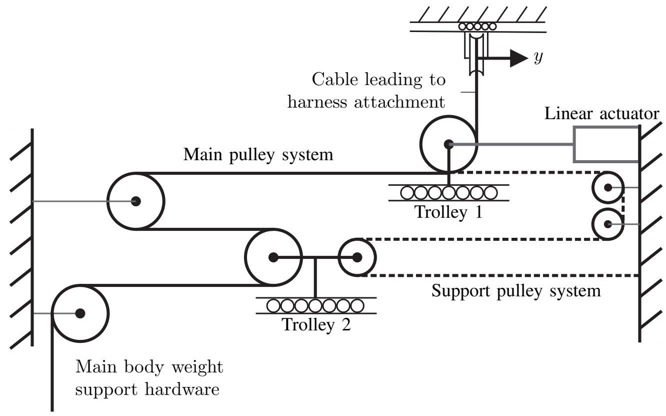


Fig. 3: Schematic of BWS extension.

The concept presented here was chosen because uncontrollable degrees of freedom should be avoided. Another advantage is the compatibility with existing body weight support systems, as the extension does not alter the forces of the main support system. In addition, it will be possible to use the system to command nonzero lateral forces. This could be useful to render subject-specific balance training environments (e.g. stabilizing or destabilizing).

IV. HARDWARE AND SENSOR IMPLEMENTATION

The components of the new BWS extension - illustrated in Fig. 4 - are mounted on a plate that is rigidly connected to the frame of the BWS system. The pulleys are manufactured from polyamid and are each equipped with two low friction ball bearings. The moveable pulley units are mounted on the trolley of a linear guideway (Hiwin®). The trolley of the first pulley system is actuated by a ball screw (with a lead of 2 mm) and electric motor (Maxon®RE40). The small lead was chosen in order to make an additional transmission superfluous.

Sensing of the lateral pulley position is realized by an encoder on the motor shaft and a linear potentiometer for redundancy and ease of initialization. The support pulley system is driven by a length stable belt and guided over crowned pulleys for self-centering. The maximal achievable force and speed of the linear unit are 565 N and 0.35 m/s, respectively, while the maximal lateral amplitude of the lateral pulley position is 0.1 m.

V. CONTROL SYSTEM

The lateral position of the new BWS extension, y, is position controlled using a simple proportional derivative (PD) controller, shown in Fig. 5; the parameters of the PD controller were tuned manually. The controller produces, via a motor torque, an actuator force, F_a, based on the error, e, between the reference (y_{ref}) and actual (y) lateral displacements.

This arrangement was chosen since the pelvis module has the task of supporting and controlling the lateral movement of the human and the idea behind the control system of the BWS in standard training mode is to minimize the

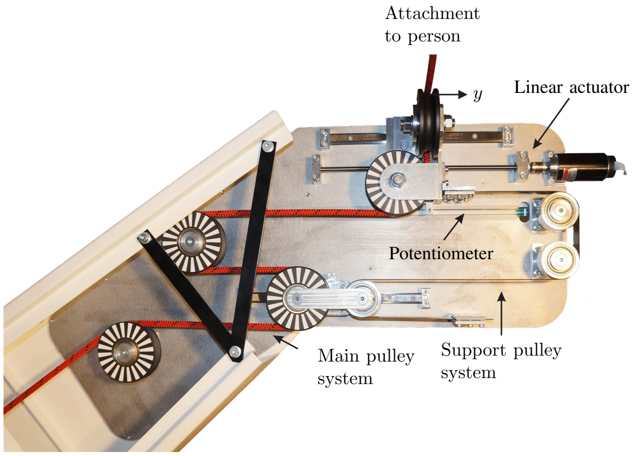


Fig. 4: The mechanical implementation of the pulley system.

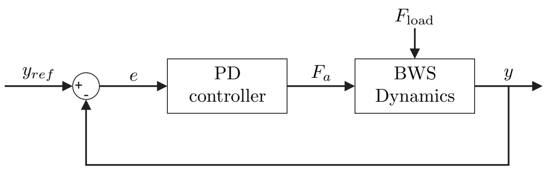


Fig. 5: The position control system of the lateral degree of freedom of the BWS system.

relative lateral position between the pelvis and BWS cable attachment point, and therefore, the unintended lateral forces which are induced by this relative displacement.

