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Short communication

Effects of constrained trunk movement on frontal plane gait kinematics

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ABSTRACT

Previously it has been shown that constraining step width in gait coincides with decreased trunk displacements. Conversely, external stabilization of the upper body in gait coincides with decreased step width, but this may in part be due to changes in passive dynamics of the leg. In the present study, trunk kinematics during gait were constrained without external stabilization by using an orthosis, to investigate whether step width and dynamic gait stability in the ML direction are changed in relation to trunk kinematics. Nine healthy young adults walked on a treadmill at three different speeds with no intervention and while wearing a thoracolumbar orthosis. Based on marker trajectories, trunk COM displacement, body COM displacement and velocity, step width, and margin-of-stability in ML direction were calculated. The results showed that the orthosis significantly reduced trunk and body COM displacements. As hypothesized, the restriction of trunk movement coincided with significantly decreased step width, while the margin-of-stability was not affected. These findings indicate that, when trunk movements are constrained, humans narrow step width, while maintaining a constant margin-of-stability. In conclusion, the present results in combination with previous work imply that in gait a reciprocal coupling between trunk kinematics and foot placement in the frontal plane subserves control of stability in the frontal plane.

1. Introduction

The dynamic stability of gait requires regulation of the centre of mass (COM) position with respect to the base of support (BOS), which in the ML direction requires active control (Bauby and Kuo, 2000). Half of the whole body mass is located in the trunk segment (Jensen and Fletcher, 1994) and therefore the trunk segment needs to be controlled in relation to the lateral border of the BOS (Woollacott and Tang, 1997), which is determined by mediolateral foot placement.

In a previous study, we showed that walking with a narrower step width coincides with changes in the COM kinematics, suggesting that trunk kinematics are adjusted when step width is constrained (Arvin et al., 2016). In addition, previous studies have shown a correlation between frontal plane trunk kinematics during the swing phase of gait and control of the subsequent step width (Hurt et al., 2010; Wang and Srinivasan, 2014), which in turn, was shown to be correlated with swing leg gluteus medius activity (Rankin et al., 2014). While these findings were interpreted as indicative of foot placement being adjusted to trunk kinematics, the observational nature of these studies does not exclude the opposite, i.e. adjustment of trunk kinematics to the planned, future foot placement. Experimental evidence, in line with foot placement being guided based on trunk kinematics, was provided by studies on walking with external pelvic stabilization. This manipulation decreases lateral displacement of the COM and coincides with decreased step width and step width variability (Donelan et al., 2004; Ijmker et al., 2013; Veneman et al., 2008). However, the external stabilization, which couples the subject's pelvis mechanically to an external rigid frame, limits pelvis movements (IJmker et al., 2014). This in turn may affect the passive dynamics of the swing leg in the frontal plane, which could account for effects on foot placement.

To test the effects of trunk kinematics on step width without external stabilization, we used a trunk orthosis in the present study to constrain trunk movement. First, we examined whether our experimental set-up was successful in restricting the trunk (in local and global reference frames) and total body COM movement (in the global reference frame) over a range of gait speeds. If so, we hypothesized that smaller movements of the trunk segment would coincide with a narrower step width. In addition, we investigated its effects on dynamic stability in the frontal plane, in terms of the margin of stability (MOS) as proposed by Hof et al. (2005). To further explain the relationship between trunk movement and step width, we analyzed trunk, pelvis, and hip angles.

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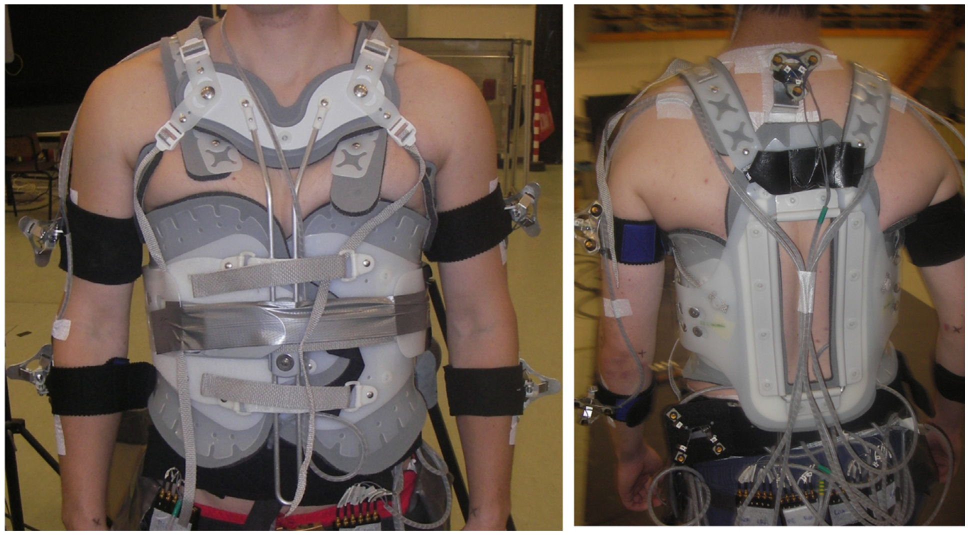

