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Axial pelvis range of motion affects thorax-pelvis timing during gait

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ABSTRACT

During gait, patients with pelvic girdle pain and low back pain demonstrate an altered phase relationship between axial thorax and pelvis rotations (thorax-pelvis relative phase). This could be the result of an increase in axial pelvis range of motion (ROM) which has been observed in these patients as well. To establish this relationship, we investigated if altered axial pelvis ROM during gait affects thorax-pelvis relative phase in 12 healthy subjects. These subjects walked on a treadmill and received real-time feedback on axial pelvis rotations. Subjects were asked to (1) walk normal, and walk with (2) decreased and (3) increased pelvis ROM. Gait speed and stride frequency were matched between trials. Subjects were able to increase pelvis ROM to a large extent, but the reduction in pelvis ROM was relatively small. Walking with large pelvis ROM resulted in a change in thorax-pelvis relative phase similar to that in pelvic girdle pain and low back pain. A forward dynamic model was used to predict the effect of manipulation of pelvis ROM on timing of thorax rotations independent of apparent axial trunk stiffness and arm swing amplitude (which can both affect thorax-pelvis relative phase). The model predicted a similar, even larger, effect of large axial pelvis ROM on thorax-pelvis relative phase, as observed experimentally. We conclude that walking with actively increased ROM of axial pelvis rotations in healthy subjects is associated with a shift in thorax-pelvis relative phase, similar to observations in patients with pelvic girdle pain and low back pain.

1. Introduction

During gait, the relative timing of axial thorax and pelvis rotations ('thorax-pelvis relative phase') changes with gait speed (Huang et al., 2010; Lamoth et al., 2002; Liang et al., 2014). This timing can be affected by pelvic girdle pain (Wu et al., 2008) and low back pain (Huang et al., 2011; Lamoth et al., 2006, 2002). The difference in timing, expressed as *relative phase,* can vary from plus to minus 180 degrees. A value of plus or minus 180 degrees corresponds to perfect out-of-phase (e.g., in the opposite direction) rotation and a value of 0 degrees corresponds to perfect in-phase rotation (Van Emmerik et al., 1999). With timing of thorax rotations expressed relative to the pelvis (i.e., thorax-pelvis relative phase), negative values indicate that thorax rotations lag pelvis rotations.

In healthy individuals, thorax-pelvis relative phase is around minus 20 degrees in slow walking (1 km/h). While speeding up, a shift occurs in timing of pelvis rotations relative to the pendular movements of the legs (henceforward 'pelvis timing') (Huang et al., 2011; Liang et al., 2014; Wu et al., 2014). The timing of the thorax relative to the legs ('thorax timing') does not change with increasing gait speed (Huang et al., 2011; Wu et al., 2008). The shift in pelvis timing while speeding up results in the observed shift in thorax-pelvis relative phase towards minus 150 degrees in fast walking in healthy subjects (Huang et al., 2011; Lamoth et al., 2002; Liang et al., 2014; Wu et al., 2014) (Fig. 1).

In pelvic girdle pain and low back pain, pelvis timing is comparable to that in healthy controls over a wide range of gait speeds (Huang et al., 2011; Prins et al., 2016; Wu et al., 2008). In these pathologies, thorax timing changes with increasing gait speed, resulting in less out-of-phase thorax-pelvis timing at high gait

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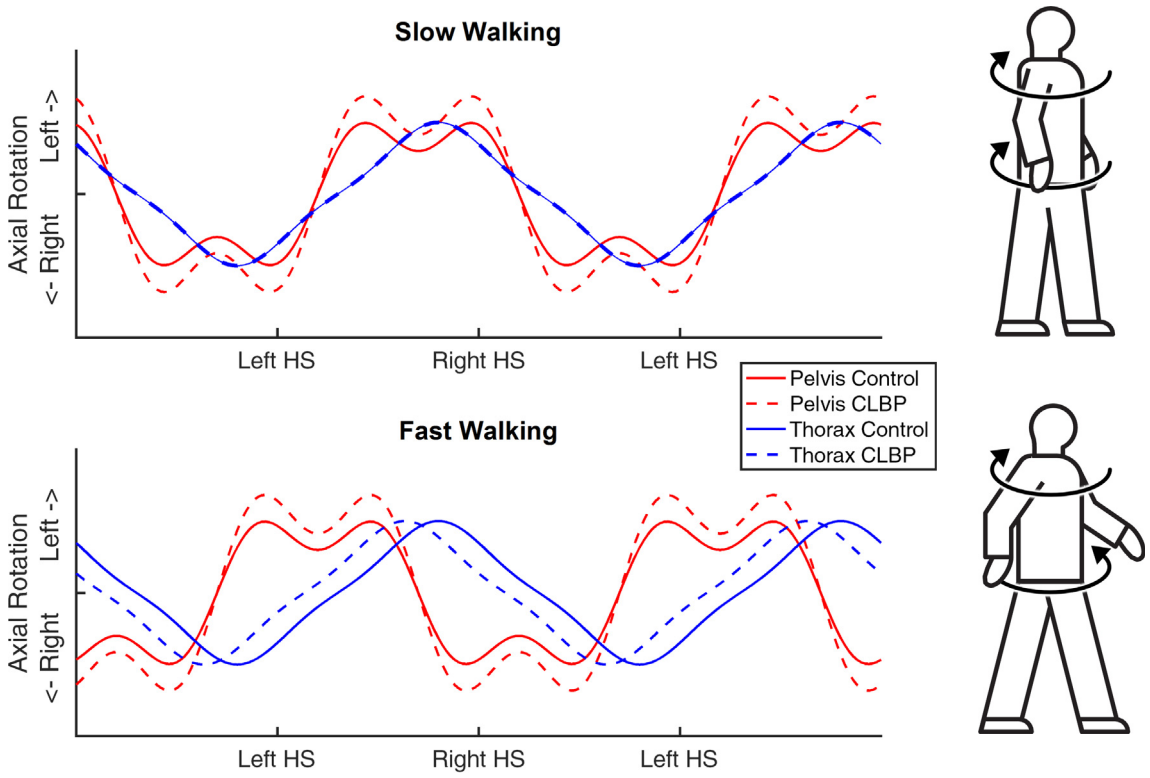

