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ORIGINAL ARTICLE

Restriction of pelvic lateral and rotational motions alters lower limb kinematics and muscle activation pattern during over-ground walking

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Abstract Restriction of pelvic lateral and rotational motions caused by robotic gait assistive devices can hinder satisfactory functional outcomes as it alters normal gait patterns. However, the effect of pelvic motion restriction caused by assistive devices on human locomotion is still unclear; thus, we empirically evaluated the influences of pelvic lateral and rotational motions on gait during over-ground walking by inhibiting the respective pelvic motions. The pelvic motions were restricted through a newly developed over-ground walking device. Variations in gait descriptive parameters as well as joint kinematics and muscle activation patterns were measured to indicate gait difference caused by pelvic restrictions. The results showed that pelvic lateral and rotational restriction significantly reduced the stride and step length as well as gait velocity and increased ratio of stance phase. It was also observed that the restriction caused a significant reduction in the range of motion of the ankle, knee, and hip joints. In addition, significantly higher muscle activations and prolonged patterns were observed in the tibialis anterior, gastrocnemius, and biceps femoris muscles, as compared to the normal patterns when the pelvis was restricted. We concluded that the pelvic restriction significantly altered normal gait dynamics, thus inhibiting the efficacy of gait rehabilitation.

Keywords Pelvic lateral and rotational movements · Pelvic motion restriction · Gait training · Over-ground walking · Robotic gait rehabilitation

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1 Introduction

Pelvis plays a central role in human locomotion. Six gait determinants (GDs), comprised of pelvic rotation (RT), obliquity, knee flexion, foot and knee mechanism, and lateral displacement (LD) of the pelvis, have been defined as the primary functions of gait which minimize vertical and LD of the center of mass (CoM) [10, 22]. The pelvic motions, which account for three of the six GDs, control the whole body balance, transmit force between lower and upper limbs, and increase energy efficiency of gait [7, 14, 15]. Pelvic LD and RT, defined as side-to-side movement of the pelvis and rotation of the pelvis about a vertical axis, respectively [1], are especially important for manipulating the vertical displacement of CoM, step and stride length, and horizontal balance during normal gait [4, 5, 9, 15].

Recently, the importance of facilitating pelvic LD and RT motions has been emphasized in the area of gait rehabilitation, in order to give a natural and esthetic gait pattern after gait training for neurologically challenged subjects. With prevalent use of robotic devices for gait rehabilitation, however, these movements are often limited by such devices [8, 24]. The restriction on pelvis leads to alterations in the gait kinematics and severely limits frontal and transverse rotations [20]. Previous studies have reported that the neurologically challenged patients have shown abnormal pelvic motions with increased pelvic LD and RT movements due to compensation for weakened and spastic muscles [4, 6, 12, 16, 21]. As correct afferent sensory inputs, which carries nerve impulses from receptors toward the central nervous system, are the most critical factor for successful gait rehabilitation [20], such pelvic restrictions caused by robotic devices can diminish the quality of gait training.

To tackle this issue, Hidler [8] suggested that there is a need for robotic gait training devices to include additional degrees of freedom (DoFs) for pelvic motion in order to facilitate more normative muscle activation patterns, after investigating abnormal electromyography (EMG) patterns caused by pelvic restriction [8]. However, the addition of extra DoFs for pelvic motion to the robotic devices without understanding their contributions to human gait makes the mechanical structure of robotic devices more complicated. Consequently, it might cause other abnormal gait patterns due to the effects of compensatory movements. Moreover, a certain level of pelvic LD and RT restriction may be beneficial for the early stages of gait intervention to increase lateral balance during walking, as neurologically challenged patients have larger pelvic LD and RT compared to healthy individuals [24].

In this aspect, it is imperative to investigate the impact of restrictions of pelvic motions on human gait to verify the impact of these motions on actual gait patterns and to provide a better robotic gait rehabilitation for the neurologically challenged patients. However, to the best of our knowledge, few studies on pelvic restrictions to lower limb dynamics are available in the literature. Within this limited information, we found only one study conducted by Veneman et al. [24], which investigated the effects of pelvic fixation in the horizontal plane during walking on a treadmill. This study reported that this fixation can affect gait kinematic patterns by reducing step width and sagittal plane trunk rotations and by increasing step length and coronal plane trunk motion [24]. However, the findings of this study were limited to a kinematic point of view, without providing clues about underlying motor control by observing muscle activation patterns. In order to have a better understanding of pelvic motion restriction, investigating muscle activation patterns with the kinematic and gait descriptive parameters is crucial. Additionally, mechanism involved between treadmill and over-ground walking are different, resulting in altered walking patterns [3, 19]. In the perspectives of the robustness of the experimental framework, it is necessary to investigate the respective effects of pelvic LD and RT restrictions on human gait dynamics during over-ground walking. Therefore, this study aimed to evaluate the biomechanical effects of pelvic LD and RT restrictions on lower limb dynamics including gait descriptive parameters, kinematics, and muscle activation during over-ground walking. We hypothesized that walking without pelvic restriction could be the most natural pattern, and that pelvic restriction would alter gait dynamics.

