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Experimental Studies On The Human Gait Using A Tethered Pelvic Assist Device (T-PAD)

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Abstract— **This paper presents the prototype of a novel tethered pelvic assist device (T-PAD). This is a purely passive device, consisting of a set of elastic tethers with one end attached to a hip brace worn by a subject walking on a treadmill, and the other end attached to a fixed frame surrounding the subject. T-PAD offers the flexibility of varying the assistance required on the pelvis by changing the configuration of the tether attachment locations, number of tethers and tether elasticity.**

Experimental studies were conducted using a full and a partial pelvic constraint configuration of T-PAD, with varying tether elasticity. The studies were aimed at observing the effect of T-PAD on the human gait. Results show that T-PAD reduced the range-of-motion for the pelvic angles with increase of tether elasticity. However, it had mixed effects on the range-of-motion of the hip angles, but negligible effect on the knee and ankle joint angles. Overall, T-PAD shows potential as a low-cost pelvic support device with pelvic motion control capabilities, and can work in tandem with existing gait trainers.

Index Terms— **Passive Assistive Device, Pelvis, Human Gait.**

I. INTRODUCTION

An individual's quality of life is greatly affected when illnesses or accidents occur that impair the ability to walk. As such, gait training using a treadmill with body weight support (BWS) and manual assistance of the legs and pelvis has become quite common [1], [2]. However, this is very labor intensive and requires therapists to control the motion of the pelvis and the legs (see Fig. 1).

Fig. 1. Traditional gait training involving therapists (adapted from [3])

This subsequently led to the development of robotic gait training devices such as Lokomat, Mechanized Gait Trainer, ARTHuR, HAL, BLEEX, ALEX, GBO and STRING-MAN. However, most of these devices do not control the pelvic motion and merely keep the pelvis suspended by utilizing BWS structures. Studies have shown that the pelvic motion is essential in gait training as it assists in the forward propulsion of the body by transferring forces from the lower extremity to the trunk [4]. It also assists in the swing initiation and modulates the vertical displacement of the body's center of mass, which is aimed at reducing energy consumption while walking [5].

In view of this shortcoming, there has been recent interests in the rehabilitation community to develop pelvic assist devices. These include KineAssist [6], PAM (Pelvic Assist Manipulator) [7], Walk Trainer [8], and several parallel structured arm designs [9], [10]. While each of these devices have their merits, these are mainly active devices, which are costly due to the hardware setup and control instrumentations. Hence there is a need to develop low cost devices, which can provide support and retain control of the pelvic motion.

This paper aims to address this shortcoming and proposes a novel tethered pelvic assist device. The proposed design is a passive system consisting of spring components which are capable of storing mechanical energy. These springs allow modulation of the cartesian stiffness in 6D space, thereby enabling certain control of the pelvic motion. This is safer and more cost-effective compared to active devices. This device also provides full pelvic support, unlike BWS structures, which just provide unilateral support in the coronal plane. The theoretical framework has been reported in the author's recent work [11], and this paper aims to present the preliminary experimental studies conducted on the developed prototype.

The organization of this paper is as follows: Section II presents the conceptual design and salient features of the proposed tethered pelvic assist device. Section III presents the experimental setup of the device, including the equipment used, the frame assignments on the lower limbs to assist in the device evaluation, and the experimental protocol. Section IV presents the experimental results obtained and the observations made. This is followed by the discussion on the potential impact of this device in Section V, and conclusion in Section VI.

II. CONCEPTUAL DESIGN OF T-PAD

The tethered pelvic assist device (T-PAD) consists of a set of elastic tethers with one end attached to a hip brace

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worn by a subject walking on a treadmill, and the other end attached to a fixed frame surrounding the subject (see Fig. 2). The elastic tethers consist of springs connected in series with cables. The design is similar to a cable-suspended robot system [12] which consists of numerous cables affixed from the base to the moving platform. For T-PAD, the elastic tethers are the cables, while the frame is the base and the hip brace is the moving platform.

