Asymmetric Adaptation in Human Walking using the Tethered Pelvic Assist Device (TPAD)

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***Abstract*—Human nervous system is capable of modifying motor commands in response to alterations in walking conditions. Previous research has shown that external perturbations that induce gait asymmetry can lead to adaptation in gait parameters. Such strategies have also been shown to temporarily restore gait symmetry in subjects with post stroke hemiparesis. This work aims to develop an experimental paradigm to induce gait asymmetry in human subjects by applying external asymmetric forces on the pelvis through the Tethered Pelvic Assist Device (TPAD). These external forces on the pelvis have the potential to influence the swing and the stance phases of both legs. Eight healthy subjects participated in the experiment where a higher resistive force was applied on the pelvis during the swing phase of the left leg as compared to the right leg. We hypothesized that such asymmetrically applied forces on the pelvis will lead to asymmetric adaptation in the human walking.**

I. Introduction

Asymmetric walking patterns are usually observed in post stroke survivors, children with cerebral palsy, persons with lower extremity amputations and persons living with traumatic brain injury [1]–[5]. These asymmetric gait patterns are often associated with higher energy costs [1]–[3] and are correlated with increase in risks for falls and serious injuries [6]. Therefore, strategies to restore symmetry of walking are often included in rehabilitation paradigms [1], [7].

Several studies have been reported in the literature toward achieving this objective. The paradigms used in these studies require application of external perturbations to develop errors in movement kinematics. Human nervous system minimizes these errors by recalibrating motor commands and such recalibrations of established motor behaviors have been referred to as motor adaptation in the literature [8], [9]. This recalibration of motor commands results in aftereffects upon removal of the perturbations. Subjects have shown adaptation in gait parameters while walking on a horizontally rotating disc [10] and on a split-belt treadmill [11], [12]. Further, walking adaptation has also been reported when external forces were applied using leg exoskeletons [13]–[17], adding weights on the leg during walking [7], [18], [19] and using cables to resist leg motion [20]. Results from these walking adaptation studies reflect human locomotion flexibility in accommodating applied perturbations by adapting both inter-limb as well as intra-limb gait parameters. Interestingly, in these studies, the applied perturbations always led to an asymmetric change in the gait pattern, irrespective of the ways they were induced. As an example, a split-belt treadmill with two belts set at different speeds move the two legs of a subject at different speeds inducing asymmetry. Similarly, application of external forces or weights on one leg of a subject alters the natural dynamics of that leg. As a result, gait asymmetry would be induced. Results from these studies are significant because they suggest that creating asymmetry in gait patterns could lead to motor adaptation. Importantly, such adaptations have been observed in both healthy as well as in subjects with impairments. Subjects with post stroke hemiparesis were reported to temporarily restore gait symmetry after walking on a split-belt treadmill set with different belt speeds [11]. Similarly, locomotor adaptation to a unilateral swing phase perturbation in [7] showed that the acquisition of symmetrical gait patterns remain unaffected by mild to moderate hemiparesis. Therefore, experimental paradigms that lead to motor adaptations by inducing gait asymmetry may have the potential to restore symmetry in walking patterns.

Recently, authors have developed a novel Tethered Pelvic Assist Device (TPAD) that consists solely of springs and cables. TPAD can apply force and moment on the pelvis, which changes the walking dynamics while retaining subject's mass and inertia properties. Pelvic motion plays an important role in walking [21], therefore adaptation strategies to applied forces at pelvis will influence the stance and swing phase gait parameters of both legs. In [22], healthy subjects modified their hip flexion angles immediately with the application of symmetrical downward forces using TPAD on the pelvis. Subjects adapted to these downward forces by altering their vertical pelvic acceleration values, such that higher foot pressure values were observed even after the applied forces were removed. In the current study, TPAD was used to apply a load on the pelvis asymmetrically in the transverse plane. A higher resistance was applied to the pelvic motion during the swing phase of the left leg within the gait cycle. The objective of this work was to demonstrate the feasibility of applying forces on the pelvis to generate gait asymmetry. It was hypothesized that healthy subjects with these applied forces on the pelvis would show an asymmetric walking pattern and the training with these forces for fifteen minutes would induce adaptive changes in the gait parameters.