2 Methods and materials

2.1 A novel robotic walker for over-ground gait rehabilitation

A novel robotic walker for over-ground gait rehabilitation has been developed. The walker is composed of an omnidirectional mobile platform with active split offset castors (ASOC), a body weight support (BWS) unit, a pelvic and trunk motion support brace, and an intuitive human–machine interface with force/torque (FT) sensor for the control (Fig. 1).

The CoM of the body moves simultaneously in forward–backward (V_{cy}), lateral (V_{cx}), and rotational (Ω) direction during walking. Following these fundamental gait principles, the omnidirectional mobile platform was designed and integrated into the walker to support these three motions without implementing complex actuators (Fig. 1b, i). This platform was developed using two sets of ASOC units consisting of two coaxial conventional wheels. The ASOC was driven independently according to velocity commands at the central point. The velocity of central point can be defined by the velocity of each wheel. With the use of the omnidirectional platform, it was possible to simplify the mechanical structure of the walker to support three DoFs pelvic motions, and it could also provide a number of advantages including high energy efficiency and robust mobility on uneven terrain. Hence, a user can consistently move in any direction and any configuration by using this omnidirectional platform. The body weight support unit was proposed to support vertical displacement of the pelvis, while pelvic tilt and obliquity were passively supported by the pelvic motion support brace (Fig. 1b, ii). Therefore, six DoFs of pelvic motions could be supported by the walker (Fig. 1a).

Control of the walker is achieved by detecting a force/torque (FT) signal from the pelvis which is tightly enclosed by a pelvic motion support brace (Fig. 1b, iii). Based on the interaction force detected, speeds in the forward, lateral, and rotation directions are generated with an adaptive admittance model which is composed of virtual mass and damper parameters [26]. With this system, users can simply focus on walking, without thinking of direction and speed control, thereby considerably reducing their mental workload. Our previous study [18] showed that walking with the developed walker did not alter the three dimensional trajectories of human CoM, by allowing normal and realistic gait patterns. Pelvic restriction was accomplished by assigning infinite virtual damping parameters for the lateral and rotational DoFs.