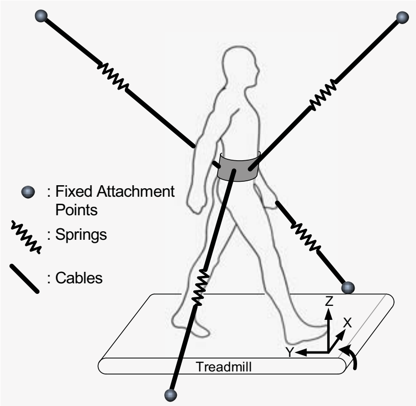


Fig. 2. Conceptual design of T-PAD

Depending on the requirements of the therapy and the amount of constraints to be placed on the pelvis, T-PAD offers the flexibility to cater to these requirements by simply changing the attachment point locations, the number of elastic tethers and the spring stiffness. Being a purely passive device, T-PAD is a low-cost and safer alternative, as compared to active devices. Unlike BWS structures which just provide unilateral support, T-PAD is capable of fully supporting the pelvis and modulating its stiffness in 6D space. This will aid the subject in the forward propulsion of the body, the swing initiation and the modulation of the vertical displacement of the body's center of mass, thereby reducing the energy consumption during walking.

III. Experimental Setup

This section presents the experimental setup of T-PAD, which includes the description of the equipment used, the frame assignments made on the human lower limb for evaluating T-PAD's performance, and the experimental protocol.

A. Equipment

As shown in Fig. 3, the experimental setup of T-PAD consists of a hip brace with elastic tethers, a treadmill, a frame structure surrounding the treadmill and a VICON motion capture system. The VICON motion capture system is utilized to track the motion of the subjects' lower limbs in order to evaluate the performance of T-PAD with different configurations and parameters, such as tether attachment points, number of tethers and spring stiffness. The VICON system tracks the reflective markers in 3D space using infrared cameras, and then uses its proprietary softwares Nexus® and Bodybuilder® to manage the data tracking and analysis, respectively. The camera (model: BONITA) has an accuracy of 1 mm within a 4 by 4 $meter$ workcell.

