A Novel Treadmill with Adjustable Bilateral Surface Stiffness

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Abstract

Surface stiffness is an important factor in proper human locomotion mechanics. To analyze the effects of surface stiffness on gait and energy expenditure, this project presents the design and development of a novel treadmill with the ability to regulate stiffness of the surface. This can introduce new rehabilitation strategies for mobility impaired patients. For proof of concept, preliminary experiments are presented that show the effect of surface stiffness regulation on the metabolic cost and gait of a healthy subject.

Introduction

Human walking can be affected by both internal and external parameters [1]. Internal parameters include muscle and tendon rigidity and flexibility [3][4]. External parameters include surface slope, viscosity, damping, and stiffness of the ground [6]. Minimum effort has been done towards investigating ground stiffness effects on walking. It is still unclear how humans react to sudden/unexpected stiffness transitions to keep their ground while walking at different speeds. Studying these effects requires a system capable of quickly and accurately regulating ground stiffness bilaterally, on each leg. In addition, such a system may give valuable insight about muscle coordination of mobility impaired patients with asymmetric gaits.

Researchers have developed several platforms that allow for stiffness adjustment of the walking surface. However, these designs allow stiffness adjustment in a purely off-line manner. Furthermore, only a limited number of stiffness values can be realized with these systems [7][8].

Recent advances in variable stiffness actuators and variable stiffness systems present new methods of altering the stiffness of a surface. Inspired by the design implemented in [9] and the stiffness adjustment mechanism presented in Actuator with Adjustable Stiffness AwAS-II by [10], Skidmore et.al. several mechanisms have been developed. One drawback of such mechanisms is the rotational surface displacement as opposed to vertical. This rotation also changes the slope of the surface and imposes an unwanted constraint on the range of motion of the ankle.

We present the design and development of a treadmill with the ability to bilaterally adjust the surface stiffness in a purely vertical direction. The stiffness adjustment mechanism is based on that of Energy efficient Linear VarIable Stiffness (ELVIS) Joint [11], where the stiffness is altered by moving the position of the pivot point of a lever between the spring and force point. Therefore it can regulate the stiffness from completely passive to very rigid (structural stiffness) [12] regardless of the lever length or spring stiffness.

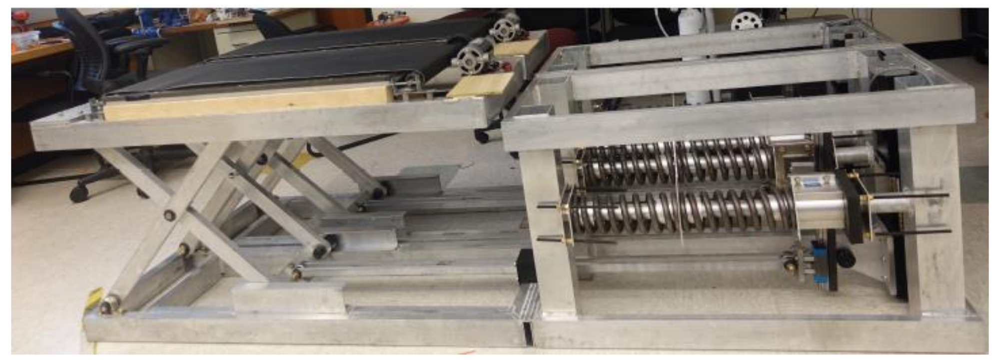

Figure 1. Physical realization of TwAS

Design

The TwAS is composed of two identical parts; the associated left and right parts. Each part has a treadmill whose speed can be controlled independently and is composed of two modules: the force transmission module and the stiffness adjustment module. The force transmission module transfers the vertical displacement of the treadmill to a horizontal movement of an input link as shown in figure 2 The scissor lift mechanism allows for purely vertical displacement. One end of the scissor arm is connected to the input link. As the treadmill surface moves downward, the input link moves out horizontally forward and transfers the vertical force to a horizontal force as shown in figure 3. The other end of the input link pushes against the lever of the stiffness adjustment module which rotates about its pivot point, and compresses two springs.