The remainder of this paper is organized as follows: Section II presents the details of the experimental setup and training protocol. Section III explains the obtained experimental results and observations. Section IV presents the discussion

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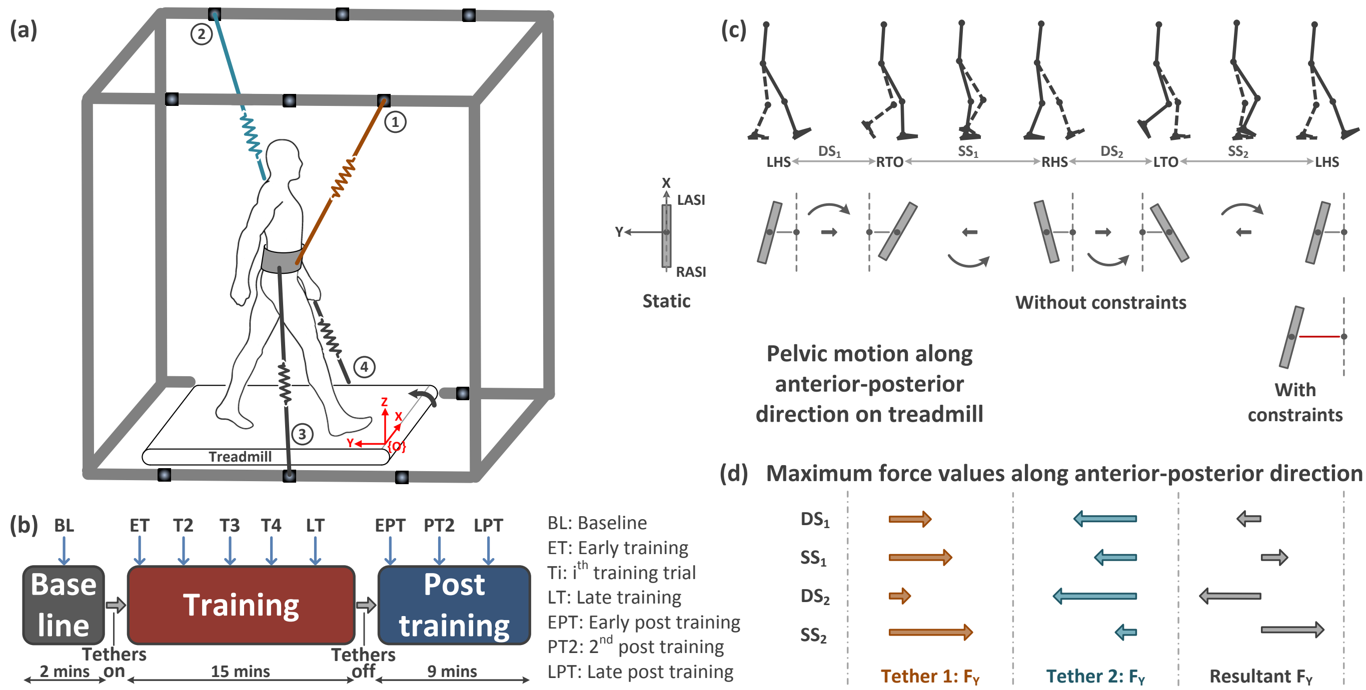

Fig. 1. (a) Experimental setup of TPAD in the asymmetric configuration. Motion capture system was used to track the reflective markers, load cells were used to measure the amount of tension in each tether and pressure pads were used to record the foot pressure. (b) Experimental protocol included baseline, training and post training periods. Data were collected at given time instances as shown by arrows for each period. (c) Pelvic anterior-posterior translation and rotation in the transverse plane for subjects walking on a treadmill without any constraints. Static position refers to the absolute pelvic position when the subject stands still and straight, where LASI and RASI are the left and right anterior superior iliac spine locations. The positioning of tethers 1 and 2 on the hip brace poses higher resistance to the pelvic motion during SS_2 phase that results in increased backward pelvic translation at LHS. (d) A qualitative representation of maximum force values in tethers 1 and 2 along the anterior-posterior direction (Y axis) during different phases of a gait cycle. F_Y represents the resultant of tethers 1 and 2 force values.

and the conclusion.