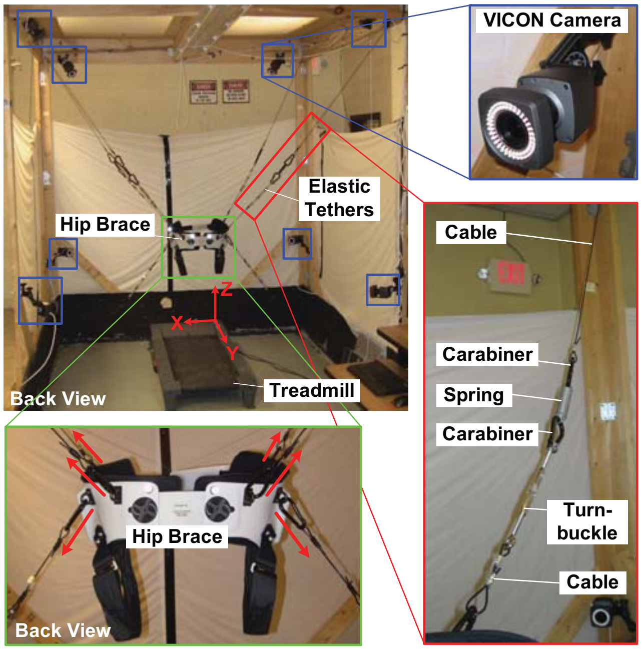


Fig. 3. Experimental setup of T-PAD

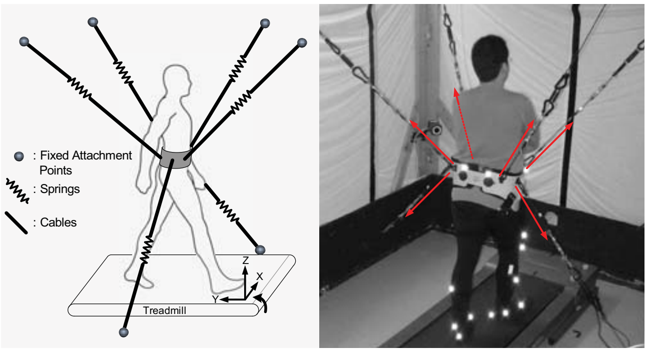


Fig. 4. Full pelvic constraint configuration using six tethers

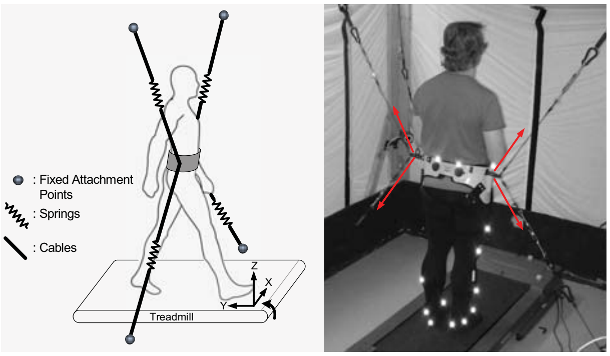


Fig. 5. Partial pelvic constraint configuration (in the coronal plane) using four tethers

In this experimental study, two configurations of T-PAD are investigated. The first configuration consists of six tethers (Fig. 4). This arrangement aims to provide full constraint to the pelvis. The second configuration consists of four tethers (Fig. 5). This arrangement aims to provide partial constraint to the pelvis in the coronal plane only. Also, three different spring stiffness are used, i.e., 13 lb/in (Low), 18 lb/in (Medium), and 24 lb/in (High). The changing of springs is made convenient with the use of carabiners. The amount of pretension in each tether is altered using turn-buckles (see Fig. 3). These turn-buckles also assist in the fine adjustment of the tether lengths to cater to different subject heights.

B. Frame Assignment on the Human Lower Limb

In order to track the subject's performance in terms of the joint range-of motion and global position of pelvis, the first step requires the attachment of reflective tracking markers on the subject to setup the local moving frames at the lower limb segments. Figure 6 presents the location of the reflective markers, and how these markers are utilized to form the local coordinate frames at each segment.

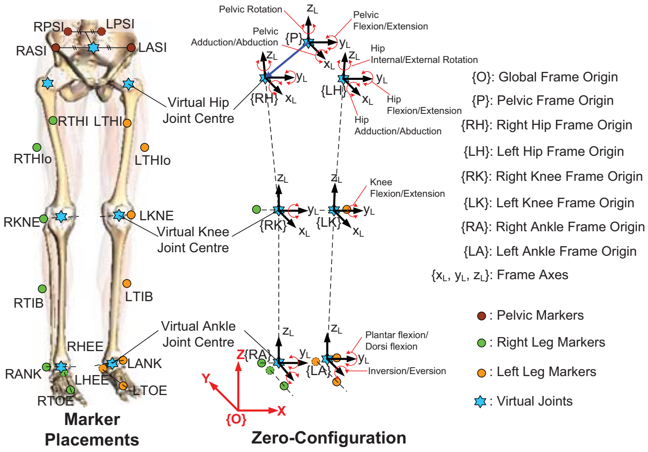


Fig. 6. Frame assignments on the lower limb based on marker locations

1) Global Coordinate Frame: The global coordinate frame is located on the treadmill. The origin, {O}, is located at the front right corner of the treadmill, with positive x-axis going from the right to left, and positive y-axis going from the front to the back (see Fig. 3). Z-axis is just the cross product between the x- and y- axes. *It is assumed in the following section that if two orthogonal axes are found, the third axis is simply the orthogonal product of these two axes.*

2) Pelvic Coordinate Frame: The pelvic frame origin, {P}, is chosen to be at the centre of RASI and LASI markers. The positive y-axis is from {P} to LASI, while the positive x-axis is from the mid-point of RPSI and LPSI, to {P}.