Fig. 1. Amplitude and timing of axial thorax and pelvis rotations during gait, The figure depicts simulated data, based on experimental data from Lamoth et al. (2002), Wu et al. (2008) and Huang et al. (2010). Top: at left heel-strike (HS), the pelvis of a typical healthy subject (red solid line) is rotated to the right (clock-wise as seen from above), almost in-phase with axial thorax rotations (blue solid line). The pelvis of a typical CLBP subject (red dashed line) moves with a larger amplitude but a similar timing relative to the legs and thorax (blue dashed line). Bottom: at high gait speeds, the pelvis of a typical healthy subject is rotated to the left at left heel-strike. Pelvis timing of a typical CLBP at this speed is similar, but again, with a larger amplitude. In healthy subjects, the timing of axial thorax rotations relative to the legs is similar as at low gait speed, now almost out-of-phase with the pelvis. In CLBP patients, the timing of axial thorax rotations is shifted more towards the pelvis at high gait speed, resulting in a smaller thorax-pelvis relative phase than observed in healthy subjects. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

speeds (Huang et al., 2011; Wu et al., 2008). Less out-of-phase thorax pelvis timing at high gait speeds in patients coincides with larger ranges of motion (ROM) of axial pelvis rotations (Huang et al., 2011; Prins et al., 2016; Wu et al., 2008) (Fig. 1).

This study is part of a research program in which we attempt to determine *what* differences exist in intersegmental coordination patterns during gait between healthy subjects and patients, to understand *how* these patterns can be modulated and ultimately understand *why* they are affected in patients (Bruijn et al., 2008; Huang et al., 2010, 2011; Lamoth et al., 2002; Liang et al., 2014; Prins et al., 2019, 2016; Wu et al., 2014). In recent years we have learned how intersegmental coordination of the thorax and pelvis differs between patients and healthy controls at various gait speeds (Huang et al., 2011; Lamoth et al., 2002; Prins et al., 2016; Wu et al., 2008) and identified mechanisms through which thorax-pelvis relative phase at a given gait speed can be modulated (Liang et al., 2014; Prins et al., 2019; Wu et al., 2014). Despite these efforts, the causation of differences in thorax-pelvis relative phase between healthy subjects and patients is still a matter of debate. Arm swing amplitude and apparent axial trunk stiffness were identified as modulators of thorax-pelvis coordination during gait (Prins et al., 2019; Wu et al., 2014), but did not account for differences in thorax-pelvis timing between patients and controls (Huang et al., 2011; Prins et al., 2019, 2016). Hence, these patients appear to reduce thorax-pelvis relative phase at high gait speeds via a different mechanism. Possibly, the altered thorax-pelvis relative phase at high gait speeds in patients is a consequence of a gait strategy with larger axial pelvis ROM (Wu et al., 2008).

The objective of this study was to determine if, and how, the ROM of axial pelvis rotations affects thorax-pelvis timing at relatively high gait speed in healthy subjects. Apparent axial trunk stiffness and arm swing amplitude can modulate thorax-pelvis relative phase and were thus included in the comparison. To evaluate if increased axial pelvis ROM directly causes more in-phase thorax-pelvis timing, a forward dynamic simulation was run in which the observed axial pelvis ROM was manipulated independent of apparent axial trunk stiffness and arm swing amplitude.

Since large axial pelvis ROM during gait has been found to coincide with more in-phase thorax-pelvis timing at high gait speeds in patients (Huang et al., 2011; Lamoth et al., 2002), we hypothesized that walking with larger (actual or simulated) axial pelvis ROM would result in more in-phase thorax-pelvis timing in healthy subjects as well. We expected that such more in-phase thorax-pelvis timing would primarily be the result of changes in thorax timing.

2. Methods

All measurements were performed at the Military Rehabilitation Centre 'Aardenburg' (MRC), Doorn, The Netherlands. The protocol was approved by the ethical committee of the Vrije Universiteit (VU) Amsterdam, The Netherlands. The study was conducted according to the principles of the Declaration of Helsinki.

2.1. Participants

Twelve healthy subjects (9 female, 3 male), with a mean age of 26 (SD 6, range 22–44) years, a mean height of 1.72 (SD 0.09)

meter, and a mean mass of 68 (SD 10) kilograms were recruited by word of mouth among Human Movement Sciences students of the VU, and personnel of the MRC. Exclusion criteria were present injuries and complaints of the lower extremities, cardiovascular problems or other present health related problems that could affect gait ability, such as low back pain and pelvic girdle pain. Subjects with uncorrected visual or auditory impairments were also excluded. Presence of exclusion criteria was checked during a physical examination by a trained physiotherapist (MP) before inclusion. Participants had to visit the MRC on one occasion for testing. All subjects gave written informed consent before the measurements.

