A Novel Body Weight Support System Extension: Initial Concept and Simulation Study

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***Abstract*—Body weight supported treadmill training is an approach to gait rehabilitation following a stroke or spinal cord injury. Although lateral control of balance is an important aspect of walking, many of the currently available body weight support systems have a fixed pulley configuration which can lead to lateral forces being developed in the supporting cables, interfering with the lateral balance task.**

In this paper, a novel extension for body weight support systems, used for treadmill walking, is presented which features a system of pulleys and trolleys. A model is developed for the device along with a basic feedback controller in order to enable simulation of the concept.

The lateral forces induced by the novel system are greatly reduced in comparison to a fixed pulley system. This device has applications in balance training within gait rehabilitation programs.

I. INTRODUCTION

Body weight supported treadmill training (BWSTT) is frequently used in stroke and spinal cord injury rehabilitation. This type of training uses partial body weight support combined with some form of assistance for moving the neurologically impaired subject's limbs. Though other forms of training such as the Bobath concept are widespread, BWSTT is a more task-specific form of gait training. Indeed, positive results, for instance, in terms of functional ambulation, independent walking and motor scores have been demonstrated for stroke [1] and spinal cord injured patients [2]. The assistance can be provided either manually by therapists or by robotic actuators. The latter approach reduces the physical labour needed from the therapists and allows greater repeatability but can also distort the gait kinematics due to the additional constraints imposed by the robot [3], [4].

In addition to generating propulsion and providing support to counteract gravity, balance control in the frontal plane is a critical aspect of gait [5]. This lateral control involves predicting the future position of the centre of mass and adjusting foot placement accordingly [6].

Several body weight systems are commercially available. For example, the Lokolift (Hocoma AG, Volketswil, Switzerland) combines a passive spring element with an electric drive under closed loop control to precisely control the level of body weight support force [7]. The ZeroG (Bioness, Inc., Valencia, CA, U.S.) employs series-elastic actuation and an active trolley system to follow the subject longitudinally for overground walking and other movement profiles such as sit-to-stand transfers [8]. However, these and several other body weight support systems can develop lateral forces in the supporting cable whenever the subject moves laterally. Such movement will produce an angle in the cable and therefore induce horizontal force components, as shown in Fig 1. These lateral forces tend to pull the subject back towards the centreline.

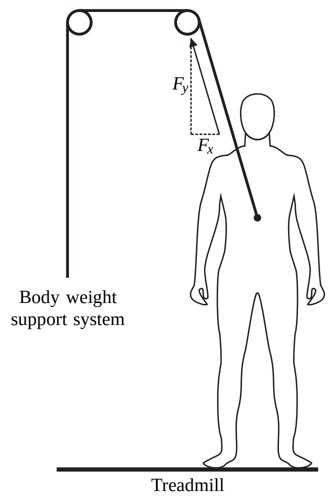

Fig. 1. Body weight support systems with a fixed pulley system induce a stabilising lateral force, F_x.

This stabilising force may pose problems during balance training. Indeed, it has been demonstrated that step width, a key index of lateral stability [9], [10], is reduced at higher levels of body weight support [11].

In this paper, a novel extension for body weight support systems is presented. The device, which is to be used for body weight support during treadmill walking, is designed to minimise lateral forces acting on the subject from the body weight support cable. A model is developed for the proposed system, along with a basic feedback control structure. Finally, the lateral forces developed by this novel system are compared with those induced in a static pulley system via simulation.

