A Preliminary Study into the Effects of Pelvic Rotations on Upper Body Lateral Translation

Andrew Pennycott*, Dario Wyss*†, Heike Vallery*‡ and Robert Riener*†
*Sensory-Motor Systems Lab, ETH Zürich, Switzerland
Email: andrew.pennycott@hest.ethz.ch
†University Hospital Balgrist, Medical Faculty, University of Zürich, Switzerland
‡Biomechanical Engineering, Technical University of Delft, the Netherlands

***Abstract*—An understanding concerning the roles of the various degrees of freedom of the human body during functions such as walking is crucial to the design of robotic devices for rehabilitation. However, the function of the three rotational degrees of freedom of the pelvis during walking remains uncertain. Theories have been previously presented postulating a role of pelvic obliquity in reducing vertical movements of the body's centre of mass, and therefore in minimising energy expenditure, but these are not fully supported by empirical evidence.**

In this paper, an alterative role of pelvic obliquity in reducing lateral movements of the upper body is proposed. Through the application of a robotic orthosis platform, a variety of walking conditions are tested with different levels of pelvic rotation and lateral movement of the upper body.

The presence of the robotic device significantly reduces the degree of pelvic obliquity. Though the data show no significant relationship between the pelvic angles and lateral movement, a trend for decreasing upper body movement with increasing pelvic obliquity is apparent.

I. Introduction

The roles of the various degrees of freedom (DoF) inherent to gait are of crucial importance to the design of robotic devices for rehabilitation, such as those employed in robot-assisted gait training. One of the most fundamental and influential design decisions is which degrees of freedom to permit and which to omit or limit. Though more robotic degrees of freedom, for instance, at the pelvis, may promote a more natural gait pattern and also give rise to a more challenging training platform, the extra actuators and joints can make the resulting device heavier, less transparent, more difficult to control and more expensive. A fundamental understanding of the roles of the various DoF is therefore relevant to the design and implementation of robot-driven gait orthoses.

The traditional view of pelvic obliquity - the rotation of the pelvis about the longitudinal axes of walking - is that it reduces the degree of vertical excursion of the centre of mass (COM), thereby reducing energy expenditure. In the classic work by Saunders [1], six 'determinants' of gait were identified, and these were said to serve the purpose of reducing lateral and vertical movements of the body. Similarly, Inman [2] suggests a role of obliquity in lowering the degree of vertical movement of the centre of mass as the trunk passes over the stance leg. However, experimental studies have shown that while the degree of list affects the mean position, vertical movements of the upper body are not diminished, and can even be slightly increased by obliquity [3]. Indeed, subsequent studies have demonstrated stronger roles of leg length, foot rocker radius and step length in determining the degree of vertical excursion of the centre of mass [4]. The latter study highlighted that the relative timing between the vertical movement of the trunk and pelvic list prevents the latter from having a significant effect in reducing the levels of vertical movement. The lack of a major influence of pelvic obliquity on vertical movements was, moreover, corroborated by the study of Croce *et al* [5].

Although a simulation study pointed to a significant cost of raising the COM in single support [6], in one series of experiments [7], subjects using flexed knees to 'flatten' their gait and produce less vertical oscillation of the COM needed higher metabolic energy expenditure during walking. The authors suggest a role of vertical movements in allowing exchange between kinetic and potential energy at different stages of the gait cycle. Similarly, although subjects in another study could reduce the displacement of the centre of mass using shorter strides and a bent knee gait, this reduction did not produce reductions in energy expenditure or mechanical work at the joints [8]. Optimal energy expenditure, therefore, does not follow from simply minimising the movements of the COM.

In this paper, a role of pelvic obliquity in reducing lateral movement of the upper body is proposed. This hypothesis is tested through an experimental protocol utilising a robotic orthosis platform. A variety of conditions in terms of pelvic rotations and upper body movement are provoked during walking, allowing the relationships between the different degrees of freedom to be explored.

II. Methods

A. Definition of Pelvic Rotations

The body-fixed frame of the pelvis is shown in figure 1, and consists of longitudinal, lateral and vertical axes, respectively denoted as x'', y'' and z''. The orientation of these with respect to the inertial frame (which has axes x, y and z) is given by a series of rotations of the pelvis. These are usually referred to as obliquity (θ_{obl}), tilt (θ_{tilt}) and transverse rotation (θ_{rot}), which roughly correspond to the familiar engineering terms roll, pitch and yaw.