2.2. Experimental manipulation of axial pelvis ROM

The Gait Real-time Analysis Interactive Lab (GRAIL) (Motek, Amsterdam, The Netherlands) was used for testing. The GRAIL consists of an instrumented split belt treadmill with a surrounding 210-degrees cylindrical screen. Subjects completed four gait trials of three minutes each at 5 km/h (1.39 m/s) during which a virtual road was projected on the screen in front of them. We selected this speed since we found in pilot work that 5 km/h was a comfortable pace for most subjects. At this relatively high speed significant differences between healthy subjects and patients with pelvic girdle pain (Wu et al., 2008) and low back pain have been observed (Huang et al., 2011; Lamoth et al., 2002). The visual flow matched the speed of the treadmill. During the first trial, subjects received no feedback and were asked to walk normally. The average step frequency of the first trial was imposed in consecutive trials using auditory feedback from a metronome. Since treadmill speed was fixed and stride frequency was imposed, stride length was similar between subjects as well (if they adhered to the imposed frequency). The first minute of each trial was used as familiarisation period. After the first trial, observed axial pelvis rotations were fed back to the subject in real-time using a bar on the screen at eye level of the subject. The orientation of the bar around the anteroposterior axis matched the observed axial pelvis rotation of the subject. Subjects were asked to either try to (1) rotate their pelvis normally, or (2) walk with small pelvis rotations, or (3) walk with large pelvis rotations. These trials will be referred to as the Normal, Small and Large Pelvis ROM Trials respectively. The last three trials were performed in quasi-random order and solely the last two minutes of each trial were used for data analyses. The experimental setup is shown in Fig. 2.

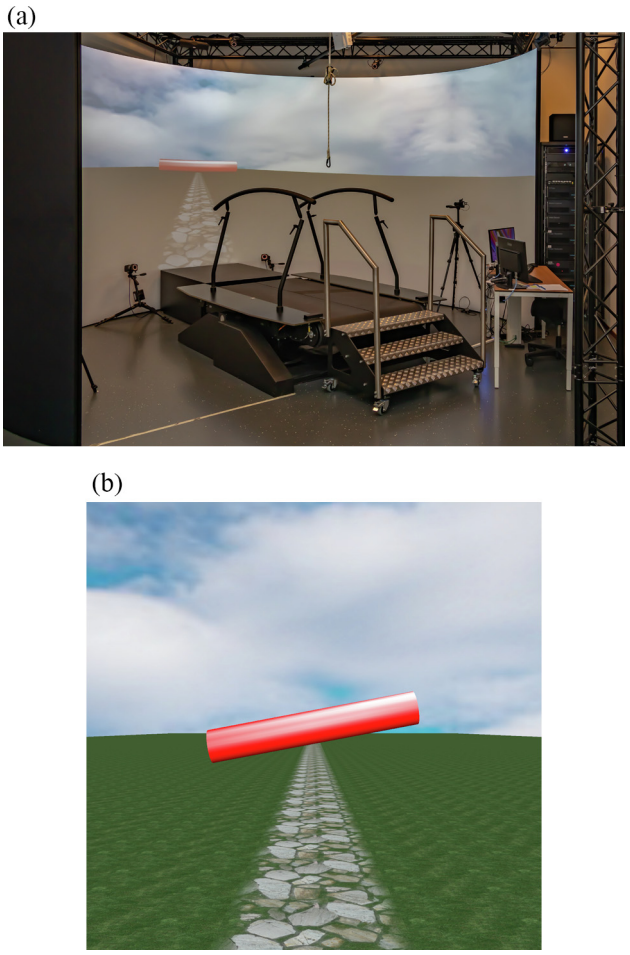

Fig. 2. Experimental setup. Left: The GRAIL on which the measurements took place. Right: The presented feedback during trials. The rotation of the red bar around the anteroposterior axis reflected the axial rotation of the subjects' pelvis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.3. Data collection

Gender, age, body weight, and height of each subject were documented. Reflective markers were placed (Full Body Plug-in Gait model, VICON) by the same trained physiotherapist (MP) for each subject before the trials (Vicon, 2017). During trials, ten infrared cameras (VICON, Oxford, UK) recorded the position of these markers at a rate of 100 samples/s. The motion capture data were analysed on-line using D-Flow Software (Motek) to generate real-time feedback.

2.4. Data analysis

2.4.1. Experimental data

Marker data were low-pass filtered using a 2nd order unidirectional (forward) Butterworth filter with a cut-off frequency of 5 Hz. During the first trial, heel strikes were identified as local peaks in the anteroposterior position of each heel marker. The average time interval between these heel strikes was used to calculate the metronome-imposed step frequency for the next trials. The rotation of the presented pelvis feedback corresponded to the angle between (1) the line connecting the midpoint between both anterior superior iliac spines and the midpoint between both posterior superior iliac spines and (2) the line of progression of the treadmill.

After the measurements took place, marker data were filtered using a 4th order bidirectional (two times 2nd order) low-pass Butterworth filter with a cut-off frequency of 10 Hz. Stride duration was calculated in the same manner as for the on-line analysis. Axial pelvis, thorax and trunk (pelvis relative to thorax) rotations and the position of the centre of mass (COM) of both arms and legs were calculated in agreement with recommendations of the International Society of Biomechanics (Wu et al., 2005, 2002), using the required anthropometric data (de Leva, 1996). Arm and leg swing were defined as the anteroposterior trajectories of the COM of each extremity.