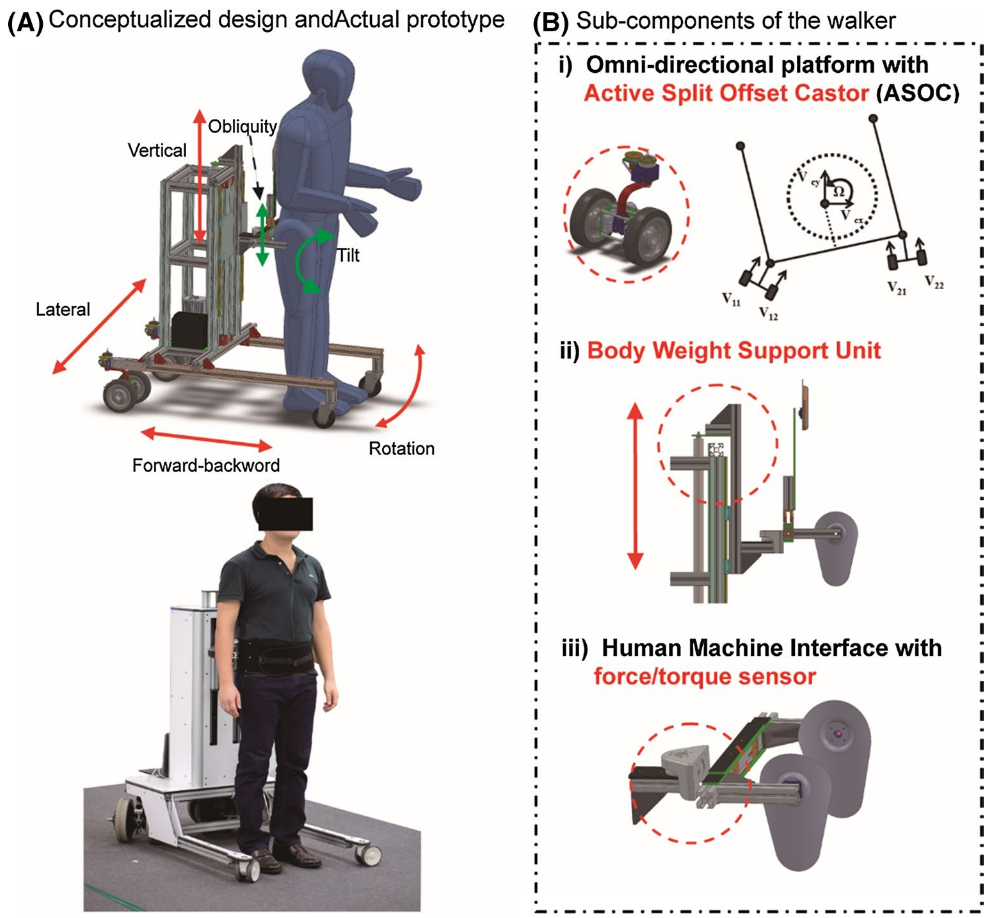

Fig. 1 **a** Conceptualized design and actual prototype of the novel robotic walker for pelvic motion support. **b** The system consists of omnidirectional mobile platform with ASOC, pelvic and trunk motion support brace unit with active BWS actuator, human–machine interface with FT sensor

2.2 Participants and experimental design

Twelve healthy subjects (26.7 ± 4.5 years, 1706.1 ± 93.1 mm, and 63.6 ± 13.5 kg) participated in this study. We excluded any subjects with any gait abnormalities or musculoskeletal and neurological disorders. All subjects were instructed to walk along the 30-m corridor for 10 min prior to the actual trials, to be acclimatized with the walker. The maximum voluntary contractions of the muscles targeted in this study were measured prior to the actual experiment. The actual trials were performed in five different conditions: (1) walking without the walker (normal walking, NW); (2) walking with walker, while pelvic LD and RT are allowed (no restriction, NR); (3) walking with the walker with only pelvic LD restriction (lateral restriction, LR); (4) walking with the walker with only pelvic RT (rotation restriction, RR); and (5) walking with the walker, with both pelvic LD and RT restricted (both restriction, BR). All subjects were instructed to walk naturally with their preferred speed on a 10-m walk way. Subjects were asked to repeat the trial until three successful strides were achieved. All subjects gave informed consent in accordance with Institutional Review Board standards.

2.3 Data collection and analysis

Data were collected with eight high-speed optical cameras (Vicon, UK) and a lightweight wireless EMG (Delsys, USA). All instruments were time synchronized. Fifteen retroreflective markers were attached to the subjects' body landmarks according to the Plug-in-gait marker set. Twelve surface wireless EMG electrodes were attached to six major muscle groups—tibialis anterior (TA), gastrocnemius (GA), vastus medialis (VM), biceps femoris (BF), gluteus medius (GM), and adductor longus (AL) with a sampling frequency of 1000 Hz.

2.3.1 Joint kinematics and gait descriptive parameters

The raw kinematic data were low-pass filtered via zero-lag fourth-order Butterworth filter with cutoff frequency of 6 Hz to remove motion artifacts and high random noise [13]. The lower limb kinematics such as ankle, knee, and hip joints angles were obtained via motion analysis software (Nexus, Vicon, UK). The RoMs of each joint were calculated based on the joint angles. The gait descriptors including the stride length, step length, step width, gait velocity, and percentage of stance phase were measured through a customized program (MathWorks, Natick, MA). The stride length and step length were normalized against the subjects' leg length.

2.3.2 EMG activation duration–intensity

The raw EMG signals were first band-pass filtered between 2 and 200 Hz to remove motion artifact and high-frequency noise. After rectification of the band-pass filtered EMG, all EMG data were normalized against the respective maximum voluntary contraction (MVC) value which was measured prior to the gait experiment. The low-pass filter with a cutoff frequency of 10 Hz was used to produce a linear envelope representation. The enveloped EMG data were then used to quantify the duration–intensity of muscle activity. Amplitudes of enveloped EMG were then classified into five groups according to the relative intensity of the selected group over MVC [2, 17], i.e., 10, 20, 30, 40, and 50 % intensities of muscle activation. Activation durations of each classified EMG were calculated during the earlier five categorized groups of the muscle intensity; for example, TA muscle duration–intensity was defined as: TA10, TA20, TA30, TA40, and TA50, respectively. The same procedure was repeated for the remaining muscles data: GA, VM, BF, GM, and AL.