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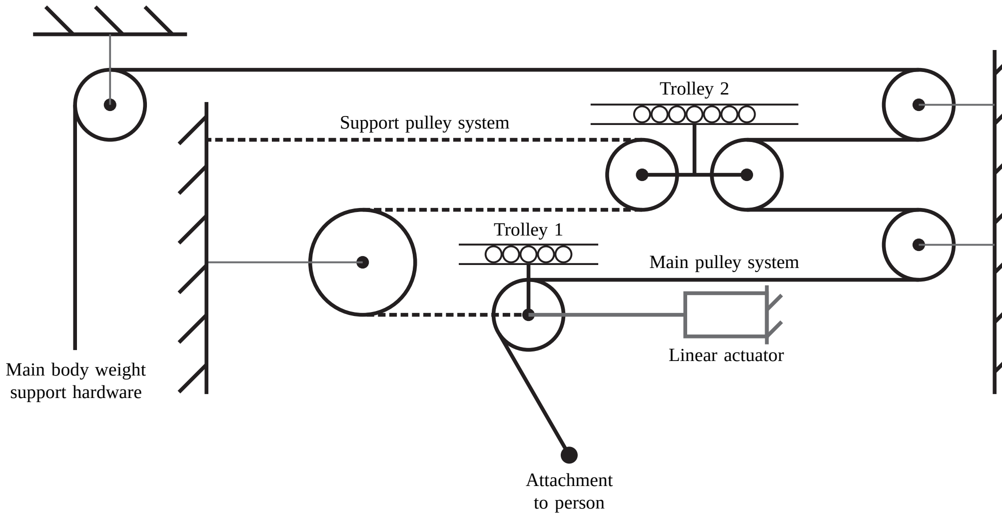


Fig. 2. Overview of novel body weight support system extension, consisting of main (solid) and support (dashed) pulley systems.

II. METHODS

A. Body Weight Support Concept

A new extension for existing body weight support systems is presented in this paper. It is comprised of two pulley systems, which are referred to as the main and support systems. These are connected to the main body weight support hardware, responsible for regulating the cable tension and therefore the supporting force provided to the subject. The proposed device is shown in Fig 2. The main pulley system allows the pulley connecting the body weight support and the human subject to move laterally in response to movement of the latter. This diminishes lateral forces acting on the subject from the cable; nevertheless, longitudinal forces may be induced due to forward-backward movement relative to the treadmill. The support pulley system ensures that the cable length of the main pulley system directly connected to the main body weight support mechanism is unchanged, irrespective of lateral movements of the pulleys. This constant cable length means that disturbances to the main body weight support system, which maintains the magnitude of the body weight support force, are minimised.

B. Model Development

A dynamic model is developed in order to investigate the ability of the system to reduce lateral forces. Let the force from the main body weight support system be F_1. Furthermore, there are two trolley position states, x_1 and x_2, which correspond to the positions of trolleys 1 and 2, respectively. A further important variable is the lateral position of the human subject, denoted as x_p. The vertical distance between the subject and the pulley is h. Fig 3 shows how these different variables are defined.

From Fig 3,

$$\sin\theta = \frac{x_p - x_1}{\sqrt{h^2 + (x_p - x_1)^2}}. \quad (1)$$

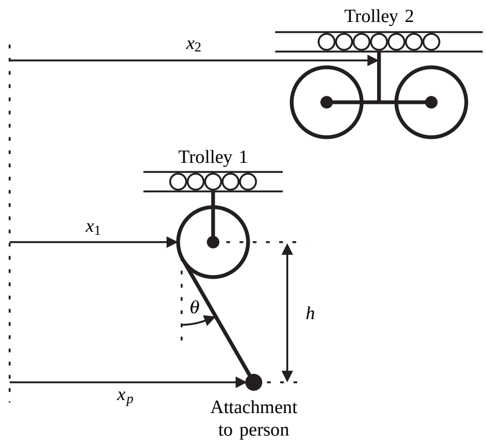


Fig. 3. Variables defining positions of trolleys and human attachment.

The friction in the pulleys is modelled by a simple efficiency term, η, which also includes friction from the bearings and from the bending of the cable. The pulley friction is illustrated in Fig 4. The force after the pulley, $F - \Delta F$, is given by

$$F - \Delta F = F\eta. \quad (2)$$

For simplicity, all the pulleys in the model are assumed to have the same efficiency, η. A value of 95% was set for the simulations.