The ROM of axial pelvis, thorax and trunk rotations and arm swing were calculated over each individual stride and then averaged over each trial. The ROM of the anteroposterior trajectories of the COM of both arms was averaged. Intersegmental timing of axial thorax and pelvis rotations, and the anteroposterior movements of the legs was expressed in terms of the relative phase of the frequency response function of these signals at the imposed stride frequency (Prins et al., 2019), resulting in three relative phases (thorax-leg, pelvis-leg, thorax-pelvis) per subject for each trial. To establish an overall time base of the combined movements of both legs, the ROM of the anteroposterior trajectories of the COM of the legs were combined for this analysis (right leg minus

left leg). A relative phase of minus and plus 180 degrees corresponded to perfect out-of-phase movement and 0 degrees to perfect in-phase movement of two segments. A negative or positive value means, respectively, that the first segment (e.g. 'thorax' in 'thorax-pelvis') is lagging or leading the second.

Using top-down inverse dynamics, the net trunk moment (i.e., between thorax and pelvis, about the vertical axis of L5S1) was calculated (Hof, 1992). Apparent axial trunk stiffness and damping of each trial of each subject were estimated by fitting a forward dynamic model (Prins et al., 2019) of which further details are discussed below. All trunk kinetics (i.e. moment, stiffness and damping) were normalized to subject height and body weight and arm swing ROM was normalized to subject height to correct for anatomical differences between subjects (Hof, 1996).

2.4.2. Simulated data

We used a forward dynamic model to simulate the effect of manipulated axial pelvis ROM on thorax timing independent of trunk kinetics and arm swing amplitude. The details of the model and this procedure are published elsewhere (Prins et al., 2019). In brief, the model predicts axial (around L5S1) thorax rotations from observed axial pelvis rotations, arm swing moment and thorax inertia. Axial trunk stiffness and damping are estimated using an optimization procedure that minimizes the root mean square error between predicted and observed axial thorax rotations. First, the model was used to estimate apparent axial trunk stiffness and damping of each subject during each trial (Fig. 3). Then, to predict the independent effect of manipulated axial pelvis ROM on thorax timing, the model was run again with the observed arm swing and estimated apparent trunk stiffness and damping from the Normal Pelvis ROM Trial, while axial pelvis rotations were obtained from the Large Pelvis ROM Trial for each subject (Fig. 4). Because the effect of the Small Pelvis ROM Trial on actual pelvis ROM was relatively small (see Section 3), we refrained from simulating the effect of walking with small pelvis ROM. The observed time-series from the Normal and Large Pelvis ROM Trial were synchronised to percentage of gait cycle by manipulating the time domain of the pelvis rotations of the Large Pelvis ROM Trial, based on left

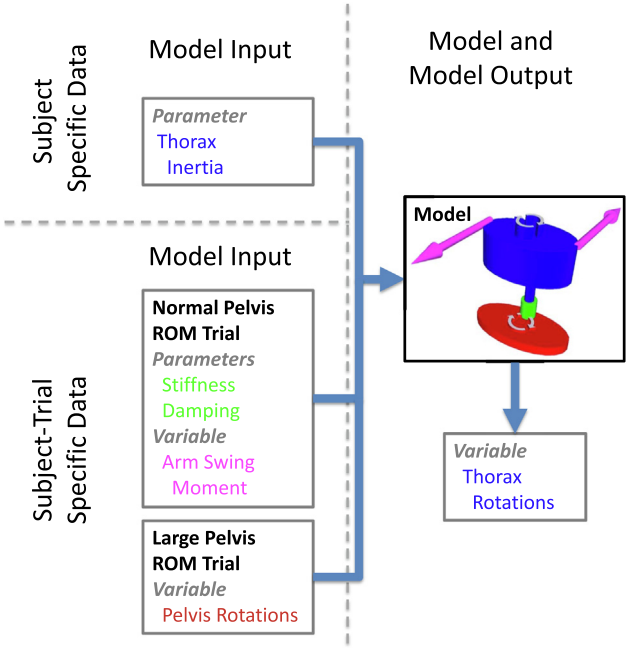

Fig. 4. Simulation of walking with increased axial pelvis ROM using a forward dynamic model, The forward dynamic model was used to predict the effect of walking with large pelvis ROM on axial thorax rotations for each subject by using estimated stiffness and damping and observed arm swing moment of the Normal Pelvis ROM Trial and axial pelvis rotations of the Large Pelvis ROM Trial.