Currently, there are two control modes implemented. In the first control mode, the desired position of the BWS is given by the actual measured lateral position of the pelvis module. In this way, the BWS tracks the lateral position of the pelvis module (and thus also the lateral position of the subject). This mode will be applied when the impedance of the lateral control of the pelvis module is low, giving the human subject a high degree of influence on their lateral position.

In the second control mode, the desired position for the control system of the BWS is directly given by the desired trajectory of the pelvis module. In this way, the movement of the two modules should be better synchronized and the tracking error and thus the lateral disturbing forces should be minimized. This mode is intended to be used when the impedance of the lateral pelvis guidance is high; in this case, the actual trajectory of the human pelvis should be tightly controlled to a reference trajectory.

Concerning other applications, the linear correlation of the displacement/angle and the disturbing lateral force provides the possibility of actually using the BWS to induce defined disturbing or stabilizing forces on the human subject. This could be used in the future for applications such as balance training in which perturbations are applied to the subject during walking to increase the challenge of maintaining balance.

As a safety feature, virtual ‘walls’ are implemented at the end points of the lateral range of motion. These provide an additional assisting component and secure against excessive lateral movements (e.g. when a subject is stumbling and in danger of falling to one side). Other safety features are current limits for the motors, emergency stop buttons for both the subject and operator, and the mechanical end-stops of the device (Fig. 4) which limit the extent of lateral movement.

VI. EXPERIMENTAL VALIDATION

In order to evaluate the concept and implementation of the system, two experiments were conducted to answer the following questions:

1) Does the pulley mechanism function in the intended way such that the supportive load for the subject does not affect the lateral system behavior (e.g. due to friction effects)?
2) Does the additional degree of freedom of the BWS system succeed in reducing the induced lateral forces?

A. Influence of Attached Mass on System Behavior

As discussed in section III, the force from the attached mass of the person should be canceled out within the pulley mechanism and therefore should not unduly influence the system’s lateral behavior. To evaluate whether the friction and other effects caused by the attached load alter the mechanical behavior, the BWS was set to a sinusoidal trajectory (6 cm amplitude) and three different masses (5 kg, 25 kg and 45 kg) were attached to the cable, as shown in Fig. 6.

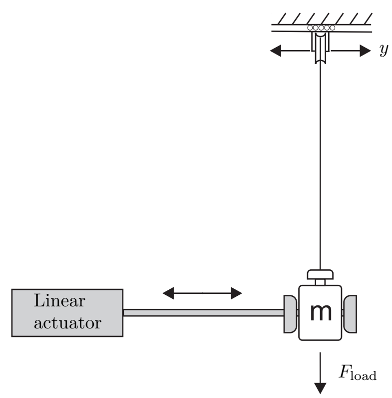
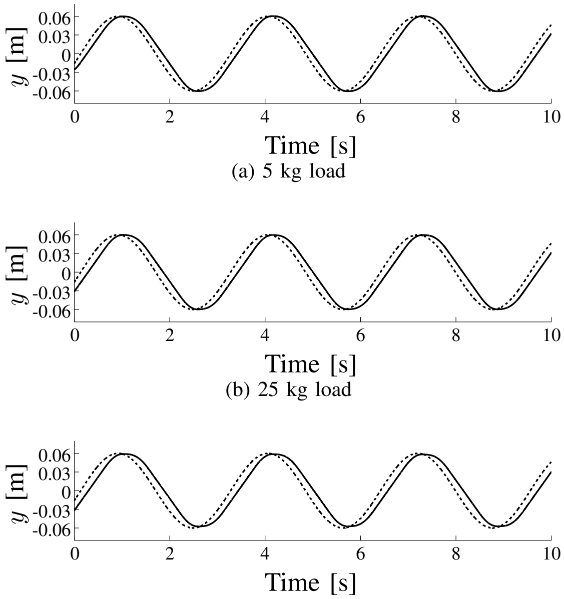


Fig. 6: The experimental setup to evaluate the system behavior under different loading conditions.