2.4 Statistical analysis

Statistical analysis (SPSS Inc., Chicago, IL) was conducted in order to identify the gait changes according to the five conditions mentioned above. One-way ANOVA was performed to distinguish the gait kinematic parameters as well as the differences in muscle activation duration–intensity parameters among the experimental conditions. In the case of significant differences found among the conditions, Tukey's post hoc test was performed subsequently. All significance levels were set at $p < 0.05$.

3 Results

3.1 Gait descriptive parameters

Table 1 shows the gait descriptive parameters according to the experimental conditions mentioned. The normalized stride and step length, and gait velocity showed significantly lower values for NR, LR, RR, and BR, as compared to the NW ($p < 0.001$). However, the NR showed significantly longer stride and step length as compared to LR and BR ($p < 0.05$). There was no significant difference in step width among the conditions. Percentage of stance phase was prolonged in the condition of LR, RR ($p < 0.001$), and BR ($p < 0.05$) compared with NW.

3.2 Kinematic profiles and Range of motions (RoMs)

Kinematic and RoMs of each joint are shown in Fig. 2 and Table 1. There were significant reductions in ankle plantarflexion at terminal stance, knee flexion at mid-swing, and hip extension at mid-stance, in LR, RR, and BR conditions

Table 1 Gait performance parameters during pelvic restriction walking

	NW	NR	LR	RR	BR
Normalized stride length	1.410 ± 0.112	1.055 ± 0.214**	0.806 ± 0.263**,ǂ	0.951 ± 0.215**	0.866 ± 0.227**,ǂǂ
Normalized step length	0.679 ± 0.063	0.543 ± 0.105	0.470 ± 0.243ǂ	0.507 ± 0.108*	0.481 ± 0.101**
Step width (m)	0.143 ± 0.019	0.122 ± 0.056	0.146 ± 0.055	0.130 ± 0.057	0.106 ± 0.052
Gait velocity (m/s)	0.977 ± 0.186	0.524 ± 0.175**	0.445 ± 0.172**	0.487 ± 0.168**	0.463 ± 0.179**
% of stance phase	61.34 ± 1.68	64.11 ± 5.17	70.70 ± 7.78**,ǂǂ	66.09 ± 6.08*	67.94 ± 8.23**
Ankle dorsiflexion	10.36 ± 4.21	10.40 ± 3.35	11.55 ± 3.59**,ǂ	9.63 ± 3.68**	10.45 ± 2.64**,ǂ
Ankle plantarflexion	22.79 ± 8.53	16.84 ± 7.59	4.36 ± 10.88	11.63 ± 9.69	8.26 ± 9.61
Ankle RoM	33.15 ± 6.16	27.24 ± 7.91	15.91 ± 11.36**,ǂ	21.26 ± 9.62**	18.71 ± 9.87**,ǂ
Knee flexion	59.76 ± 7.16	54.28 ± 8.10	47.92 ± 12.02**	46.25 ± 12.65**,ǂ	46.49 ± 11.04**,ǂ
Knee extension	1.97 ± 4.52	4.22 ± 6.22	5.84 ± 6.18*	4.09 ± 5.50	4.67 ± 5.10
Knee RoM	57.79 ± 5.30	49.76 ± 6.64*	42.08 ± 9.11**,ǂ	42.36 ± 10.80**,ǂ	41.82 ± 9.32**,ǂ
Hip flexion	30.15 ± 5.64	32.24 ± 6.57	30.97 ± 4.97	30.50 ± 4.57	30.99 ± 5.20
Hip extension	11.55 ± 8.41	4.41 ± 7.48*	1.04 ± 6.97**	2.95 ± 7.89**	1.97 ± 7.31**
Hip RoM	41.69 ± 4.24	36.64 ± 5.68*	32.01 ± 5.94**,ǂ	33.45 ± 6.02**	32.97 ± 6.70**,ǂ