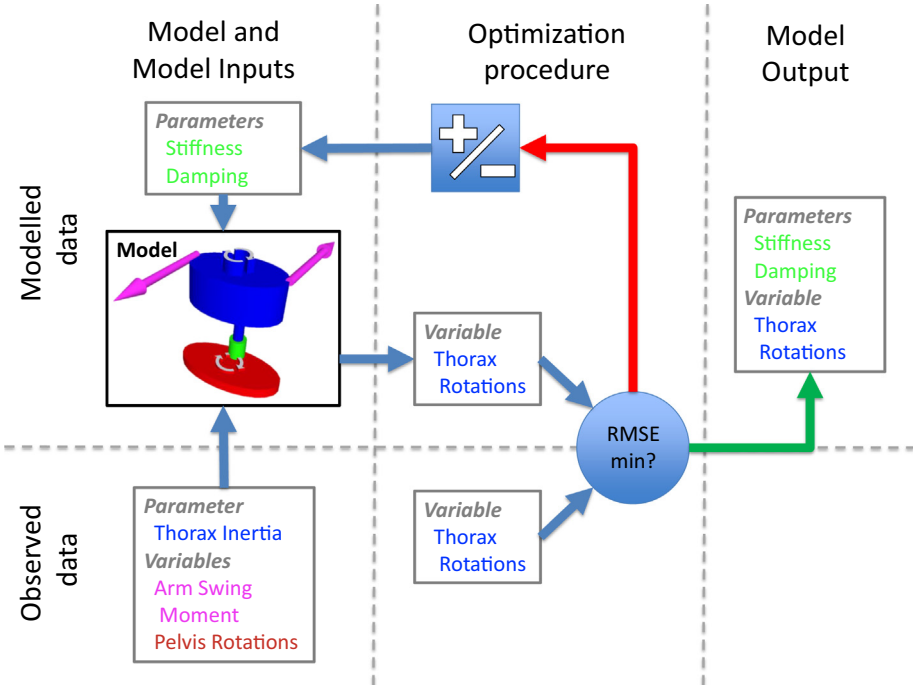

Fig. 3. Estimation of apparent axial trunk stiffness and damping using a forward dynamic model, For each trial of each subject, the apparent axial trunk stiffness and damping were estimated using a forward dynamic model. The model predicted axial thorax rotations based on experimentally obtained thorax inertia, arm swing moment and pelvis rotations. Using an initial guess for stiffness and damping, the model predicted axial thorax rotations. These rotations were compared to observed rotations by calculating the root mean square error (RMSE). Then, stiffness and damping were adjusted and the model was run again. This iterative process was repeated until a minimum in RMSE was obtained.

heel strikes. In other words, left heel strikes of all time-series, as used as input for the model occurred at the same instance.

2.5. Statistical analysis

The alpha level was set to 0.05 for all analyses. Because some of the statistical tests required circular statistics, we refrained from using repeated measures analyses. All comparisons were performed between the Normal and Small Pelvis ROM Trial and between the Normal and Large Pelvis ROM Trial.

First, we checked whether our manipulations were successful by comparing the axial pelvis ROM and stride frequency between trials using paired sample t-tests. The same test was used to compare linear outcomes (ROMs and trunk kinetics) between trials. Circular outcomes (relative phases) were compared between conditions using 'circ_mtest.m' from the circular statistics toolbox (Berens, 2009). This function is the circular equivalent of a one sample *t*-test. The difference in relative phase between two paired samples (i.e. thorax-pelvis relative phase of the Large minus that of the Normal Pelvis ROM Trial) was used as input. The function calculates if this difference significantly deviates from zero for a given alpha value (Zar, 1999). The function was run multiple times until the lowest alpha level, with three decimals yielding a significant difference. This alpha level was documented as the p-value. All statistical analyses were performed in MATLAB 2018A (The MathWorks, Inc. Natick, MA).

3. Results

3.1. Experimental manipulations

Compared to the Normal Pelvis ROM Trial, subjects succeeded in reducing axial pelvis ROM in the Small Pelvis ROM Trial (mean difference −1.5 degrees) and in increasing pelvis ROM in the Large Pelvis ROM Trial (mean difference + 13.7 degrees) (Table 1). The difference in stride frequency, and hence stride length, between the Normal and Small Pelvis ROM Trial was small (0.02 Hz) but significant. The stride frequency did not significantly differ between the Normal and Large Pelvis ROM Trial.

3.2. Effect of experimental manipulation of axial pelvis ROM on Thorax-Pelvis timing

Below, two individual examples of the effect of the experimental manipulation of axial pelvis ROM on thorax-pelvis timing are presented for illustrative purposes, followed by the overall results.

3.2.1. Individual examples

The axial segmental rotations of one subject are displayed in the two upper panels of Fig. 5. In this subject, axial pelvis ROM was 10.3 degrees in the Normal Pelvis ROM Trial, slightly smaller in the Small Pelvis ROM Trial (9.6 degrees) and much larger in the Large Pelvis ROM Trial (28.1 degrees). Axial thorax-pelvis relative phase was considerably different between the Normal and Large Pelvis ROM Trial (−103 and −18 degrees respectively), which appeared to be mainly associated with a difference in thorax-leg relative phase (−144 vs −40 degrees) and not pelvis-leg relative phase (−40 vs −21 degrees). Not all subjects demonstrated a large difference in thorax-pelvis relative phase between the Normal and Large Pelvis ROM Trial, as can be seen in the lower two panels of Fig. 5. In this subject, increased pelvis ROM (12 degrees difference) in the Large Pelvis ROM Trial coincided with a small difference in thorax-pelvis relative phase (3 degrees difference).

3.2.2. Overall results

Compared to the Normal Pelvis ROM Trial, axial thorax-pelvis relative phase was not significantly different in the Small Pelvis ROM Trial, but significantly more in-phase in the Large Pelvis ROM Trial (Table 2). Note that this latter difference (52 degrees difference) appeared to be mainly associated with a difference in thorax timing (45 degrees difference) and not pelvis timing (8 degrees difference), however, neither of these two reached significance. Compared to the Normal Pelvis ROM Trial, the ROM of axial thorax and trunk rotations were significantly smaller in the Small Pelvis ROM Trial and larger in the Large Pelvis ROM Trial.