3) Hip Coordinate Frame: The hip frame origin is chosen at the virtual hip joint centre (HJC). This is based on the pelvis anatomical landmark (AL) method [13]. As the name suggests, AL is based on the anterior-superior iliac spine (ASIS) landmarks. Expressed as a percentage of the distance between the right and left ASISs, the HJC is located 30% distal, 40% medial and 22% posterior to the ASIS, with 95% certainty [13]. There is another more accurate approach known as the greater trochanter (GT) method [14]. As the name suggests, this method is based on the greater trochanter landmarks. For this method, HJC is located at one-quarter of the distance from the ipsolateral to the contralateral greater trochanter. The AL method was adopted as the hip brace prevents attaching any marker to the greater trochanter. The positive z-axis is along the line connecting from the knee joint centre to HJC. The y-axis is chosen to lie parallel to the knee joint flexion axis, and positive direction being from the right side to the left side. This assignment is adopted to both hips.

4) Knee Coordinate Frame: The knee frame origin is chosen at the virtual knee joint centre (KJC). KJC is determined using the VICON Bodybuilder software, which uses the knee and thigh markers to determine the approximate knee centre locations [15]. The positive z-axis is along the line connecting from the ankle joint centre to KJC. The y-axis is chosen to lie along its flexion axis, and positive direction being from the right side to the left side. This assignment is adopted to both knees.

5) Ankle Coordinate Frame: The ankle frame origin is chosen at the virtual ankle joint centre (AJC). AJC is determined using the VICON Bodybuilder software, which uses the ankle and tibia markers to determine the approximate ankle centre location [15]. The y-axis is chosen to lie along its flexion axis, and positive direction being from the right side to the left side. The positive x-axis is chosen to lie parallel to the line connecting from the heel to the toe markers. This assignment is adopted to both ankles.

C. Experimental Protocol

The experimental studies are conducted on five healthy male subjects within the age range of 20 to 30 years. The study was approved by the University of Delaware Internal Review Board. For each T-PAD configuration, the experimental protocol is designed as follows:

- Session 1: The subject is suited up with the reflective markers and the hip brace. He is then asked to walk on the treadmill at a walking speed of 2.5 mph for two minutes to get comfortable with the hip brace. (*Note:* This walking speed of 2.5 mph is used throughout the entire experiment to exclude the effect of walking speed.)
- Session 2: Data collection begins from hereon. The subject is asked to walk on the treadmill for two minutes, wearing only the hip brace.
- Session 3: The tethers are now attached to the brace with the low stiffness springs, and the subject is asked to walk on the treadmill for another two minutes.
- Session 4: The springs are replaced with those of medium stiffness, and the subject is asked to walk on the treadmill for another two minutes.
- Session 5: The springs are replaced with those of high stiffness, and the subject is asked to walk on the treadmill for the final two minutes. The trial and data collection ends after this.

Sessions 1-5 are then carried out on the second T-PAD configuration for the same subject. For both configurations, subjects are asked to fold their arms around their chest to avoid any interference with the elastic tethers. There is also no concern of having any learning effect since each session consists of just two minutes. This is insufficient to allow any learning.

IV. EXPERIMENTAL RESULTS AND OBSERVATIONS

The experimental study aims to observe the influence of the T-PAD configurations and the spring stiffness on the human gait parameters. The collected marker data are processed using VICON's Bodybuilder software which has in-built functions to determine the relative angles between the assigned coordinate frames at the various lower limb segments. This is based on the moving YXZ Euler angles representation. These data are then segmented based on the gait cycle, followed by averaging the data over a gait cycle. This is done for each subject undergoing Sessions 2 to 5 for the two T-PAD configurations.

For each configuration, statistical analysis using the paired t-test method is carried out to see the effects on the range-of-motion of the lower limb joints, as well as the global position of the pelvis, over the entire group of subjects. The data from session 2 (i.e. wearing just a brace) are compared with data from sessions 3 to 5 (i.e., with low, medium and high spring stiffness, respectively). The statistical analysis is carried out using the '$ttest$' function in MATLAB. The null hypothesis made in all test cases is that there is no difference in the mean value of population A (i.e., wearing only the brace), and population B (i.e., when wearing the brace attached with the elastic tethers). A '$p\ value$' of less than 5% indicates that there a significant change in the mean of the two populations and that the null hypothesis is rejected. Prior to carrying out the t-tests, the data are first verified of its normal distribution using the Lilliefor's test [16]. This is done by using the '$lillietest$' function in MATLAB.

