Influence of Arm Joint Limitation on Interlimb Coordination during Split-belt Treadmill Walking

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Abstract During walking, arm and leg swings in healthy people are closely coupled temporally by interlimb coordination. A split-belt treadmill contains two belts that can be driven at different velocities, and is used to demonstrate the adaptability of human bipedal locomotion. Previous studies focusing on the use of split-belt treadmills in patients with neurological disorder demonstrated the existence of impaired temporal limb coordination in such patients, but the influences of neural and nonneural factors on interlimb coordination could not be examined separately. Further, the influence of limiting one joint of an arm on temporal coupling was unclear. The purpose of this study was to clarify the influences of limiting one arm joint and the corresponding compensation by the unlimited arm. Ten healthy young adults walked on a double-belt treadmill equipped with force sensors, during a tied-belt period (velocity of both belts = 0.9 m/s, 3 min) followed by a split-belt period (belt velocities = 0.9 m/s and 1.8 m/s, 6 min). The following experimental conditions were studied: slow side restrained, fast side restrained, and unrestrained (NR). A non-flexible bandage-type restraint limited the elbow extension to 20°. The correlations between the trajectories of arm and leg swings were analyzed using a Vicon motion capture system. The correlation coefficients between the restraint arm swing and slow- or fast-side leg swing were significantly lower in the restraint conditions compared to other condition in both tied-belt and split-belt periods. In particular, the anti-phase swing of the ipsilateral arm and leg and the in-phase swing of the contralateral arm and leg decreased. These results suggest that elbow limitation inhibits interlimb temporal coordination. The unrestrained arm swing increased in spatial amplitude, but maintained higher temporal coupling with the leg. Non-neural factors are expected to cause reduction of interlimb coordination in individuals having neurological disorders and joint limitations.

Keywords: walking, arm swing, restraint, split-belt treadmill, interlimb coordination.

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1. Introduction

Human bipedal locomotion involves spatial and temporal coordination in the motor output of arm and leg movements [1–4]. In particular, arm and leg swings are closely coupled temporally by interlimb coordination [5–8]. Previous studies have clarified that healthy people alternate between anti-phase and in-phase swings of the ipsilateral and contralateral arms and legs, respectively [9, 10]. Individuals with neurological disorders (such as post-stroke, Parkinson’s disease, and multiple sclerosis) suffer from impaired limb coordination [11–15]. However, many patients possess spatially asymmetric bodies due to non-neural factors such as limited range of motion [16, 17]. Given these conditions, previous experiments performed on individuals with neurological disorders were not able to separate and clarify the neural and non-neural factors pertaining to temporal interlimb coordination.

Investigations of interlimb coordination using split-belt treadmills have recently been reported [3, 18, 19]. A split-belt treadmill is an experimental tool to demonstrate the adaptability of human bipedal locomotion based on a process in which a participant walks on a double-belt treadmill, the two belts of which can be driven at different speeds. Previous studies have clarified that temporal coupling between arm and leg swings is higher...
during split-belt treadmill walking [20]. Another study [21] using a split-belt treadmill has demonstrated that leg swings are markedly influenced by unilateral arm swings (induced by arm restriction or weight on the wrist). Therefore, split-belt treadmill walking is a useful experimental task that can help clarify the interlimb coordination in walking. However, the effect of limitation of a single joint in one arm on interlimb coordination has not yet been appropriately studied. Individuals with neurological disorders (such as post-stroke and Parkinson’s disease) suffer passive joint limitation owing to chronic rigidity and spasticity. Before conducting experiments involving such patients, the influence of joint limitation, which is a non-neural factor, on interlimb coordination in healthy people without neurological disorders should be clarified.

To this end, this study aimed at examining the influence of partial restraint of an arm on interlimb coordination, to clarify the physical influence of gait control in patients suffering from joint limitation. Understanding the influence of arm joint limitation on interlimb coordination during walking is clinically significant for individuals having both neural and non-neural disorders. We hypothesized that restraint of a single joint in one upper limb influences lower coordination involving the contralateral arm and contralateral or ipsilateral legs.

2. Methods

Ten healthy young adults (males, age: 22 ± 1 years, weight: 60.5 ± 5.4 kg, and height: 1.75 ± 0.06 m) were recruited from the Saitama Prefectural University community. No participants had any history of neurological or musculoskeletal disorders. All participants provided written informed consent in accordance with the Declaration of Helsinki prior to the start of the proposed investigation. The study was approved by the ethics review committee in the Saitama Prefectural University.

2.1 Split-belt protocol

The experimental protocol is depicted in Fig. 1. All participants were instructed to walk on a double-belt treadmill, the two belts of which were equipped with force sensors (ITR5018-11, Bertec, US, 1000 Hz; Fig. 2). The two belts were controlled to operate at the same or different speeds by independent motors. The treadmill was operated under the following two conditions: symmetric condition (both belts moving at the same speed; “tied-belt”) and asymmetric condition (two belts moving at different speeds; “split-belt”). The fast- and slow-moving sides of the treadmill during the asymmetric condition were termed “fast side” and “slow side,” respectively. Both treadmill belts were set at the same speed of 0.9 m/s during symmetric operation (3 min). Subsequently, the speed of one belt was increased to 1.8 m/s with an acceleration of 0.5 m/s² during asymmetric operation (6 min).