3.3. Effect of experimental manipulation of axial pelvis ROM on arm swing ROM and axial trunk kinetics

3.3.1. Individual example

The axial trunk kinetics of one subject are displayed in Fig. 6. Compared to the normalized apparent axial trunk stiffness of the Normal Pelvis ROM Trial (0.069 *unitless*), the stiffness was higher in the Small Pelvis ROM Trial (0.083 *unitless*) and lower in the Large Pelvis ROM Trial (0.038 *unitless*). Note that a decrease in axial trunk stiffness *alone* (i.e., if axial pelvis ROM and anteroposterior arm swing ROM would be identical between trials) would result in more out-of-phase thorax-pelvis timing (Prins et al., 2019), whereas this subject demonstrated more in-phase thorax-pelvis timing in the trial with the lowest axial trunk stiffness (i.e., the Large Pelvis ROM Trial). A consistent result was found for the Small Pelvis ROM Trial, i.e., changes in the opposite direction. Although apparent axial trunk stiffness was lower in the Large than in the Normal Pelvis ROM Trial, the normalized trunk moment amplitude was larger in the Large Pelvis ROM Trial (Normal 0.007, Large 0.011 *both unitless*). This could be the result of the relatively large trunk excursions; as trunk moment is a product of apparent axial trunk stiffness and axial trunk angle.

3.3.2. Overall results

Arm swing ROM was significantly smaller in the Small compared to the Normal Pelvis ROM Trial, but not significantly different between the Normal and Large Pelvis ROM Trial (Table 3). Apparent axial trunk stiffness was significantly lower in the Large

Table 1
Evaluation of the success of experimental manipulations.

	Normal Pelvis ROM Trial	Small Pelvis ROM Trial		Large Pelvis ROM Trial	
	Avg (SD)	Avg (SD)	p[¥]	Avg (SD)	p[¥]
Pelvis ROM (deg)	9.8 (4.6)	**8.3 (4.0)**	**.005**	**23.5 (8.7)**	**<.001**
Stride Frequency (Hz)	0.98 (0.03)	**1.00 (0.04)**	**.003**	0.98 (0.03)	.09

ROM = Range of Motion.
SD = Standard Deviation.
[¥] = Compared to the Normal Pelvis ROM Trial.

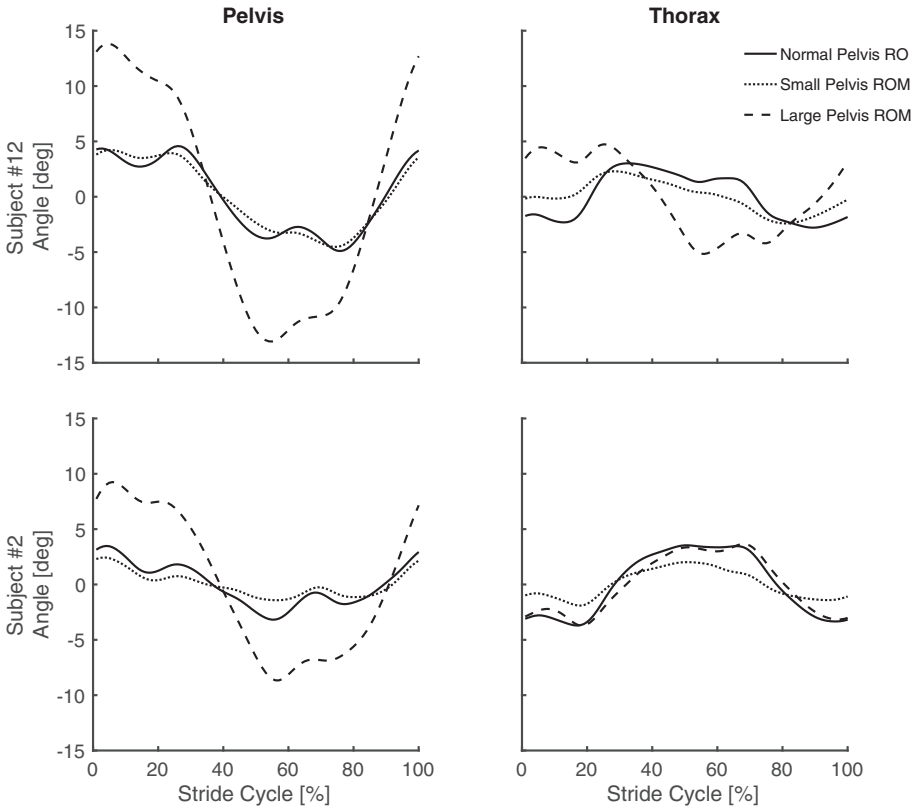

Fig. 5. Two individual examples of axial pelvis and thorax rotations in the Normal, Small and Large Pelvis ROM Trial, Each graph displays segmental movements averaged over strides of each trial. The horizontal axis runs from right heel strike (0%) to right heel strike (100%). The vertical axis of the two graphs displays the axial rotation of pelvis and thorax. A positive value for pelvis or thorax rotation corresponds to a counter-clockwise rotation, as seen from above.

Table 2
Effects of experimental manipulation of pelvis ROM on (inter)segmental ROM and timing.

	Normal Pelvis ROM Trial	Small Pelvis ROM Trial		Large Pelvis ROM Trial	
	Avg (SD)	Avg (SD)	p[¥]	Avg (SD)	p[¥]
Relative Phase					
Thorax–Pelvis (deg[§])	−89 (44)	−82 (37)	.50	**−37 (46)**	**.03**
Thorax–Leg (deg[§])	−146 (32)	−139 (31)	.19	−101 (68)	.09
Pelvis–Leg (deg[§])	−42 (39)	−48 (29)	.96	−34 (42)	.72
ROM					
Thorax (deg[§])	7.1 (1.3)	**5.6 (1.1)**	**.005**	**14.2 (7.2)**	**.008**
Trunk (deg[§])	11.6 (3.4)	**8.9 (3.5)**	**<.001**	**19.5 (3.1)**	**<.001**

ROM = Range of Motion.
SD = Standard Deviation.
[¥] = Compared to the Normal Pelvis ROM Trial.
[§] Note that degrees relative phase is a description of phase shift and degrees ROM is a description of segmental orientation.

compared to the Normal Pelvis ROM Trial, but not significantly different between the Normal and Small Pelvis ROM Trial. Trunk moment amplitude was significantly lower in the Small and larger in the Large Pelvis ROM Trial compared to the Normal Pelvis ROM Trial.