Tables I and II present the paired t-test results for the two T-PAD configurations. A dash (-) indicates that the null hypothesis has been accepted and that the mean of the two population are similar. On the other hand, when the null hypothesis is rejected, this means that the mean of the two population are different. This is indicated by the percentage value of increase (or decrease) in the range-of-motion between the two population, as well as the '$p\ value$' obtained. The results presented are of those joint angles with significant changes. For the hip and knee data presented, only the left side is presented, as the right side obtained similar results. Figures 7 and 8 present the average range-of-motion plots of the significant parameters, while Fig. 9 presents the average global position plots of the RASI and LASI pelvic markers. Figures 10 and 11 are the average 'angle versus angle' plots among the different joints' angles.

The following observations were made from the experimental results:

- *Pelvic segment:* As seen from the t-test results in Tables I and II, it was clearly evident that T-PAD reduced the pelvic motion in the coronal plane, i.e., Global X-Z plane (see Fig. 9), as well as significantly reduced the range-of-motion of the pelvic anterior/posterior tilt and rotation (see Fig. 10). The effects were more significant for the full constraint configuration with a reduction of

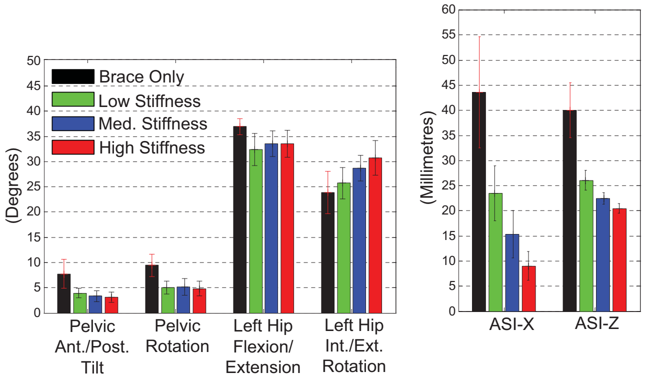


Fig. 7. Average range-of-motion plots of significant parameters during full pelvic constraint configuration

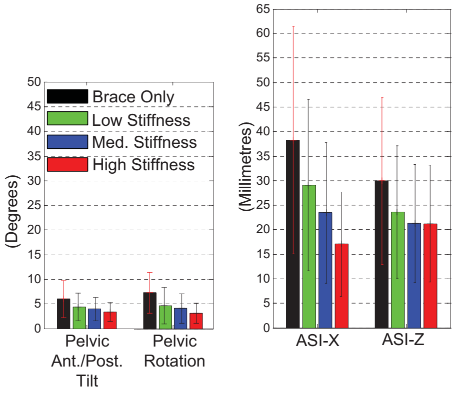
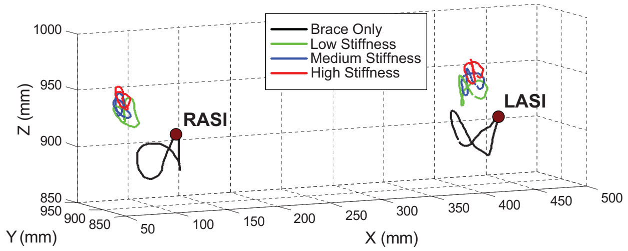
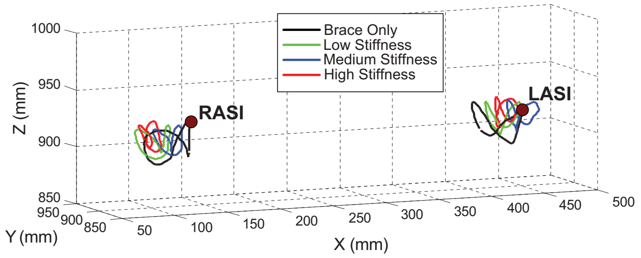