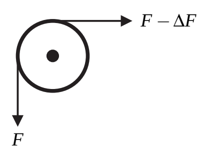
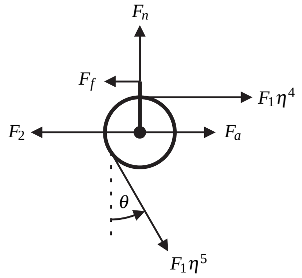
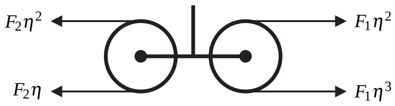


Fig. 4. Modelling pulley friction.

Fig 5 depicts free body diagrams for the two trolleys. m_1 refers to the mass of the trolley 1 plus the effective mass of



(a) Trolley 1



(b) Trolley 2

Fig. 5. Free body diagrams of trolleys 1 and 2.

the actuator, including the reflected mass from gearing; m_2 is the mass of trolley 2. The differential equations governing the motion of the two pulleys are

$$m_1\ddot{x}_1 = F_a + F_1(\eta^5 \sin\theta + \eta^4) - F_2 - F_f \tag{3}$$
$$m_2\ddot{x}_2 = F_1(\eta^3 + \eta^2) - F_2(\eta^2 + \eta). \tag{4}$$

Consider the rates of change in the positions of trolleys 1 and 2, and the length of the support pulley system cable. Through inspection of Fig 2,

$$\dot{l}_2 = \dot{x}_1 + 2\dot{x}_2 \tag{5}$$

and since the cable is of constant length, $\dot{l}_2 = 0$,

$$\dot{x}_2 = -\frac{1}{2}\dot{x}_1 \tag{6}$$

and

$$\ddot{x}_2 = -\frac{1}{2}\ddot{x}_1. \tag{7}$$

The two dynamic equations become

$$m_1\ddot{x}_1 = F_a + F_1(\eta^5 \sin\theta + \eta^4) - F_2 - F_f \tag{8}$$
$$-\frac{1}{2}m_2\ddot{x}_1 = F_1(\eta^3 + \eta^2) - \left(\eta^2 + \eta\right) F_2. \tag{9}$$

To simplify the expressions, let

$$\rho = 2\eta^2 + 2\eta \tag{10}$$
$$\gamma = \rho\eta^4 - 2\eta^3 - 2\eta^2. \tag{11}$$

On elimination of F_2, the governing differential equation is

$$(\rho m_1 + m_2)\ddot{x}_1 = \rho F_a - \rho F_f + F_1(\gamma + \rho\eta^5 \sin\theta). \tag{12}$$

The friction F_f acting on trolley 1 is modelled as Coulomb friction[1]. The Coulomb friction force F_c is

$$F_c = \mu F_n. \tag{13}$$

Neglecting the weight of the trolley, the normal force F_n is

$$F_n = F_1\eta^5 \cos\theta. \tag{14}$$

[1]The friction acting on trolley 2 is neglected due to the lower normal force.

and the friction force is then

$$F_f = F_c \mathrm{sign}(\dot{x}_1). \tag{15}$$

However, to avoid solution problems due to the discontinuous sign function, the continuous approximation below, using the constant, k_{tan}, is used.

$$F_f = F_c \tanh(k_{tan}\dot{x}_1) \tag{16}$$

In this dynamic system, the main inputs are the cable tension, F_1 and the actuator force, F_a. The system has states corresponding to the position and velocity of trolley 1 while the output is the cable angle, θ. For simplicity, the cable tension, F_1, which is controlled by the main body weight support unit, is assumed to be constant.

C. Control Design

A simple feedback controller is used to set the actuator forces in this paper. The controller is used to drive the cable angle to zero by setting appropriate values of the actuator force, F_a.