II. Method

A. Experimental setup

TPAD is a passive system and its design details were described previously in [23]. In the current experiment, Fig. 1(a), four tethers were used. One end of each tether was attached to a hip brace while the other to an inertially fixed frame such that the pelvis was asymmetrically loaded in the transverse plane. Tether 1 was attached to front right side of the pelvis, tether 2 was attached to back left side while tethers 3 and 4 were in the coronal plane. Each tether was equipped with a load cell in series with a spring to monitor the tension. Spring stiffness was 4.04 N/mm and an initial tension of 90-100 N was set in each tether when the subject stood still and straight. With these values, subjects were able to walk safely on a treadmill at 2.5 mph (1.12 m/s) during fifteen minutes of training without causing tethers to slack. Experimental setup also included a motion capture system to track the lower limb motion, and three force sensing resistor (FSR) pads on each shoe insole to measure the normal foot pressure. These systems were the same as in our previous work and the details can be found in [22].

Eight healthy male subjects, all right handed, participated in the study and provided their written consent. The age range was 24-31 years (mean age: 27 yrs and SD: 2.33 yrs) and mean weight 76.12 kg (SD: 12.38 kg). The training protocol was approved by the University of Delaware Internal Review Board and involved baseline, training and post training sessions, as shown in Fig. 1(b). Data was collected at pre-decided instances as indicated by arrows BL, ET, etc. in the figure. Similar protocol was used in [22].

Data collected from the motion capture system, the tension sensor system and the foot pressure pads were divided into gait cycles following the gait events detection using the positions of toe and heel markers with respect to the sacrum marker as illustrated in [24]. Each gait cycle was defined from left heel strike to subsequent left heel strike and the time histories of all gait parameters were normalized in time to 100% of the gait cycle. Repeated measure ANOVA was performed to determine the statistical significance (defined as $p < 0.05$). Tukey's post-hoc honestly significant difference test was performed when a statistical significance was identified. Further, values plotted in the following sections are the means $\pm$ standard errors. An asterisk, '$*$', mark indicates significant difference between the means of the two sessions.

B. Pelvic motion and expected force

Walking on a treadmill involves rhythmic forward and backward pelvic anterior-posterior translation as well as clockwise (CW) and counter-clockwise (CCW) rotation in the transverse plane. Subject data from the baseline period were used to illustrate the typical pelvic anterior-posterior translation and rotation in the transverse plane as shown in Fig. 1(c). At heel-strike (HS) pelvis was observed to be behind the static position, while at toe-off (TO) it was ahead. Static position refers to the absolute pelvic position when a subject stood still and straight on a treadmill, also shown in Fig. 1(c). Hence, during double support (DS) phases, the pelvis translated forward toward the front of the treadmill and during single support (SS) phases it translated backward toward the back of the treadmill. The backward shift in the absolute pelvic position was due to the treadmill belt motion. Furthermore, treadmill walking without constraints involved pelvic rotation in the CW direction during DS_1 and SS_2; and in the CCW direction during SS_1 and DS_2.

In the presence of tethers while walking on a treadmill, subjects have to overcome the tethers pull over the complete gait cycle. Particularly, the placement of tethers 1 and 2 on subjects' hip brace poses a higher resistance to the anterior-posterior pelvic motion during left leg swing phase (SS_2). Such placement of tethers also applies a CCW moment on the pelvis, which would develop an offset in transverse plane pelvic rotation. Importantly, since the treadmill belt motion brings the pelvis backward during SS phases, the chosen tether positioning would result in larger backward pelvic translation during SS_2. This has been represented by larger pelvic offset from the static position at LHS when compared to without constraints condition in Fig. 1(c). To continue walking on treadmill with this increased backward translation in one phase of the gait cycle, subjects would have to make an effort to bring the pelvis forward in the other phases.