Fig. 1. Anterior and posterior views of the trunk orthosis.

2. Methods

2.1. Participants

Nine healthy young adults (all males, mean age 23 SD 3 years; height 1.80 SD 0.05 m; body mass 69 SD 4 kg) voluntarily participated in this study. They were included if they had no known pathology, including neurological or orthopaedic disorders that would interfere with gait. The local ethics committee approved the protocol and all participants gave their written, informed consent before participation.

2.2. Experimental protocol

Participants were asked to walk on a treadmill (EN-BO system, Bonte technology, Amsterdam, The Netherlands) at speeds of 3.6, 4.4, and 5.2 km/h, in two different conditions. First they walked normally with no intervention (reference condition). Subsequently, they walked with a trunk orthosis (Aspen LSO, Aspen Medical Products, Long Beach, CA, USA), which restricted the trunk motion at the level of the thoracolumbar spine (orthosis condition; Fig. 1). The speed trials were performed in order of increasing speed, and the experiment always started with the reference condition, followed by the orthosis condition. For all trials and conditions, the participants walked for 35 s, while the measurements were performed during the final 20 s. Before the measurement, the participants had 2.5 min to get used to each condition.

2.3. Data collection

The Optotrak LED marker clusters were attached with straps on the posterior surface of the heels, shanks, thighs, arms, forearms, and the thorax at the level of T1. The cluster for the pelvis was placed laterally at the left hand side distal to the iliac crest to avoid contact with the brace. The markers were tracked by two Optotrak camera systems (Optotrak® Northern Digital Inc., Waterloo, Ontario) at 50 samples/s.

Before the trials, anatomical landmarks were digitized in an upright posture, using a probe with six markers. A 3D linked segment model, developed by Kingma et al. (1996), was used to calculate the trajectories of the segments based on the *x*, *y* and *z* coordinates of the markers and anatomical landmarks. All trajectories were low pass filtered with a cut off frequency of 5 Hz. The mass of each segment was estimated based on the segment lengths plus segment circumference (Zatsiorsky, 2002), anthropometric parameters and sex (Faber et al., 2013). Body COM was calculated as the weighted sum of segment COM over all segments.

2.4. Data analysis

The instants of right heel strike (rHS) were detected as the local minima of the right toe landmark vertical velocity (Pijnappels et al., 2001). For further analyses, the time-series in the ML direction were used to calculate the parameters in the frontal plane. The mean value of all variables was obtained by averaging over 20 s of walking, which contained 17 (SD 1) strides.

2.5. Trunk and whole body COM kinematics

To test whether our experimental set-up was successful in constraining the trunk kinematics, the peak-to-peak amplitudes of the local (with respect to the pelvis) and global trunk displacements in ML direction were calculated between two subsequent rHS. Local trunk displacement was estimated as the relative displacement between the clusters on pelvis and thorax. Trunk and body COM velocity in ML direction were calculated as the first derivatives of the position time-series. The ML body COM position and velocity were used to calculate the peak-to-peak amplitudes within each stride, which were again averaged over strides.

2.6. Step width and dynamic stability

To test the effect of restricted trunk kinematics on foot placement and gait dynamic stability in frontal plane, the step width was calculated as the distance between right and left heel in ML direction at rHS. The extrapolated COM was calculated based on ML body COM position and velocity time series (Hof et al., 2005). The minimal distance between the heel and extrapolated COM within each stance phase was calculated and averaged over trials to obtain an estimate of the margin of stability (MOS) (Hof et al., 2005).

2.7. Pelvis and hip angles

To assess how hip movements link trunk kinematics to foot placement, the local trunk lateral flexion angle with respect to the pelvis segment, the global pelvis tilt angle, i.e., the pelvis orientation in the frontal plane, and local hip abduction/adduction angles with respect to the pelvis segment were calculated based on ISB recommendations (Wu et al., 2002). Peak left and right trunk lateral flexion, pelvis up- and downward tilt and hip adduction and abduction angles were defined as the minima and maxima between two subsequent rHS. Peak angles were averaged over strides and hip angles also over left and right sides.