Assuming zero friction, i.e. $\mu = 0$ and $\eta = 1$, the equation governing x_1 is

$$(\rho m_1 + m_2)\ddot{x}_1 = \rho F_a \tag{17}$$

which can be written in state-space form as

$$\begin{bmatrix} \ddot{x}_1 \\ \dot{x}_1 \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} \dot{x}_1 \\ x_1 \end{bmatrix} + \begin{bmatrix} \frac{\rho}{\rho m_1 + m_2} \\ 0 \end{bmatrix} F_a. \tag{18}$$

Pole placement is used to give desired closed loop poles for this nominal system. Setting the closed-loop poles at $-100 \pm 10j$ and using the parameters of table I, the required control law is

$$F_a = -3110x_1 - 61.6\dot{x}_1. \tag{19}$$

The goal is to drive the difference $x_p - x_1$ to zero. Rather than measure x_p and x_1 individually, equation (1) can be used to approximate the difference. Assuming $h \gg (x_p - x_1)$ and small values for θ:

$$x_p - x_1 \approx h\theta \tag{20}$$

Therefore, the control law used is

$$F_a = 3110h\theta + 61.6h\dot{\theta}. \tag{21}$$

D. Simulation Example

A simple example is used to demonstrate the effectiveness of the system. The novel, actuated pulley system presented here is compared with a static pulley system under conditions representing the lateral movement of a human subject during normal walking.

Within each gait cycle, the lateral translation of the pelvis has an approximately sinusoidal form with an amplitude of around 0.02 m [12]. Assuming that the gait cycle period is 1 s (corresponding to a walking cadence of 120 steps per minute), the following form is used for x_p:

$$x_p = 0.02\sin(2\pi t) \tag{22}$$

Parameter	Value
h	0.5 m
m_1	0.2 kg
m_2	0.4 kg
F_1	500 N
η	0.95
μ	0.05
k_{tan}	100

TABLE I
PARAMETERS USED IN SIMULATION EXAMPLE.

The values assigned to the remaining parameters for the simulation are included in Table I.

Note that for a static pulley system, the angle developed in the cable is given by

$$\sin\theta = \frac{x_p}{\sqrt{h^2 + x_p^2}}. \tag{23}$$

III. RESULTS AND DISCUSSION

A comparison between the actuated concept and a fixed pulley system in terms of the cable angle is provided in Fig 6.

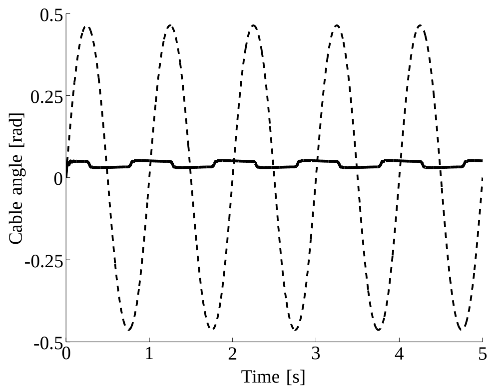


Fig. 6. Angles and lateral forces developed by actuated trolley system (solid line) and static pulley (dashed line).

The root mean square (rms) values of the cable angle and corresponding lateral force for the two different cases of static and actuated pulley systems are given in table II. The actuated system reduces both angles and lateral forces by a factor of eight.

Parameter	*rms*, actuated system	*rms*, static pulley
θ	0.0420 rad	0.339 rad
F_x	21.0 N	165 N

TABLE II
ROOT MEAN SQUARE (RMS) VALUES OF ANGLE AND LATERAL FORCE FOR ACTUATED AND STATIC SYSTEMS.

The actuated pulley system greatly reduces the lateral forces developed in the body weight support system cable, whilst also keeping changes in cable length due to lateral movement to a minimum. This will thus greatly reduce the stabilising effect of the system when the human subject moves laterally, and will hence ensure that the challenge of the lateral balance task is retained during body weight supported treadmill training in gait rehabilitation programs.

The modelling approach presented here has a number of simplifications. For example, the inertia of the pulley wheels has been neglected. However, since there is effectively only one degree of freedom, this inertia could be added to the mass of the trolleys. More sophisticated friction models could also be used, accounting for variations in friction due to changes in the cable angle, for example.

IV. CONCLUSIONS

An extension for body weight support systems frequently utilised in treadmill training for stroke and spinal cord rehabilitation has been designed which aims to reduce the magnitude of lateral forces acting on the human subject. Simulation results demonstrate that the system can reduce lateral forces by a factor of eight, suggesting a potential application of the concept in balance training as part of rehabilitation programs for stroke and spinal cord injured patients.

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