* Statistical difference between NW and NR, LR, RR, and BR, $p < 0.05$

** Statistical difference between NW and NR, LR, RR, and BR, $p < 0.01$

ǂ Statistical difference between NR and NW, LR, RR, and BR, $p < 0.05$

ǂǂ Statistical difference between NR and NW, LR, RR, and BR, $p < 0.01$

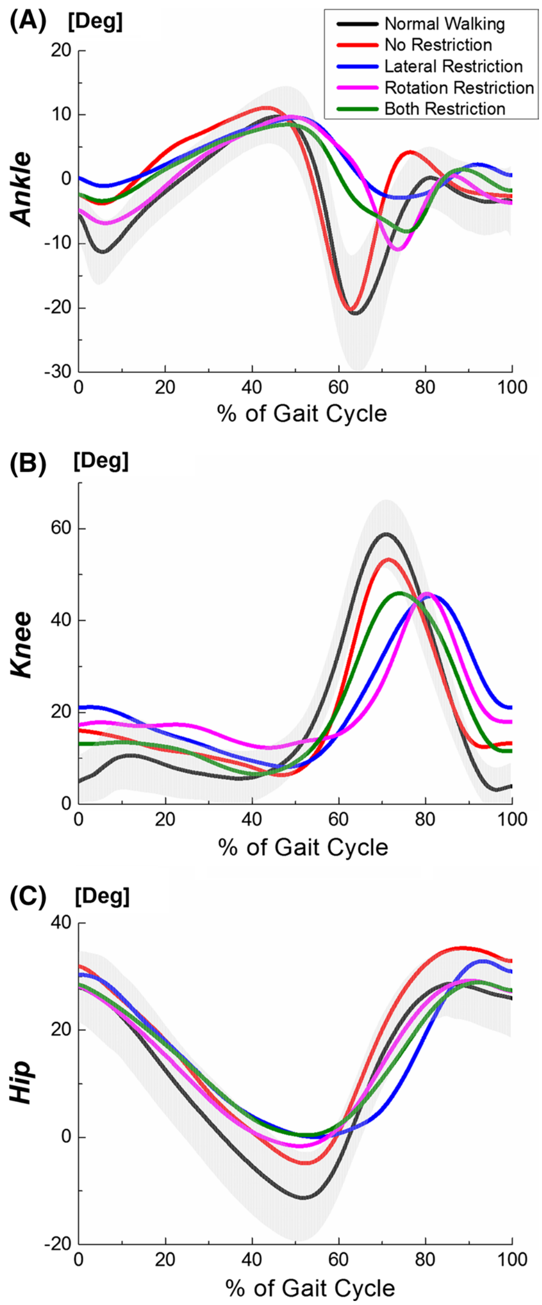

Fig. 2 Comparison of **a** Ankle, **b** knee, and **c** hip joint kinematics profiles during the gait under the condition of NW (*black*), NR (*red*), LR (*blue*), RR (*pink*), and BR (*green*) (color figure online)

as compared to NW ($p < 0.001$), (Table 1). The ankle, knee, and hip joint angular profiles of NR condition resembled that of NW and showed no significant deviation from normal walking. The RoMs of ankle, knee, and hip joints were reduced for all conditions as compared to NW. However, significant reduction of ankle RoM in LR and BR ($p < 0.05$), knee RoM in LR, RR, and BR ($p < 0.05$), and hip RoM in LR and BR ($p < 0.05$) was found as compared to the NR. These reductions showed that a fixation of the pelvic LD and RT movements reduced the RoMs of ankle, knee, and hip joints by altering their excursion during gait.

3.3 Duration–intensity of EMG activation

Muscle activation profiles and activation duration–intensity are shown in Figs. 3 and 4. There is no significant alteration in NR compared with NW. However, the TA muscle in LR and BR conditions showed significant over-activation from the mid-stance to terminal swing. The profile of the GA muscle showed prolonged activation patterns in the mid-stance, showing an enlarged stance phase (Table 1) in the LR and BR conditions. In addition, the BF muscle in the RR condition showed significant higher activation during the stance phase. These results can be statistically quantified through EMG duration–intensity analysis as shown in Fig. 4. The EMG duration–intensity data for TA and BF during stance phase were significantly higher in LR and BR, compared to NW ($p < 0.05$). TA10, TA20, TA30, TA40 were significantly increased in LR and BR conditions, while BF10 was increased in RR condition compared with NW in stance phase. For the swing phase, TA20 and TA30 showed significantly larger activation duration in LR compared to NW and NR conditions. Finally, GA10 and GA20 in LR and BR conditions were significantly increased compared to NW ($p < 0.01$) and NR ($p < 0.05$). No statistical difference was found in VM, GM, and AL muscles.