2.8. Statistics

The assumption of normality was checked by the Shapiro-Wilks test. Homogeneity of variance was checked using Levene's test. No violations of these assumptions were found. To test whether the trunk orthosis affected the dependent variables at different gait speeds, two-way (conditions [reference, orthosis] × speed [3.6, 4.4, 5.2 km/h]) repeated measures analyses of variance (ANOVA) were performed. Bonferroni corrected post-hoc paired *t*-tests were used to determine at which speeds significant differences occurred between conditions. For all analyses, p-values < 0.05 were considered significant and statistical analyses were performed using IBM SPSS statistics 21.0.

3. Results

All ANOVA results are summarized in Table 1.

3.1. Trunk and body COM kinematics

Mediolateral trunk displacements and velocity in the global and local coordinate systems were significantly lower when participants walked with the trunk orthosis in comparison to the reference condition (Fig. 2). For local trunk velocity an interaction between orthosis and speed was found, but the effect of orthosis was consistent across speeds. With respect to the ML body COM kinematics, displacement and velocity were lower when walking with the trunk orthosis.

Table 1
Results of ANOVAs for effects of orthosis and gait speed and their interaction.

	Orthosis		Speed		Orthosis*Speed	
	$F_{1,8}$	p	$F_{2,8}$	p	$F_{2,8}$	p
Local trunk displacement	**11.9**	**0.009**	1.2	0.322	1.0	0.380
Local trunk velocity	**24.6**	**0.001**	**9.9**	**0.002**	**7.9**	**0.004**
Global trunk displacement	**8.5**	**0.019**	**49.4**	**< 0.001**	0.3	0.751
Global trunk velocity	**6.17**	**0.038**	**11.5**	**< 0.001**	6.0	0.011
COM displacement	**10.6**	**0.012**	**21.9**	**< 0.001**	2.5	0.115
COM velocity	**13.2**	**0.007**	**9.4**	**0.002**	0.7	0.492
Step width	**5.5**	**0.047**	1.7	0.212	0.9	0.422
Margin of Stability	0.5	0.504	**40.5**	**< 0.001**	1.6	0.231
Local trunk flexion	**17.7**	**0.003**	**24.5**	**< 0.001**	**3.9**	**0.042**
Pelvis tilt	**17.5**	**0.003**	**22.5**	**< 0.001**	**6.5**	**0.008**
Hip adduction (stance)	3.1	0.114	**34.9**	**< 0.001**	**4.9**	**0.022**
Hip abduction (swing)	3.1	0.114	2.3	0.137	0.6	0.540

3.2. Step width and dynamic stability

In line with our hypothesis, participants walked with significantly narrower steps in the orthosis condition than in the reference condition, while speed did not affect step width (Fig. 3). The orthosis condition did not affect the MOS, but MOS increased slightly with increasing speed. These results may suggest that step width is regulated to attain a constant MOS in the frontal plane.

3.3. Trunk, pelvis and hip angles

In line with the trunk kinematics, local trunk lateral flexion was significantly smaller in the trunk orthosis condition compared to the reference condition (Fig. 4). Furthermore, with the orthosis, the downward tilt of the pelvis on the swing side was significantly decreased. As indicated by an interaction of orthosis and speed, the concomitant hip adduction on the stance side was decreased at the two higher gait speeds. Hip abduction angles of the swing leg were not significantly affected by wearing the orthosis. Overall these results suggest that step width regulation was partially achieved through control of pelvis tilt over the stance leg, instead of modulation of swing leg abduction.

4. Discussion

4.1. Trunk and whole body kinematics

The trunk orthosis successfully constrained ML trunk kinematics, in terms of angular movement relative to the pelvis as well