3.4. Effect of simulated large axial pelvis ROM on thorax-pelvis timing

Forward dynamic simulation of an increase of pelvis ROM of the Normal Pelvis ROM Trial, keeping arm swing and axial trunk stiffness constant, resulted in significantly more in-phase thorax-pelvis timing ($p = .001$) (Table 4). In contrast to the experimental Large Pelvis ROM Trial, trunk ROM was not significantly affected by a simulated increase in axial pelvis ROM ($p = .43$).

4. Discussion

The objective of this study was to assess if the ROM of axial pelvis rotations has an impact on thorax-pelvis timing during gait in healthy subjects. As hypothesized, we found that an experimentally induced increase in axial pelvis ROM resulted in more in-phase thorax-pelvis timing in healthy subjects. This was mainly associated with a change in thorax timing and not in pelvis timing, which is similar to the coordination pattern observed in pelvic

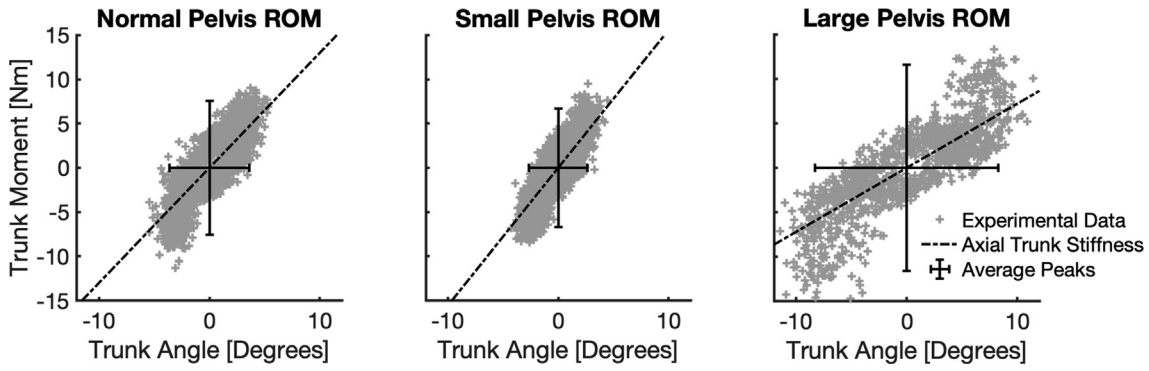

Fig. 6. Example of apparent axial trunk stiffness in the Normal, Small and Large Pelvis ROM Trial in one subject, Grey scatter plots of trunk angle (horizontal axis) and trunk moment (vertical axis) of each trial of one subject. The slope of the dashed black line is the apparent axial trunk stiffness. Apparent axial trunk stiffness was estimated using a forward dynamic model; it is not the regression line of the actual data. The solid black bars represent the average trunk ROM (horizontal) and trunk moment amplitude (vertical).

Table 3
Effects of experimental manipulation of pelvis ROM on trunk kinetics.

	Normal Pelvis ROM Trial	Small Pelvis ROM Trial		Large Pelvis ROM Trial	
	Mean (SD)	Mean (SD)	p[¥]	Mean (SD)	p[¥]
Arm Swing ROM[§] * 10^2	1.17 (0.24)	**0.80 (0.30)**	**<.001**	1.29 (0.21)	.21
Trunk Kinetics					
Apparent Stiffness[§§] * 10^2	4.39 (1.58)	4.49 (1.89)	.54	**3.06 (1.04)**	**.004**
Moment Amplitude[§§] * 10^3	6.46 (0.99)	**5.17 (1.36)**	**<.001**	**7.75 (1.83)**	**.03**

ROM = Range of Motion.
SD = Standard Deviation.
[¥] = Compared to the Normal Pelvis ROM Trial.
[§] = Normalized for subject height (m).
[§§] = Normalized for subject height (m) and weight (N).

Table 4
Effects of a simulated increase of pelvis ROM on (inter)segmental ROM and timing and trunk kinetics.

	Experimental Normal Pelvis ROM Trial Mean (SD)	*Simulated* Large Pelvis ROM Trial Mean (SD)	p
ROM[¥]			
Pelvis (deg[§])	9.8 (4.6)	**23.3 (8.8)**[*]	**<.001**
Thorax (deg[§])	7.1 (1.3)	**21.6 (7.9)**	**<.001**
Trunk (deg[§])	11.6 (3.4)	11.8 (3.6)	.43
Relative Phase[¥]			
Thorax–Pelvis (deg[§])	−89 (44)	**−9 (17)**	**.001**
Thorax–Leg (deg[§])	−146 (32)	**−44 (56)**	**.003**

ROM = Range of Motion.
SD = Standard Deviation.
[*] = Note that this value is derived from actual axial pelvis rotations in the Large Pelvis ROM Trial, see methods.
[¥] = Pelvis timing, arm swing amplitude and axial trunk stiffness were not manipulated between trials and therefore not reported in this table.
[§] Note that degrees relative phase is a description of phase shift and degrees ROM is a description of segmental orientation.

girdle pain (Wu et al., 2008) and low back pain (Huang et al., 2011; Prins et al., 2016).