4 Discussion and conclusion

From the perspective of gait kinematics and muscle activation, we observed significant reductions in gait performances and RoMs of kinematic profiles as well as increases in muscle activation patterns when the pelvic LD and RT were restricted during over-ground walking.

The gait descriptive parameters, especially the normalized stride and step length, showed significant reductions in LR and BR conditions compared with NR. It is important to note that the stride and step length were severely affected by restricting lateral displacement rather than the rotational restriction. However, these results differ from the outcomes on the pelvic fixation during treadmill walking as reported by Veneman et al. [24]. The previous study reported that a pelvic horizontal restriction resulted in a longer step length, and claimed that pelvic fixation could be helpful in increasing step length in actual clinical trials. The difference between the results of our study and the previous study could be attributed to variations in experimental designs. It might be due to either different walking mechanisms between walking on treadmill and over-ground or different methods for restricting pelvic motions during experimental trials. Specifically, walking on a treadmill can be different

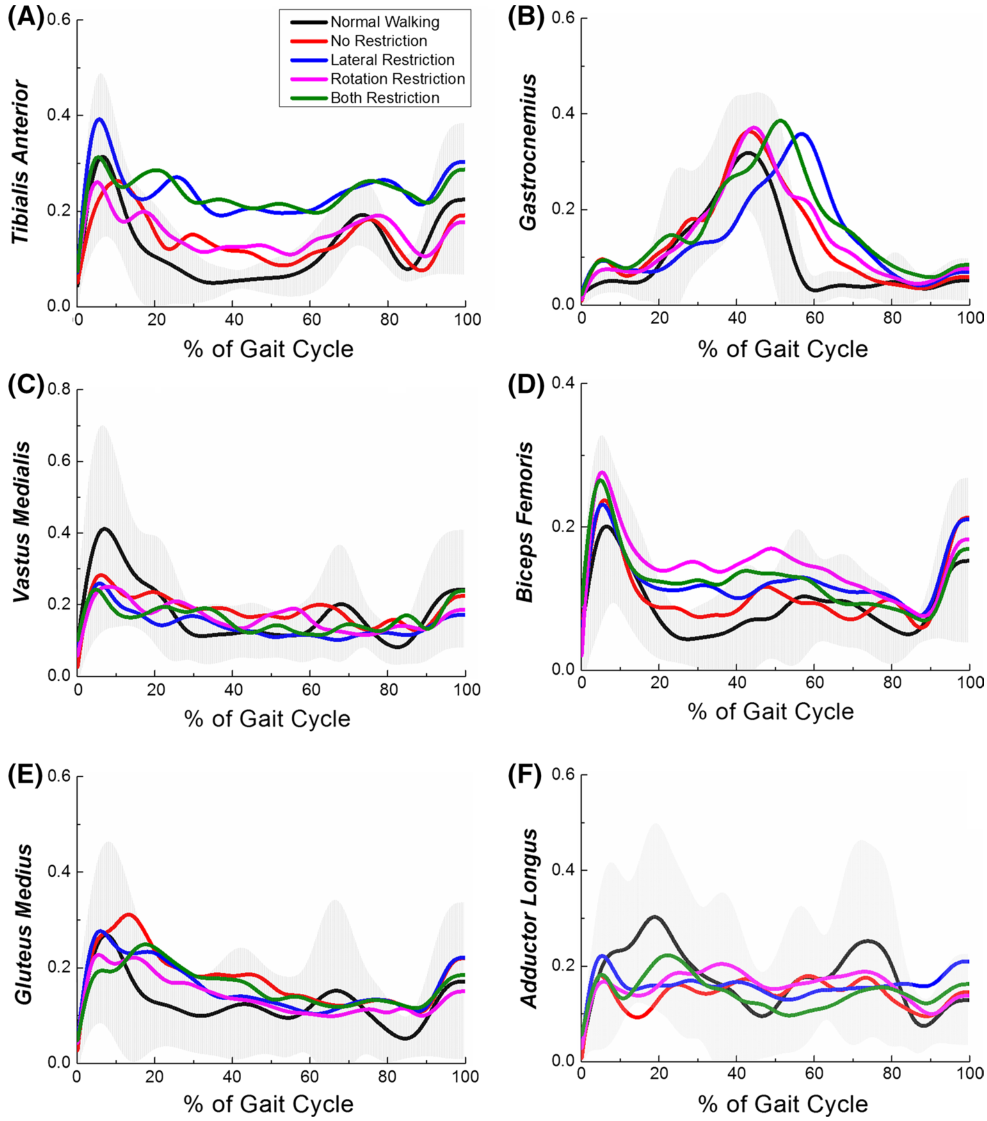

Fig. 3 Averaged and enveloped surface EMG profiles for six major muscles: **a** TA, **b** GA, **c** VM, **d** BF, **e** GM, and **f** AL under walking conditions. The *black* and *gray lines* show the NW and its standard deviation. *Red*, *blue*, *pink*, and *green lines* show the NR, LR, RR, and BR, respectively (color figure online)