This range was chosen as it represents realistic loads for body weight supported treadmill training: 45 kg would represent 50% support for a 90 kg person. To ensure that the additional load is only applied in a vertical (negative y-direction) and that no (or very low) dynamic lateral forces are applied to the BWS, the added masses were additionally guided by a linear actuator that moved them in a lateral direction. The fixation utilized ensured that no vertical forces were transferred to this pelvic lateral guidance system. The linear actuator concept is applied here in order to simulate the intended application in which all the lateral forces between the subject and the robot should be transferred to the pelvis module of the gait rehabilitation system.

Fig. 7 compares the desired and actual sinusoidal trajectories for the different loads. It can be seen that there is almost no difference in the tracking performance of the position control system for the three different loads attached to the BWS.



(a) 5 kg load

(b) 25 kg load

(c) 45 kg load

Fig. 7: The desired sinusoidal trajectory compared to the actual recorded trajectories with three different loads (5kg, 25 kg and 45 kg) attached to the BWS. Dotted and solid lines represent the reference and actual positions, respectively.

As an additional indicator of whether the system behavior is altered by the different levels of supported mass, the control outputs of the position control were recorded for the three different load cases and then compared. Time histories are shown in Fig. 8. The root mean square force output is increased by around 16% when the attached load is increased from 5 kg to 45 kg.

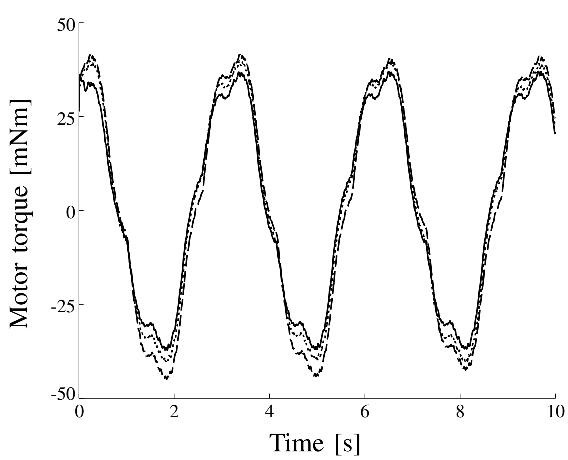


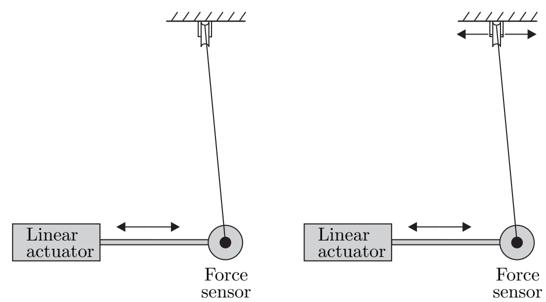
Fig. 8: Motor torque of the control system for the three different load cases. Solid, dotted and dashed lines represent loading at 5 kg, 25 kg and 45 kg, respectively.

B. *Influence of the Lateral DoF on the Disturbing Forces*

In order to answer the second question concerning whether the new lateral degree of freedom of the BWS system effectively helps to reduce the disturbing lateral reaction forces, an experiment was conducted to measure this force. Firstly, the experiment was conducted with a locked DoF, while in the latter phases, the lateral DoF was unlocked and the control system activated in two different modes. There were thus three different settings:

1) Lateral DoF locked;
2) Lateral DoF permitted, first control mode;
3) Lateral DoF permitted, second control mode.

The setup of the experiment is illustrated in Fig. 9. The cable of the BWS was attached to a 6 DoF force sensor that in turn was attached to an additional linear actuator that could move laterally (with all other DoFs fixed). The vertical distance between the force sensor and the attachment point was approximately 0.75 m, a height that represents a realistic value in the setup. During the tests, the linear actuator moved the added mass in a sinusoidal pattern with an amplitude of 6 cm.