Fig. 8. Average range-of-motion plots of significant parameters during partial pelvic constraint configuration



(a) During full pelvic constraint configuration



(b) During partial pelvic constraint configuration

Fig. 9. Average global position plots of RASI and LASI markers

TABLE I

Paired T-Test Results for Full Pelvic Constraint Configuration

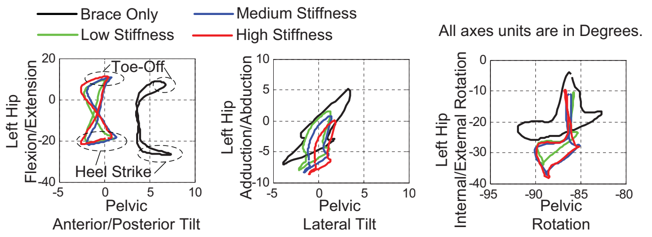
	ASI (mm)			Pelvis (Degrees)			Left Hip (Degrees)		
	X	Y	Z	Ant./Post. Tilt	Lateral Tilt	Rotation	Flexion	Abduction	Rotation
BO vs LS	-46.2% ($p = 0.0024$)	-	-34.8% ($p = 0.0029$)	-49.7% ($p = 0.0204$)	-	-46.9% ($p = 0.008$)	-12.2% ($p = 0.005$)	-	-
BO vs MS	-64.8% ($p = 0.0016$)	-	-43.9% ($p = 0.0012$)	-57.2% ($p = 0.019$)	-	-45.1% ($p = 0.028$)	-9.2% ($p = 0.017$)	-29.7% ($p = 0.049$)	20.6% ($p = 0.038$)
BO vs HS	-79.3% ($p = 0.0011$)	-	-48.9% ($p = 0.0013$)	-60.3% ($p = 0.019$)	-	-49.3% ($p = 0.026$)	-9.2% ($p = 0.0203$)	-	28.7% ($p = 0.009$)

Note: ASI is the mid-point between RASI and LASI
BO: Brace only; LS: Low Stiffness Springs; MS: Medium Stiffness Springs; HS: High Stiffness Springs

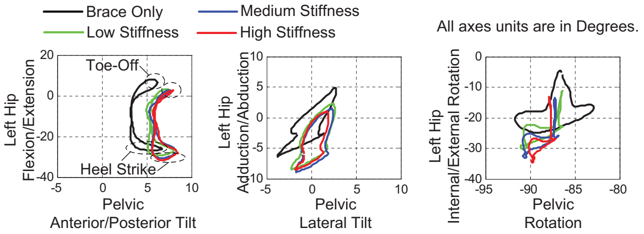
TABLE II

Paired T-Test Results for Partial Pelvic Constraint Configuration

	ASI (mm)			Pelvis (Degrees)		
	X	Y	Z	Ant./Post. Tilt	Lateral Tilt	Rotation
BO vs LS	-30.0% ($p = 0.012$)	-	-19.1% ($p = 0.006$)	-27.0% ($p = 0.001$)	-18.7% ($p = 0.046$)	-35.7% ($p = 0.016$)
BO vs MS	-42.7% ($p = 0.003$)	-	-27.0% ($p = 0.001$)	-36.5% ($p = 0.005$)	-18.0% ($p = 0.022$)	-42.1% ($p = 0.003$)
BO vs HS	-58.4% ($p = 0.0008$)	-	-27.7% ($p = 0.003$)	-43.2% ($p = 0.011$)	-	-57.2% ($p = 0.0001$)