Pelvic forward and backward motion during different phases of the gait cycle would either pull or relax a tether. An initial tension was set in each tether at the start of training period to eliminate possible slack during walking. Tether 1 would be extended beyond the initial tension length during SS phases while the same would be true for tether 2 during DS phases. Expected maximum tension values along the anterior-posterior direction in tethers 1 and 2, incorporating the large pelvic translation during SS_2, have been illustrated qualitatively in Fig. 1(d). Tether 1 tension values would be higher during SS_2 because of the large backward pelvic displacement, which would imply a higher tension in tether 1 at LHS than at RHS. Therefore, tether 1 tension values would be higher during DS_1 when compared to DS_2. Further, the large backward pelvic displacement during SS_2 would also result in lower tension values in tether 2, such that tether 2 tension value at LHS would be less than its tension value at RHS. Therefore, tether 2 would have higher tension values during DS_2 when compared to DS_1. The maximum value of resultant force along anterior-posterior direction on pelvis, F_Y, can then be predicted qualitatively during a gait cycle, as shown in Fig. 1(d). A subject during training would experience higher F_Y values during DS_2 and SS_2 phases, which would mean larger backward pull during DS_2 and larger forward pull during SS_2. We were interested in determining subjects' response to this asymmetrically distributed force.

III. Results

Subjects' pelvic motion was described by the midpoint of their left and right anterior superior iliac spine markers (LASI and RASI). Figure 2(a) shows the pelvic anterior-posterior translation for a representative subject. To remove the offset caused by subject's movement on the treadmill

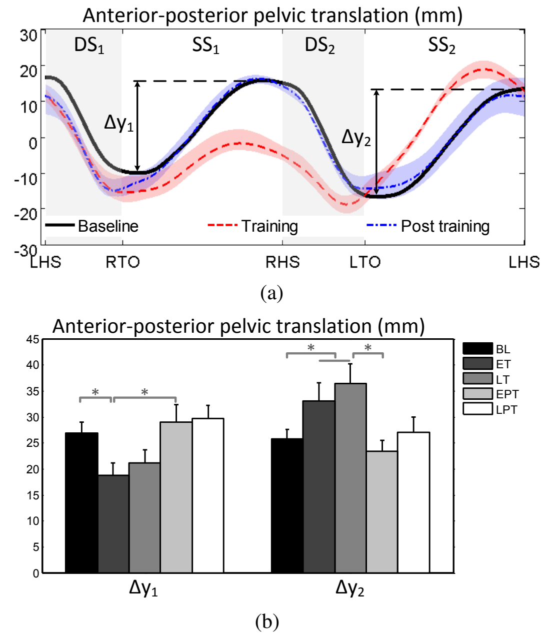

Fig. 2. (a) Pelvic translation along anterior-posterior direction for a representative subject with respect to its midpoint during a gait cycle. Single and double support phases have been illustrated using heel strike and toe off events of BL period. (b) Pelvic translation during SS_2 phase, $\triangle y_2$, increased during training while pelvic translation during SS_1 phase, $\triangle y_1$, decreased during training for the group. '$*$' denotes significant difference ($p < 0.05$).

between sessions, the pelvic translation data for each gait cycle were represented with respect to its midpoint value for that gait cycle. It was observed that the pelvis translates forward during DS and backward during SS, noting that the global Y axis points toward the treadmill rear side. During the training period, the pelvic backward translation was comparatively larger during SS_2 than during SS_1. To quantify this difference over the group, net pelvic translation during each SS phase was calculated and represented as $\triangle y_1$ and $\triangle y_2$. It was observed that $\triangle y_2$ increased significantly from BL to ET and LT, while $\triangle y_1$ decreased significantly from BL to ET ($p < 0.05$) over the group, as seen in Fig. 2(b). During post training period, the net pelvic translation values during SS phases were not statistically different from the baseline values.