from over-ground walking, showing an increase in cadence and decreases in stride length and joint excursion on a treadmill [25]. In addition, the pelvic fixation was implemented using a waist girdle connected to a frame of the treadmill in the previous study, while the pelvic restriction has been accomplished by assigning infinite virtual damping parameters for LD and RT movements in this study. In addition, the gait was restricted only in sagittal plane on the treadmill, and variation in speed of CoM which is natural in normal walking was not allowed in the previous study. Despite the inconsistency between these two studies, our results suggest that pelvic restriction significantly affected the gait descriptive parameters by reducing the normalized stride and step length, and gait velocity and by increasing percentage of the stance phase.

In terms of lower limb kinematics, the pelvic restrictions caused limited ankle plantarflexion at the terminal stance, knee flexion at mid-swing, and hip extension at mid-stance, contributing to reduction of RoMs in all of the joints in the lower limbs. These reductions in RoMs and altered kinematic profiles might cause other abnormal gait patterns in the subjects due to compensatory strategies [23]. Furthermore, since ankle RoMs is a key factor for gait efficiency for cerebral palsy patients [11], the reduced RoM in the ankle joint due to pelvic restriction might hinder the efficiency and performance of the actual clinical trials.

We identified the muscle activation patterns in terms of both duration and intensity of major muscles in lower limbs. The muscle activation patterns provided mechanistic causes of kinematic patterns and showed clear indication of the biomechanical effects of the walker with and without pelvic motion facilitation. It appeared that profiles of the EMG amplitude were not significantly altered from that of normal gait when the pelvic motions were free. However, a significant increase in EMG activation duration–intensity at the TA muscles was found in LR and BR compared to that