2.2 Joint limitation—elbow restraint condition

Experiments were performed in accordance with the abovementioned split-belt protocol under two conditions: with and without one-elbow restraint. The elbow restraint using a nonflexible elastic bandage (CB-25, NI-TREAT, Japan, Fig. 2) limited the range of motion to 20–145°. This restraint did not limit flexion, and only extension was restrained to angular displacements within 0–20°. During elbow restraint, the order of assignment of the side with elbow restraint and the fast-side belt was randomized across participants. The following restraint conditions were examined: (1) non-restraint (NR), (2) slow-side elbow restraint (SR), and (3) fast-side elbow restraint (FR).
2.3 Data collection

Three-dimensional marker trajectory data were collected using a 17-camera Vicon motion-capture system (Oxford, UK; 100 Hz) with the Plug-in-Gait full-body AI model marker setting. The collected data were low-pass filtered at 5 Hz using a second-order zero-phase-lag Butterworth filter. Arm and leg swings were defined by their amplitude in the anteroposterior direction of the relative peripheral limb marker trajectories to the central limb marker. The trajectories of a wrist marker relative to a shoulder marker were used to determine the arm swing. Similarly, the trajectories of an ankle marker relative to the midpoint between the anterior and posterolateral iliac spine markers were used to determine the leg swing. Gait events (heel contact and toe off) were defined based on the vertical component of the ground reaction force (Fz) followed by low-pass filtering at 5 Hz using a fourth-order zero-phase-lag Butterworth filter. Data were recorded during the first 30 s of symmetric operation (tied-belt period) and last 30 s of asymmetric operation (split-belt period). The data recorded over 20 strides were analyzed.

2.4 Data analysis and statistics

The mean elbow angle during each period was calculated, and a paired t-test was performed. Pearson correlation coefficients were calculated for right arm swing versus left arm swing, right leg swing versus left leg swing, right leg swing versus left arm swing, and left leg swing versus right arm swing, during each stride. The mean symmetrical ratio of arm amplitude was calculated during each period and under each condition. The symmetrical ratio was calculated using amplitudes of the fast- and slow-side arms. The mean ratio of arm amplitude during the split-belt period was normalized to that during the tied-belt period under each condition. A two-way repeated measures ANOVA was used to test for statistically significant differences in correlation coefficients between the restraint conditions (NR, SR, and FR) and periods (tied- and split-belt). A one-way repeated measures ANOVA was next used to compare the correlation coefficients and ratios pertaining to the restraint conditions (NR, SR, and FR) during each period (tied- and split-belt). When the ANOVA results yielded a significant effect, post hoc analyses were performed employing Bonferroni’s test (p < 0.05). All analyses were performed using the MATLAB package (MathWorks Inc., USA).

3. Results

Table 1 lists the maximum extension angles of the elbow joint during walking. Significant differences (p < 0.05) were observed between the restrained and unrestrained sides under SR and FR conditions.

All correlation coefficients indicated that there were no interactions between the restraint conditions and periods [F (2,18) = 0.34–2.29, p = 0.12–0.71]. The differences in correlation coefficient between the slow- and the fast-side arm swings were not significant during both tied-belt and split-belt periods (Fig. 3A). Similarly, the differences in correlation coefficient between the slow-side and fast-side leg swings were not significant during both tied-belt and split-belt periods (Fig. 3B). The correlation coefficient increased significantly from tied-belt to split-belt periods in all conditions.

The correlation coefficient between the slow-side arm and fast-side leg swings during the tied-belt period was significantly smaller under the SR condition compared to FR during tied-belt as well as split-belt periods (Fig. 3C). The correlation coefficient increased significantly from tied-belt to split-belt period in all conditions. Likewise, the correlation coefficient between the slow-side arm and slow-side leg swings was significantly smaller under the SR condition compared to FR during

|                | Tied-belt       |                | Split-belt      |                |
|----------------|-----------------|----------------|-----------------|----------------|
|                | Restraint (NR = right) | Non-restraint (NR = left) | p-value | Restraint side (NR = right) | Non-restraint (NR = left) | p-value |
| NR             | 28.77 ± 6.20    | 26.79 ± 6.94   | 1               | 27.86 ± 5.28   | 27.32 ± 7.29   | 1               |
| SR             | 44.28 ± 18.84   | 27.30 ± 7.30   | <0.05           | 41.63 ± 21.42  | 26.58 ± 8.12   | <0.05           |
| FR             | 44.25 ± 14.18   | 27.48 ± 8.44   | <0.05           | 45.03 ± 19.29  | 26.50 ± 7.99   | <0.05           |

P values for SR and FR: differences between restraint and non-restraint sides. P values for FR: differences between left and right sides
the tied-belt period (Fig. 3D). The corresponding difference during the split-belt period was, however, not significant (Fig. 3D). The correlation coefficient between the fast-side arm and slow-side leg swings was significantly smaller under the FR condition compared to those under the NR and SR conditions during the tied-belt and split-belt periods (Fig. 3E). The correlation coefficient between the fast-side arm and fast-side leg swings was significantly lower under the FR condition compared to those under the NR and SR conditions during the tied-belt and split-belt periods (Fig. 3F). The correlation coefficient increased significantly from tied-belt period to split-belt period in all conditions.