More in-phase thorax-pelvis timing in the Large Pelvis ROM Trial coincided with a lower apparent axial trunk stiffness. At first glance, this appears to contradict the findings of our previous simulation study where we found that a lower apparent axial trunk stiffness results in more out-of-phase thorax-pelvis timing (Prins et al., 2019). However, since the simulation of walking with large Pelvis ROM without altering axial trunk stiffness resulted in an even larger shift in thorax-pelvis timing than observed in the experimental data, the increase in pelvis ROM and the reduction in apparent axial trunk stiffness had opposite effects on thorax-pelvis timing. The effect of increased pelvis ROM (more in-phase thorax-pelvis timing) was larger than the effect of reduced apparent trunk stiffness (more out-of-phase thorax-pelvis timing), resulting in a net shift towards in-phase thorax-pelvis timing. The reduction in stiffness *limited* the effect of pelvis ROM on thorax-pelvis timing in that trial. This raises the question how pelvis ROM can affect thorax-pelvis timing independent of apparent axial trunk stiffness. In a second order system, the timing between two segments (i.e., thorax and pelvis in our paradigm) depends on the oscillation frequency of the driving segment, not on the oscillation amplitude. However, the balance of forces of the arms acting on the thorax and of forces produced by lumbar connections with the pelvis changes when pelvis amplitude changes, causing an effect of pelvis amplitude on thorax timing. With a small pelvis ROM, thorax timing is mainly driven by arm swing, whereas the effect of pelvis rotation on thorax timing increases with increasing axial pelvis ROM.

The increase in axial trunk ROM and reduced apparent trunk stiffness in the Large Pelvis ROM Trial has not been observed in low back pain patients (Huang et al., 2011; Lamoth et al., 2002; Prins et al., 2019, 2016). Forward dynamic simulation of increased axial pelvis ROM without manipulating axial trunk stiffness (i.e., as observed in low back pain), resulted in more low-back-pain-like

behaviour; more in-phase thorax-pelvis timing with no significant change in ROM of axial trunk rotations. Probably, the mechanism that causes patients to walk with larger pelvis ROM is different than that of healthy subjects who intentionally alter pelvis ROM.

The next step to better understand altered axial thorax-pelvis coordination in patients, is to discover why and how patients with low back pain walk with increased pelvis ROM. It has been hypothesized that a reduction in step length as a result of limited hip flexion mobility (with an extended knee as in the straight leg raise test) would be compensated by increased axial pelvis ROM (Wu et al., 2008). However, the contribution to step length of increased pelvis rotations is small (Liang et al., 2014), so it is questionable if patients would choose this strategy to increase step length. Possibly, the increased passive elastic contribution of hip extensors that was found in low back pain patients (Hines et al., 2018) causes pelvis ROM to increase during gait, as this would affect hip moments.

Subjects went to great extents to achieve a relatively small reduction of axial pelvis ROM: arm swing amplitude was reduced by 31%, thorax ROM by 19% and trunk ROM by 25%, coincident with a reduction in pelvis ROM of only 14% (1.5 degree). This reduction in axial pelvis ROM is small compared to the standard deviation of pelvis ROM between subjects in the Normal Pelvis ROM Trial (4.6 degrees). If one subject has a 'natural' axial pelvis ROM of 5 degrees and another subject of 15 degrees, one may expect that the subject with small natural pelvis rotations can achieve 15 degrees, but apparently the subject with large natural pelvis rotations cannot achieve an amplitude close to 5 degrees. These results could indicate that the lower limit in axial pelvis ROM is restricted by anatomical constraints, such as hip mobility, pelvic width or leg weight.

This study has some limitations that need to be addressed. First, the difference in pelvis ROM between the Normal and Large Pelvis ROM Trial was considerably larger than between healthy controls and patients with pelvic girdle pain and low back pain. If the relation between pelvis ROM and thorax-pelvis timing is not linear, effects could be considerably different in patients. Second, walking with larger pelvis ROM did not result in a shift in thorax-pelvis timing in all subjects. This could indicate that mediators exist between these two variables that we did not measure. Third, there is a limitation in comparing mechanisms of active intentional change of pelvis ROM and changes in pelvis ROM resulting from a disorder. Finally, tests were performed on a treadmill and thus, results cannot necessarily be extrapolated to natural overground walking. Performing similar research overground can be challenging because timing of axial pelvis rotations is affected by gait speed and therefore, walking speed should be controlled.

Given the results of the present study future research may have to focus on the cause of increased pelvis range of motion during gait in low back pain instead of the cause of altered timing of thorax rotations.

5. Conclusion

Walking with actively increased ROM of axial pelvis rotations in healthy subjects is associated with a shift in thorax-pelvis relative phase, similar to observations in patients with pelvic girdle pain and low back pain. These findings shift the focus for future research from finding causes of altered thorax timing during gait in these patients toward finding causes of increased pelvis ROM.

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Authors' contributions

MRP co-designed the study, carried out the measurements and data analysis, was involved in the interpretation of data, and drafted the manuscript; LEC was involved in the data analysis, the interpretation of data and drafting the manuscript; OGM was involved in the interpretation of data and drafting of the manuscript; PvdW was involved in the interpretation of data and drafting of the manuscript; SMB co-designed the study, was involved in the data analysis, the interpretation of data and drafting of the manuscript; JHvD co-designed the study, was involved in the interpretation of data and drafting of the manuscript. All authors gave final approval for publication.

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Declaration of Competing Interest

The authors declare no competing financial and personal relationships with other people or organizations.

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