Resultant force component in the anterior-posterior direction, F_Y, for a representative subject, resolved at the midpoint of LASI and RASI markers position, is plotted in Fig. 3(a). A positive value of F_Y indicates that there was a net backward force on the pelvis, i.e., the pelvis was being pulled backward. F_Y values for this subject were observed to increase during the early part of double support (DS) phases to a maximum and decrease during the early part of single support (SS) phases to reach a minimum. It can further be observed that the magnitude of F_Y minimum value for the early training (ET) period was higher during SS_2 than during SS_1 phase. Further, the difference between the F_Y minimum values during two SS phases decreases with the progression of training period. The difference between F_Y minimum values during SS phases and the difference between F_Y maximum values during DS phases has been plotted in Fig. 3(b), here two subjects were observed to be outliers and were not included in the statistical analysis. It was observed that the difference between minimum values

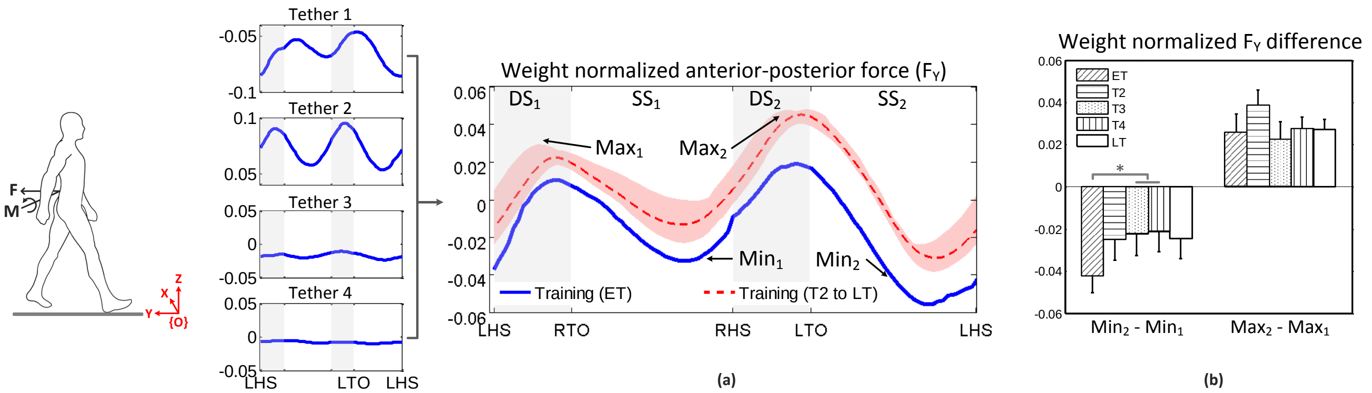

Fig. 3. (a) Weight normalized resultant force along anterior-posterior direction on the pelvis of a representative subject. Single and double support phases have been illustrated using heel strike and toe off events of ET period. (b) The magnitude of difference between two F_Y minimum values decreased with training for six out of eight subjects. '$*$' denotes significant difference ($p < 0.05$).

decreased significantly from ET to T3 and T4 ($p < 0.05$), while the changes in the difference between F_Y maximum values were not statistically significant over the training period.

Inter-limb angle was defined as the angle between two lines joining the sacrum marker to the two knee markers in the sagittal plane, as shown in Fig. 4(a). The absolute magnitude of inter-limb angle for a representative subject is plotted in Fig. 4(a) and it was observed to decrease during the training period at LHS. The absolute magnitudes of inter-limb angle at left and right heel strikes for the group have been plotted in Fig. 4(b). Significant reduction was observed in the angle magnitudes at LHS from BL to ET ($p < 0.05$), while the changes in angle magnitude were not statistically significant at RHS. The sagittal plane hip, knee and ankle joint angles for each leg did not shown any statistical significant change over the experiment. Figure 4(c) presents the duration of single support phases as a percentage of the gait cycle over the group. The duration of SS_2 phase increased significantly from BL to ET and LT ($p < 0.05$), though the difference between baseline and post training values was not statistically significant. Further, the changes in the duration of SS_1 were not significant over the experiment.

