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 [5]. 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 offline 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 ActHapt 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 (ELVLS) Joint [11], where the stiffness is altered by moving the position of the pivot point at 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.

Design

The TwAIS 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 tandem 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 scissors lift mechanism allows for purely vertical displacement. One end of the scissors arm is connected to the input link. As the treadmill surface moves downward, the input link moves 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.

Preliminary Experimentation

Figure 4 shows the 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:

\[ \Delta h = \frac{K \Delta v_0}{(1 + \frac{K}{\alpha})} \]

The initial height of the surface h0 is set to be around 1m. With the initial a0=45degrees, the length of the scissors arm of the scissors 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 with more than 90 degrees can achieve up to 1cm, in the angle of less than 15 degrees. We can assume that the vertical displacement of the treadmill surface is equal to the horizontal movement of the input link, i.e., \( \Delta h = \Delta v \). Therefore the surface stiffness is found to be:

\[ K = \frac{\alpha \Delta v_0}{\Delta h} \]

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

Figure 6 shows how the stiffness changes 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 bilaterally 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 effects 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.

References

1. Oda, Hideyuki; Suehiro, Hideo; Nakamura, Yuki. "Knee joint control with variable stiffness as a result of changing some weight ratio, the representative of the gait system. The slope of each curve represents the stiffness of the surface. Dotted lines show expected forces.

Figure 7 shows oxygen consumption for different surface stiffness and walking speed.

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

Figure 9. Bilateral Stiffness Modulation

Figure 10. Vertical Displacement

Figure 11. Vertical Displacement of the surface: \( \Delta h \). (Vertical Displacement is the amount of displacement of the ground with respect to the subject's movement.)

Figure 12. Changes in the surface displacement \( \Delta h \) as a result of varying some weight ratio, the subject of the LiteGait system. The slope of each curve represents the stiffness of the surface. Dotted lines show expected forces.

Figure 13. Oxygen consumption for different surface stiffness and walking speed.

Figure 14. Knee flexion trajectories for different surface stiffness and walking speeds.