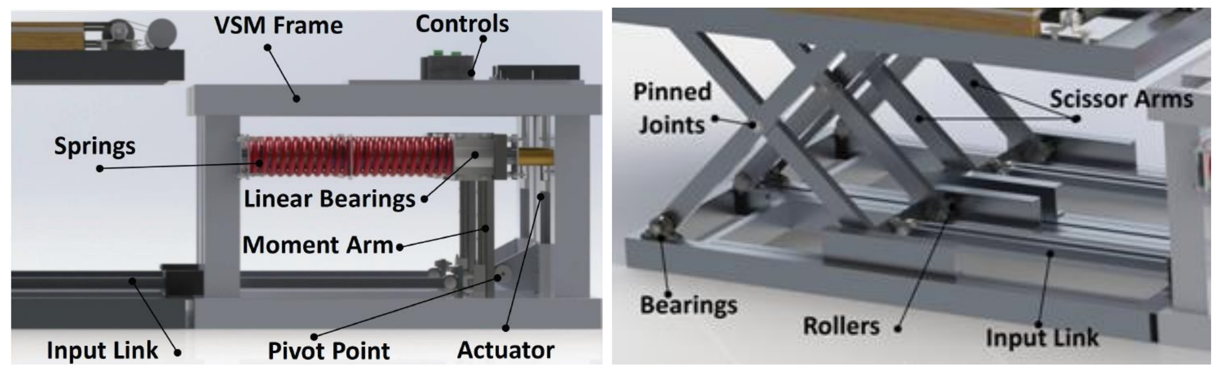

Figure 2 and 3 show force transmission and stiffness adjustment modules.

Stiffness Formulation

The following equation shows how the vertical displacement of the surface is related to the horizontal movement of the input link:

$$\Delta h = \frac{cos\alpha_0 - cos\alpha_1}{sin\alpha_0 - sin\alpha_1}\Delta x$$

The initial height of the surface h0 is set to be around 1m. With the initial α0=45degree, the length of the scissor arms of the scissor lift should be around 1.4m. With these conditions, we can achieve up to the considerable amount of 25cm vertical displacement of the surface and yet limit the change in the angle α to less than 10 degrees. We can assume that the vertical displacement of the treadmill surface is equal to the horizontal movement of the input link, i.e. Δh=Δx. Therefore the surface stiffness is found to be

$$K = K_s\left(\frac{l_2}{l_1}\right)^2$$

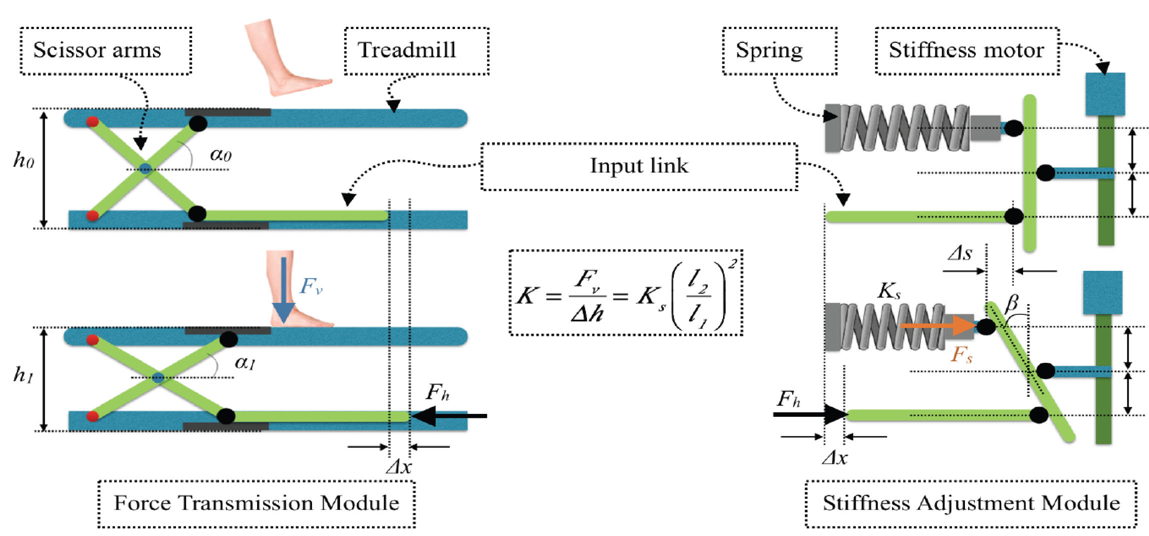

Figure 3. Schematic of the mechanical design of TwAS; the effective vertical stiffness can be adjusted from very soft to very rigid through moving the pivot point.