IV. Discussion and Conclusion

Experimental paradigms that are used to study human walking adaptations in the literature can be classified into two broad categories, as described in [19]. One where perturbations are applied bilaterally by modifying the walking surface and second where perturbations are applied only to a single leg. Irrespective of the ways these perturbations are applied, they always result in asymmetric walking pattern. Studies using a horizontal rotating disc [10] and split-belt treadmill [11], [12] fall under the first category. Walking on either of these surfaces would immediately lead to asymmetric gait. Similarly, walking adaptation studies using leg exoskeletons [13]–[17], adding weights on a leg [7], [18], [19] and attaching cables to resist leg motion [20] fall under the second category. In these studies, applied perturbations manipulate single limb dynamics that induce gait asymmetry.

The use of TPAD to study human walking adaptations actually results in both symmetric as well as asymmetric gait patterns, depending on the nature of the applied constraints. In

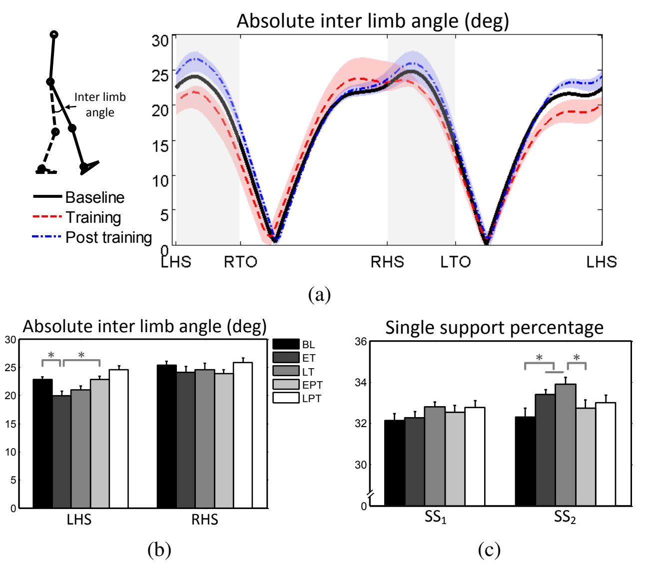

Fig. 4. (a) Absolute values of inter-limb angle, defined as the angle between lines joining sacrum marker to two knee markers in the sagittal plane, are plotted for a representative subject. Single and double support phases have been illustrated using heel strike and toe off events of BL period. (b) During training period, all subjects showed a reduction in the inter-limb angle at LHS. (c) The duration of SS_2 phase as a percentage of gait cycle increased during training session for the group. '$*$' denotes significant difference ($p < 0.05$).

[22], healthy subjects showed adaptations in gait parameters while retaining gait symmetry, when subjected to symmetrical downward forces on the pelvis using TPAD. In the current study, the application of asymmetric forces on the pelvis using TPAD resulted in an asymmetric gait pattern. The chosen tether placement required higher effort from the subjects during left leg swing as compared to right leg swing, which resulted in longer left leg swing phases, SS_2. This led to asymmetric pelvic displacement in the anterior-posterior direction during single support phases of a gait cycle. The difference between inter-limb angle magnitudes between left and right heel strikes also represented the asymmetric nature of the applied constraints.

In the previous study with TPAD [22], it was shown that the healthy subjects adapted to the vertical component of the resultant force on pelvis. In the current study, healthy subjects were subjected to an asymmetric force distribution at the start of the training period. Subjects took the early phase of the training period to get used to the applied constraints and were able to distribute the anterior-posterior force component more symmetrically over the gait cycle as training progressed. This was demonstrated by the reduced difference between F_Y minima magnitudes during the two swing phases over the training period. Therefore, healthy subjects adapted to the anterior-posterior component of the asymmetrically applied force on the pelvis. Subjects with hemiparetic gait or lower limb amputation, children with cerebral palsy and persons with traumatic brain injury are population groups who demonstrate asymmetric gait [1], [6]. Symmetric gait has the inherent advantage of stability in addition to being efficient in terms of energy consumption [1]–[3], [6]. In future, studies will be conducted with these population groups using TPAD to address subject specific gait needs by applying force and moment on the pelvis both in magnitude and direction.

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