(a) 2D BWS locked

(b) 2D BWS active

Fig. 9: Experimental setup for the experiments on the disturbing forces, with the lateral DoF of the BWS blocked (left) and active (right).

The resulting forces were recorded (no torques were transmitted due to the mechanical interface to the sensor) and low pass filtered with a 20 Hz cutoff frequency. Fig. 10 shows the lateral forces that were measured under the three different settings. It can be seen that the lateral degree of freedom with the feedback controller greatly reduces the induced lateral forces.

The root mean square (RMS) results are summarized in Table I. The RMS values are reduced by around 80% from condition 1 to condition 2 and by another 40% from condition 2 to condition 3.

The correlation between the lateral force and the lateral displacement between the cable attachment point at the BWS and the lateral position of the force sensor is shown in Fig. 11. It can be seen that the correlation is fairly linear over the analyzed range of motion and that hysteresis is low. This shows that in addition to the reduction in the lateral disturbance, the BWS extension presented in this paper could be used to apply intended stabilizing or disturbing forces, for example in a stand-alone application without the additional

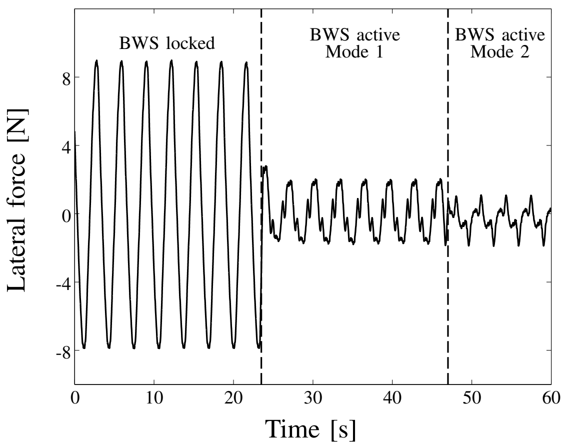


Fig. 10: Measured lateral forces under different control settings, with the lateral DoF was blocked (left-hand section), unlocked (middle section) and position control set to the tracking mode, and the trajectory of the BWS synchronized with that of the linear actuator (right-hand section).

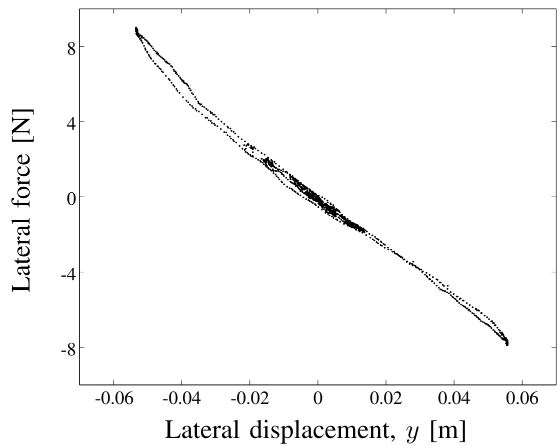


Fig. 11: The lateral forces over the lateral displacement between the attachment point of the rope at the BWS and the force sensor.

modules (i.e. the robotic orthosis device) of the complete gait rehabilitation system.

Condition	RMS [N]	Amplitude [N]
1	5.8	8.5
2	1.25	2
3	0.71	1.5

TABLE I: Lateral forces (RMS and amplitude) for the three different conditions.

Tests will shortly be conducted to evaluate the performance when human subjects are supported by the device and walking at different speeds. This will introduce additional challenges such as a variation in vertical load and a more complex pattern of lateral movement.

VII. CONCLUSIONS

An extension for body weight support systems which reduces lateral stabilizing forces through tracking lateral movements of the subject's pelvis has been designed, constructed and tested. The system can accurately follow a reference sinusoidal lateral displacement under various levels of vertical supporting force. The body weight support system extension substantially reduces the induced lateral forces while effects on the vertical support forces are kept to a minimum. The system will be applied to advanced body weight supported treadmill training in which subjects are required to actively maintain their balance.

ACKNOWLEDGMENT

This work was developed under funding from the Commission for Technology and Innovation (CTI) of Switzerland.

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