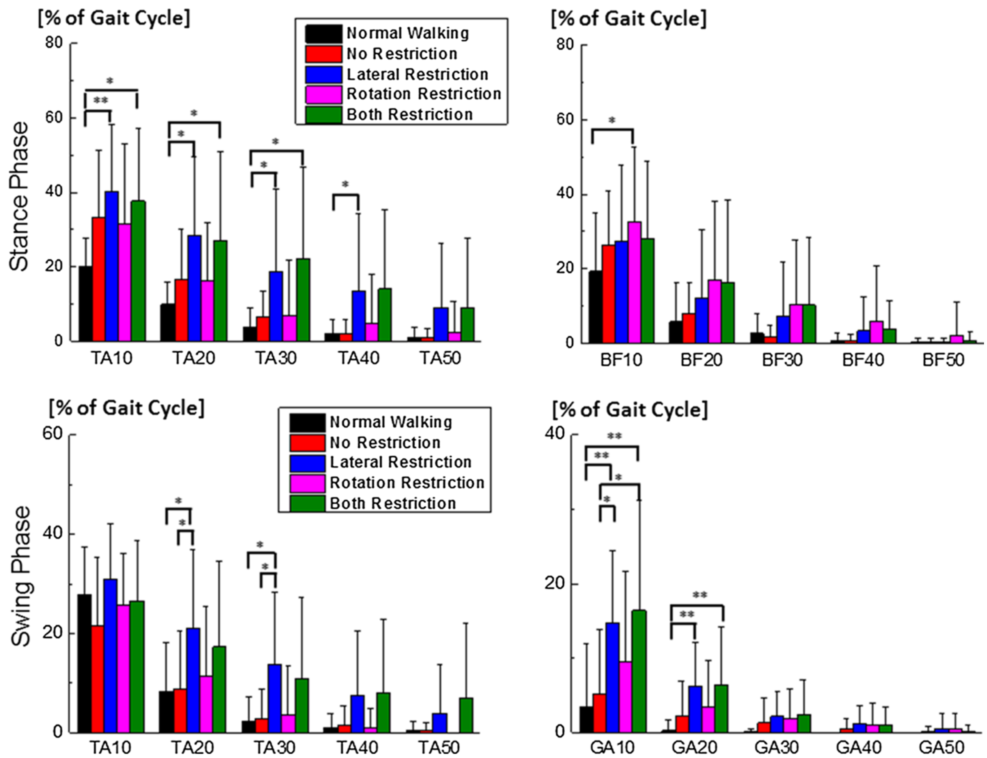

Fig. 4 EMG duration–intensity results according to the experiment conditions. *Black bar* shows the condition for NW, *red* for NR, *blue* for LR, *pink* for RR, and *green* for BR (color figure online)

of NW in both the stance and swing phases. However, there was no significant difference between the NR and RR. From the results described above, the pelvic lateral restriction may cause body load concentration toward the stance limb for weight acceptance. Consequently, the applied body load may cause an increased muscle activation intensity–duration at the TA muscle during the single-limb stance period as the subjects were trying to maintain sagittal plane balance. In addition, the GA muscle duration–intensity was significantly increased with prolonged EMG profiles in LR and BR conditions, especially in the swing phase. The prolonged GA activation is an indication of a raised stance period (Table 1) to stabilize the gait patterns caused by LR and BR walking. Furthermore, the pelvic rotational restriction caused an increased activation duration in the BF muscle (BF10). This might be attributed to a compensation for the increased knee flexion during mid-stance (Fig. 2); thus, the BF muscle was over-activated to maintain the flexed knee motion and to achieve locomotion against the pelvic rotational restriction.

In summary, gait with pelvic motion facilitation can elicit normal muscle activation patterns in a natural manner without altering normal gait dynamics. On the other hand, gait with pelvic restriction severely affected gait dynamics by reducing the gait performances with significant decreases in the RoMs of the ankle, knee, and hip angles, and increases in lower limb muscles activation duration–intensity. These alterations will hinder the subjects from learning natural gait patterns and having correct afferent sensory input and sensory feedback which are the most critical factors for successful gait training. Therefore, the efficacy or functional outcome after gait rehabilitation can be significantly reduced if the pelvic lateral and rotational motions are restricted. Additionally, the pelvic restriction may result in a higher metabolic cost for gait training as it requires increased and prolonged muscle activity [7]. These findings can serve as a cornerstone of the further development of robotic gait rehabilitation by providing clear evidence of the pelvic LD and RT restriction on the lower limb gait dynamics. However, it is important to be aware that gait rehabilitation is a mix of recovery and compensation depending on patients' condition. Thus, the pelvic LD and RT restriction might be provided for severe patients in the beginning of the gait training to normalize gait functionality, as patients recover during the rehabilitation process, different levels of the pelvic facilitation can be given so that patients can achieve optimized gait patterns.

There were a few design parameters that could be improved by incorporating the role of trunk motion against the pelvic restrictions as a future scope of this work. It should be noted that the main contribution of this study is to examine the biomechanical effects of the pelvic LD and RT restrictions on the lower limb, and we believe that this study would help the scientific community to develop a better understanding on the pelvic restriction during over-ground walking. While the results of this study showed the necessity of pelvic motion facilitation while walking, an experiment with healthy young subjects may not be enough to provide clinical influence for neurologically challenged patients.

5 Conclusion

The effects of pelvic LD and RT restriction on the lower limb during over-ground walking in terms of gait kinematics, gait descriptive parameters, and muscle activation were investigated in this study. It can be concluded that gait dynamics are altered when the pelvic motions are restricted, and the altered dynamics change the subjects gait in terms of kinematics, gait descriptive parameters, and muscle activation. Therefore, artificial restrictions that lead to alterations in gait are not desirable for a training device, unless a specific training is required. As a future scope of research, we are looking to address this issue by conducting preliminary experiments with neurologically inhibited patients. An awareness of the results of this study combined with clinical verification will allow therapists to provide decently designed robotic gait training.

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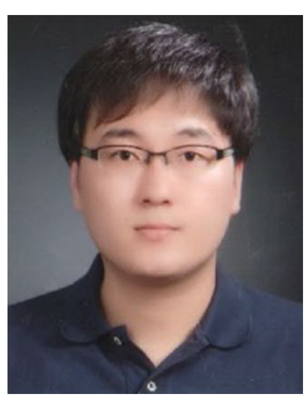

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