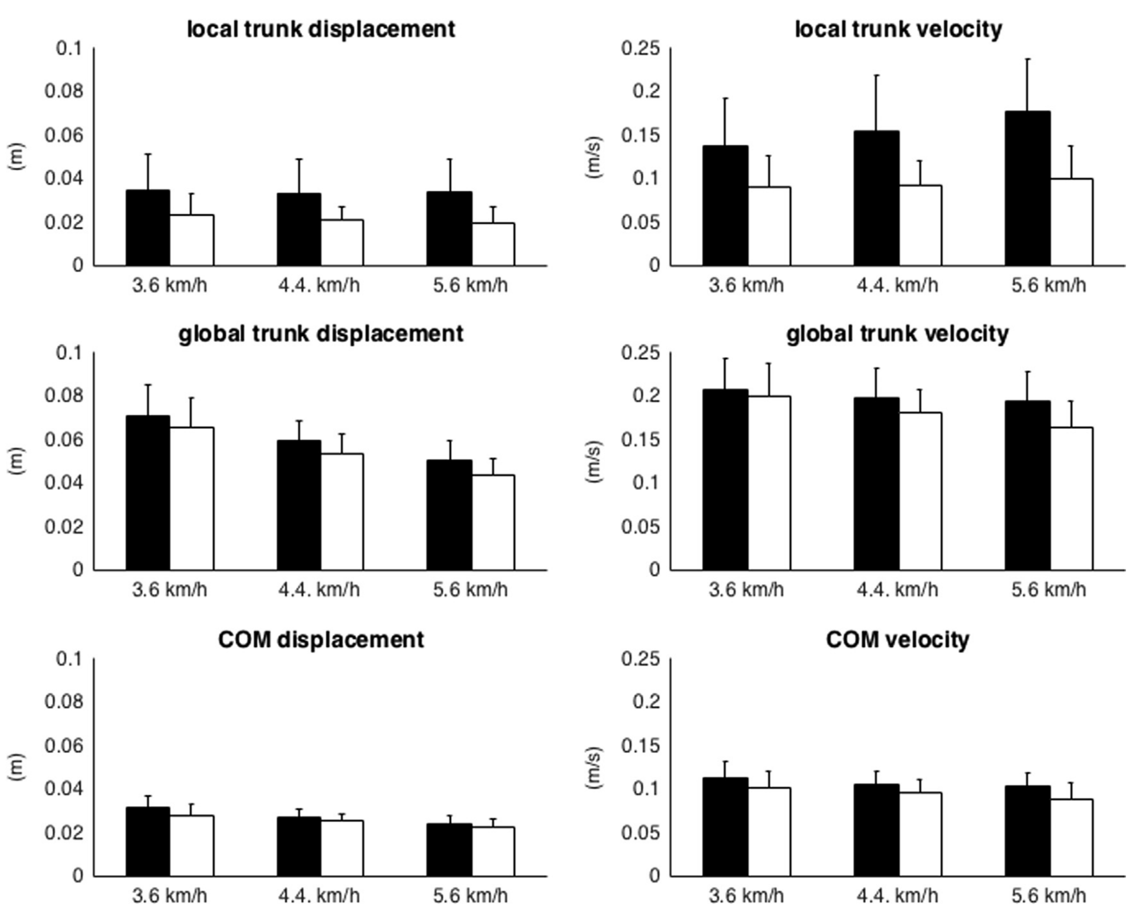

Fig. 2. Group averages of peak-to peak displacement and velocity of the trunk and of the body COM in the frontal plane for the reference (black bars) and trunk orthosis (white bars) conditions at three gait speeds. The error bars indicate standard deviations.

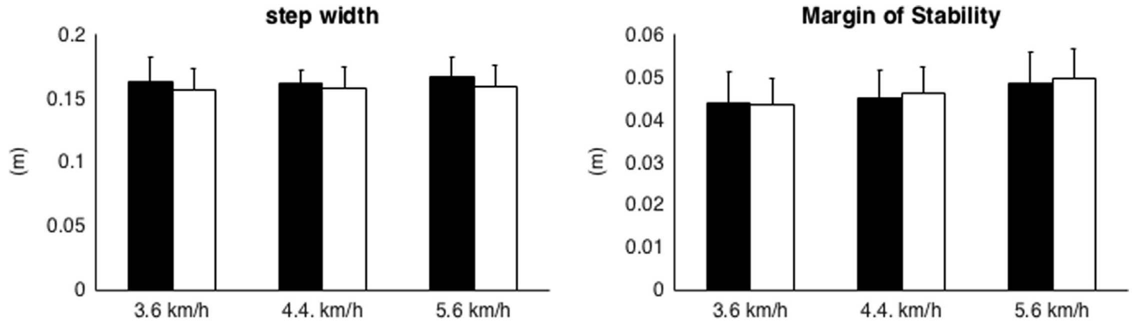

Fig. 3. Group averages of step width and frontal plane Margin of stability for the reference (black bars) and trunk orthosis (white bars) conditions at three gait speeds. The error bars indicate standard deviations.