Preliminary Experimentation

Bilateral Stiffness Modulation

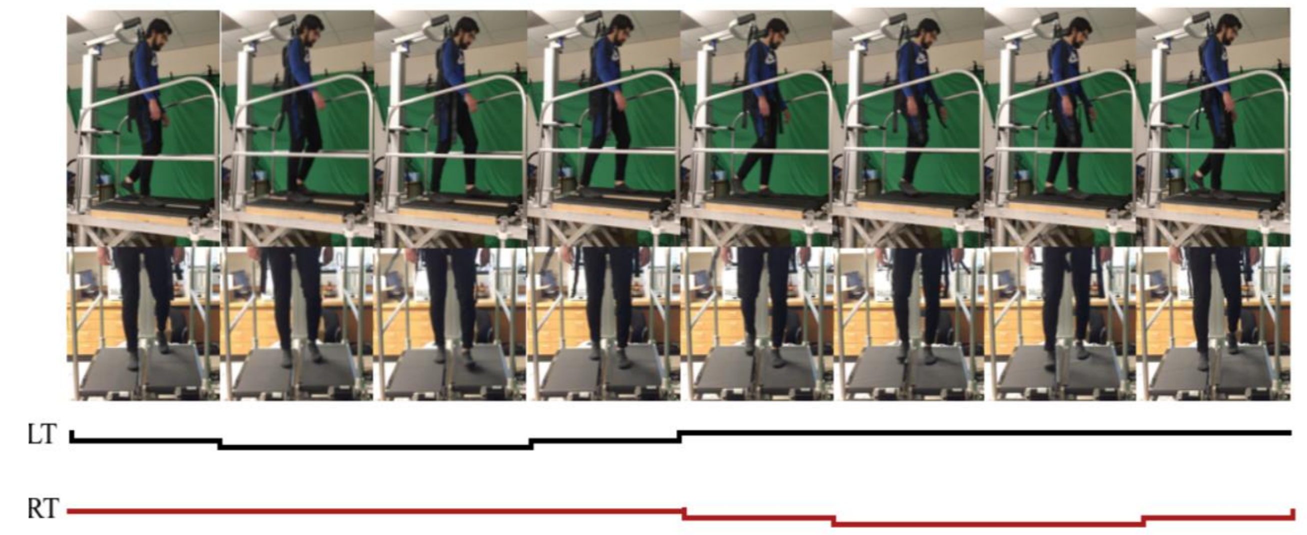

Figure 4 Bilateral surface stiffness adjustment for left and right legs, RT (Right Treadmill) and LT (Left Treadmill) lines show the surface displacement captured using Vicon motion capture system.

Vertical Displacement

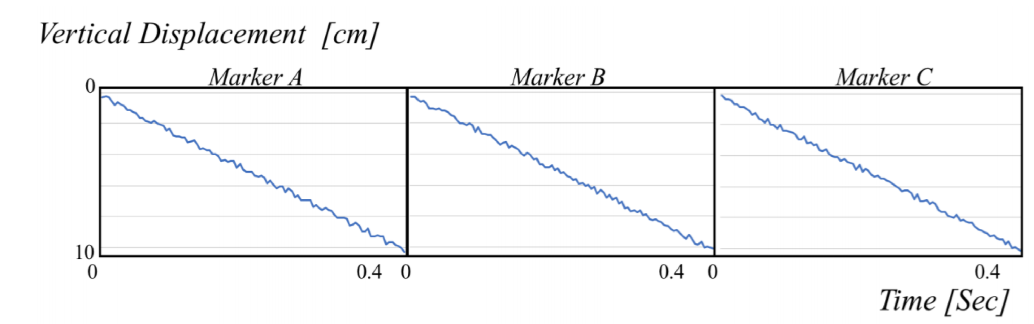

Figure 5. Vertical trajectories of three markers placed along the treadmill surface showing equal displacement..

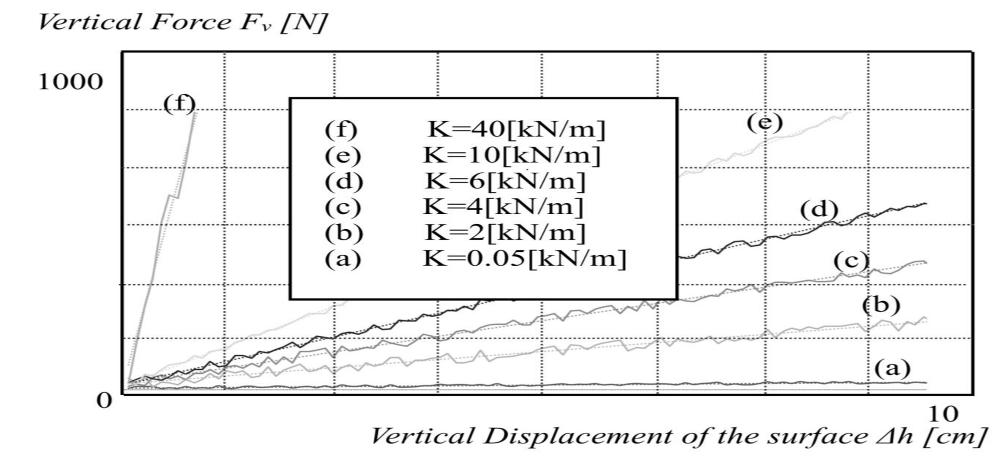

Figure 6 Changes in the surface displacement Δh as a result of canceling some weight F_v of the subject with the LiteGait system. The slope of each curve represents the stiffness of the surface. Dotted lines show expected forces.