**Figure 4** depicts the mean symmetrical ratios of arm amplitudes under each of the three conditions—NR, SR, and FR. During the tied-belt period, no significant difference in amplitude of the unrestrained arm was observed between the NR (1.18), SR (2.32), and FR (2.29) condi-
Interlimb coordination usually manifests via ipsilateral arm and leg and in-phase swing of the contralateral limbs [23]. Based on the contribution of the central nervous system, MacLellan [20] reported that the temporal coupling between arm and leg swings is stronger during split-belt treadmill walking. For example, post-stroke patients and those with Parkinson’s disease experience contractures in arm joints owing to rigidity or spasticity of biceps brachii [24], similar to the restraint conditions examined in the present study. This is because such contractures are typically limited to manifestation along the extension direction. Individuals having such neurological disorders likely possess physical restraint factors similar to the model examined in this study, in addition to neural factors. Based on this result, such patients may also be affected by inhibition of interlimb coordination owing to physical constraints.

4.2 Emphasis on unrestrained side arm swing
The arm amplitudes on the slow and fast sides during the split-belt period differed only slightly compared to those in the tied-belt period under each condition (Fig. 5). However, during the tied-belt period, the symmetrical ratio (unrestrained / restrained side) was much greater than 1.00 in both SR and FR conditions (Fig. 4). In addition, during the split-belt period, the symmetrical ratio (fast / slow side) was greater than 1.00 in SR and smaller than 1.00 in FR (Fig. 4). This finding also indicates that the arm swing amplitude on the unrestrained side became greater than that on the restrained side. Therefore, in the present study, the arm swing amplitude on the unrestrained side was observed to increase regardless of the side being slow or fast. At a speed ratio of 2:1 during split-belt walking, MacLellan et al. [20] demonstrated an increase in arm swing amplitude exclusively on the slow side, and not on the fast side. They explained that upper-limb amplitudes correspond to those of the fast-moving lower limb, thereby indicating an adaptation to maintain symmetric upper limb movements governed by the central nervous system, as proposed in the lower limbs [18, 20]. Under the restraint conditions examined in this study, the influence of restraint on upper limbs led to compensatory increase in swing of the contralateral arm. Moreover, the observed compensatory effect was stronger compared to that of the difference in belt speed.

During split-belt walking with elbow restraint, the fast-side arm could swing emphatically to compensate for the restraint. Bondi et al. [21] performed a study on arm swing using the split-belt treadmill and examined the conditions of excessive arm swinging and weight attachment on the arm. They observed an increase in leg swing time under the condition of excessive arm swinging, but a tendency of decrease in the case of weight attachment to the arm. An interpretation of these results is that the observed increase or decrease in rhythmic arm swing amplitude is transferred to the lower limbs medi-
ated by the overall supra spinal involvement, thereby affecting symmetric leg swings. The findings reported by Bondi et al. [21] support the results obtained in our study concerning the influence of arm joint limitation on interlimb coordination.

4.3 Compensation of unrestrained side arm swing

As the spatial amplitude of arm swing on the unrestrained side became larger, temporal coupling with the leg increased (FR values in Figs. 3C and 3D; SR values in Figs. 3E and 3F). Previous studies using split-belt walking demonstrated that trunk movement also becomes tightly coupled to the leg [20, 25], suggesting that the leg directly drives trunk rotation through biomechanical linkages and the arm swing is used to balance the trunk torques. Therefore, in individuals experiencing passive limitation in one arm, the contralateral arm may continue to demonstrate temporal coupling with both legs. Therefore, in individuals experiencing joint limitations and movement disorders in the arm and leg on the same side, such as in post-stroke patients, the above result suggests that such individuals may swing the nonparetic arm in a compensatory manner to facilitate easy swing of the paretic leg.

5. Limitation

The present study had a methodological limitation, in that only young male adults were recruited for this study. It is, therefore, unclear whether findings of this study could be generalized to other populations. Future investigations should include post-stroke patients to verify the clinical application of the proposed concept.

6. Conclusion

The present study demonstrates that for arm swing during split-belt walking, joint limitation of one elbow inhibits the temporal interlimb coordination between the ipsilateral arm and both legs. As the spatial amplitude of the contralateral arm swing becomes greater, temporal coupling with the leg increases. Based on this result, individuals with neurological disorders and passive joint limitation may experience inhibition of interlimb coordination owing to physical constraints.

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