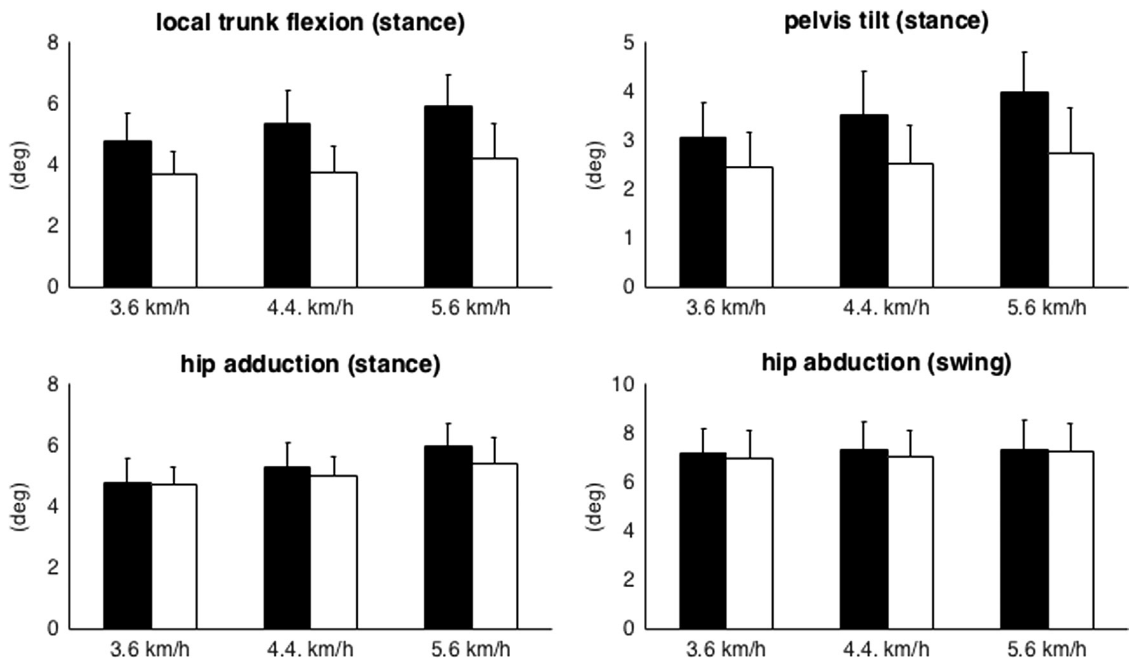

Fig. 4. Group averages of peak-to-peak trunk lateral bending and pelvis tilt and group averages of peak hip adduction in the stance phase and peak hip abduction angles in the swing phase for the reference (black bars) and trunk orthosis (white bars) conditions at three gait speeds. The error bars indicate standard deviations.

as translation in the global coordinate system. Previous studies (Donelan et al., 2004; Veneman et al., 2008) used lateral stabilization of the pelvis level to stabilize movement in the frontal plane. An important difference between lateral stabilization and our approach using a trunk orthosis is the (absence) of mechanical coupling to an external support. Nevertheless, the orthosis also restricted ML trunk kinematics in the global coordinate system. This confirmed that our experimental set-up allowed examining the effect of the trunk kinematics on foot placement and dynamic stability in the frontal plane, while avoiding mechanical effects of the fixation on leg dynamics.

4.2. Step width and dynamic stability

As hypothesized, the decreased ML trunk and whole body COM displacement coincided with narrower steps. The present results in combination with our previous work (Arvin et al., 2016) imply that in gait a reciprocal coupling between trunk kinematics and foot placement in the frontal plane subserves control of stability. This suggests that humans take advantage of the constrained trunk movement, possibly to lower the energy cost of walking by narrowing step width (Donelan et al., 2004; Ijmker et al., 2013). The constant MOS would then suggest that dynamic stability functions as a constraint in optimizing energetic costs. Ijmker et al. (2013) found that lateral pelvis stabilization caused a 24% decrease in step width coinciding with a 6% decrease in energetic costs. It should be noted that the decrease in step width shown here of about 4% was much smaller than this and hence it is unsure whether this would to lead a notable decrease in energy costs.

4.3. Pelvis and hip angles

Walking with the orthosis coincided with a decrease in the downward tilt of the pelvis on the swing side during stance phase of gait. The angular movement of the trunk and pelvis segments are coupled out of phase (Krebs et al., 1992). Possibly, the constrained lateral bending of the trunk due to the orthosis caused the reduction in pelvis drop on the swing side. The changes in pelvis kinematics may have contributed to changes in step width particularly because swing hip abduction angle was not significantly affected by wearing the trunk orthosis.

Conflict of interest statement

The authors declare that there are no conflicts of interest.

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