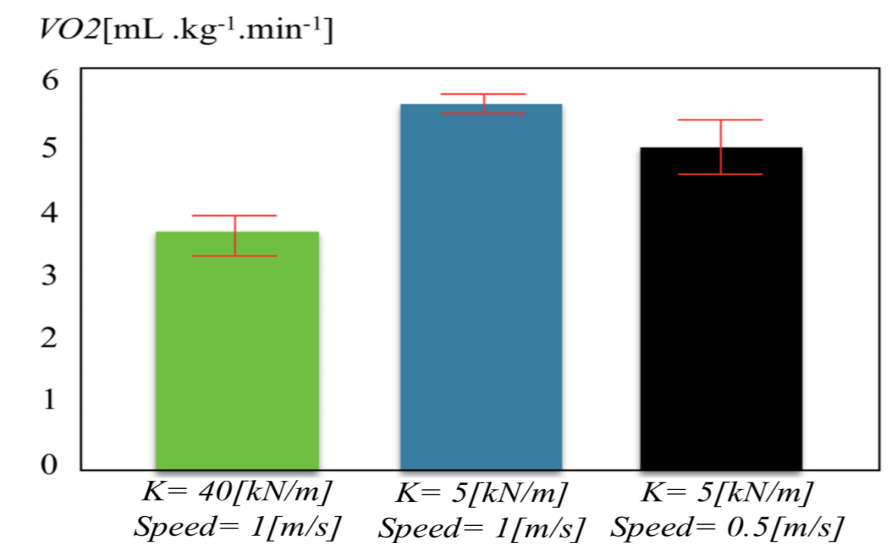

Figure 7 Oxygen consumption for different surface stiffness and walking speed.

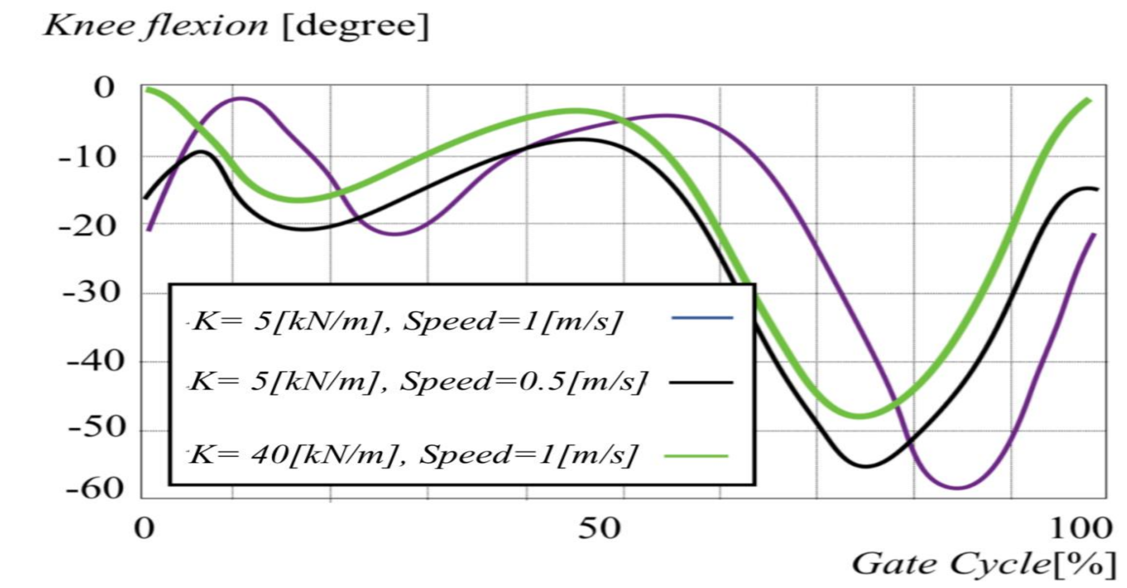

Figure 8. Knee flexion trajectories for different surface stiffness and walking speeds.

Conclusions

- Stiffness regulation through position control of the pivot point achieved.
- Purely vertical displacement of the surface accomplished in a bilateral manner
- Ground stiffness has a noticeable effect on the oxygen consumption of the human
- Ground stiffness had a noticeable effect on the walking gait of the human.

Future Work

- Measuring the affects on the recovery process of mobility impaired patients.
- Damping and adjustable slope system capability
- In depth analysis of the effects of different combinations of surface stiffness and speed on human gait

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