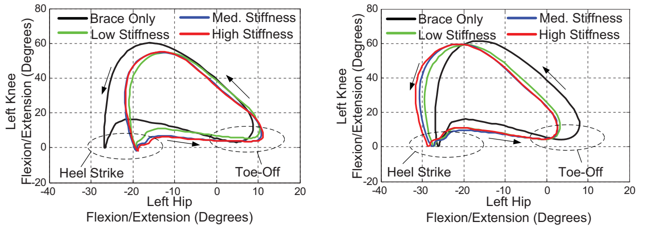


(a) During full pelvic constraint configuration



(b) During partial pelvic constraint configuration

Fig. 10. Average range-of-motion plots of Pelvic versus Left Hip



(a) During full pelvic constraint configuration (b) During partial pelvic constraint configuration

Fig. 11. Average flexion/extension plots of Left Hip versus Left Knee

more than 50% in their range-of-motion, but negligible effect on the lateral tilt and the Global Y position. This was probably due to the the subject walking consistently at the same Y-position and posture on the treadmill. Also, as seen in Fig. 10(a), the mean of the pelvic anterior/posterior tilt angle was shifted to approximately zero degrees when using the full constraint configuration. This indicated that the subjects had an upright walking stance. These observations were intuitively expected with the increased physical constraints placed on the pelvis. However, for the partial constraint configuration, the mean of the pelvic tilt angle shifted to a more positive value, indicating that the subject was walking with a constant anterior tilt. This may be attributed to the configuration of the four tethers which allowed freedom of motion in the sagittal plane.

- *Hip segment:* For the full constraint configuration, T-PAD reduced the flexion angles of the hip, and increased the hip rotation. This reduction in the hip flexion angles was not significant for the partial constraint configuration. These results were consistent with the visual observation made on the subjects when wearing T-PAD in the full constraint configuration. As the spring stiffness increased, subjects began to walk similar to a fashion model walking on the catwalk, indicating a larger hip rotation.
- From Fig. 11, although unable to be supported by the t-tests, it can be seen that for the full constraint configuration, heel-strike occurred at a larger hip extension angle with the same toe-off. On the other hand, for the partial constraint configuration, toe-off occurred at a smaller hip flexion angle with the same heel-strike. Both configurations led to a shorter stance phase as compared

to the 'brace only' configuration.

- As a general observation, the effect of spring stiffness mainly effected the pelvic and hip range-of-motion. There were no significant effects on the knee and ankle joints.

V. DISCUSSION ON THE POTENTIAL IMPACT

From the results and observations in Section IV, increasing the stiffness of the springs led to a reduction in both the translational motion of the pelvis, and the range-of motion for the pelvic angles. This reduction was more significant when using the fully constrained configuration. There was mixed effect on the range-of-motion of the hip angles but there were no significant effect on the knee and ankle joints. This indicates that T-PAD has the capability of influencing the pelvic and hip range-of-motion without significantly affecting the knee and ankle joints. This opens the possibility of using T-PAD in tandem with other robotic gait trainers to provide pelvic motion control, without interfering with the therapy program of these gait trainers.

T-PAD positions itself as a low-cost full pelvic support device, with the capability to modulate the stiffness in 6D and allowing certain control of the pelvic motion. This is unlike the BWS structures which provide only a unilateral support in the coronal plane, and the costlier active pelvic assistive devices. Future work will include verification of the developed theoretical model with the actual performance of T-PAD, and investigation on the effects of an asymmetric T-PAD configuration on the human gait.

VI. CONCLUSION

This paper presented the prototype of a novel tethered pelvic assist device (T-PAD). This is a purely passive device, consisting of a set of elastic tethers, with one end attached to a hip brace worn by a patient walking on a treadmill, and the other end attache-d to a fixed frame surrounding the patient. Experimental studies were carried out on two different configuration of T-PAD under different spring stiffness. From the results obtained, T-PAD reduced the overall range-of-motion for the pelvis with increasing spring stiffness for both configurations. While there were mixed effects on the range-of-motion for the hip, it did not have any significant effect on the knee and ankle joints. Further investigation is still necessary to assess its full capabilities. Overall, T-PAD shows potential as a low-cost pelvic support device with pelvic motion control capabilities, and can work in tandem with existing gait trainers.

VII. ACKNOWLEDGMENT

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