The final orientation of an object described by such Euler angles is dependent on the order of the rotations. However,

978-1-4673-6024-1/13/$31.00

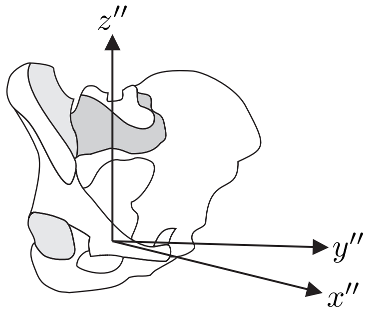


Fig. 1. Body-fixed frame of pelvis.

there is no universally accepted order of rotations concerning the orientation of the pelvis, and therefore, no accepted precise mathematical definition for the different degrees of freedom of the pelvis. The convention used in many human movement studies e.g. [9] and commercial software is the sequence tilt, obliquity and transverse rotation (TOR). However, this can lead to values that do not reflect the clinical concept of obliquity [10]: the inclination of the line joining the two hips with respect to the transverse plane. For example, if the TOR convention is used, tilt and transverse rotations can produce an apparent level of obliquity even if the pelvis is level with respect to the transverse plane. Consequently, the convention suggested by Baker [10] of rotation, obliquity and tilt (ROT) is used in this study. Table I gives the resulting definition of the various rotational degrees of freedom of the pelvis.

Angle	Description
Transverse rotation	Rotation about the z-axis.
Obliquity	Rotation about the the x'-axis.
Tilt	Rotation about the y''-axis.

TABLE I
DEFINITION OF PELVIC ROTATION ANGLES.

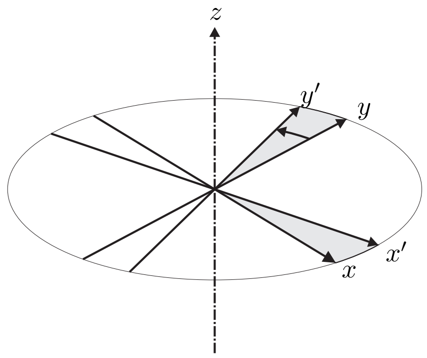
Figure 2 provides an illustration of the sequence of pelvic rotations used in this study. The first rotation, transverse rotation, consists of a rotation θ_{rot} about the the inertial z-axis. This is followed by obliquity, a rotation θ_{obl} about the new axis x'. Lastly, pelvic tilt is a rotation θ_{tilt} about the axis y''.

B. Proposed Role of Pelvic Obliquity

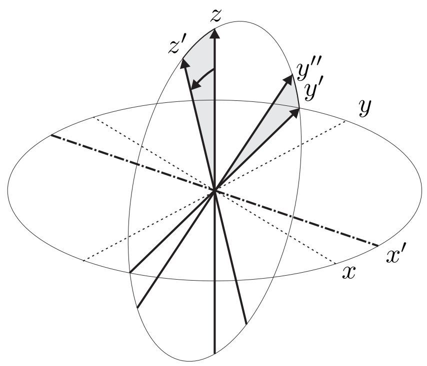
In this paper, it is hypothesised that pelvic obliquity can reduce the level of upper body lateral translation since, depending on the relative phase of the two movements, the rotation about the longitudinal axis can translate the upper body relative to the lateral position of the pelvis. Figure 3 illustrates the relationship between the lateral translation of the upper body, y_u, the lateral translation of the pelvis, y_p, the relative translation, y_r and the pelvic obliquity (list), θ_{obl}.

y_u is related to y_p and θ_{obl} through the equation

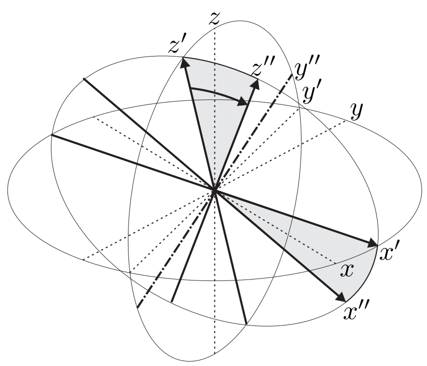
$$y_u = y_p - r\sin\theta_{\text{obl}} \qquad (1)$$



(a) Transverse rotation, θ_{rot}, about z



(b) Obliquity, θ_{ob}, about x'



(c) Tilt, θ_{tilt}, about y''

Fig. 2. Order of pelvic rotations.

which, for small angles, can be approximated as

$$y_u = y_p - r\theta_{\text{obl}}. \qquad (2)$$

C. Experimental Procedure

Four able-bodied subjects walked on a treadmill, both in a robotic orthosis device and also unconstrained. The characteristics of the subjects are included in table II. In each case, the participants walked for approximately two minutes with different step widths - narrow, normal and wide - in order to elicit different levels of pelvic rotations. The combination of these two factors thus gave rise to a total of six conditions, as shown in in table III. The six conditions were applied in random order.

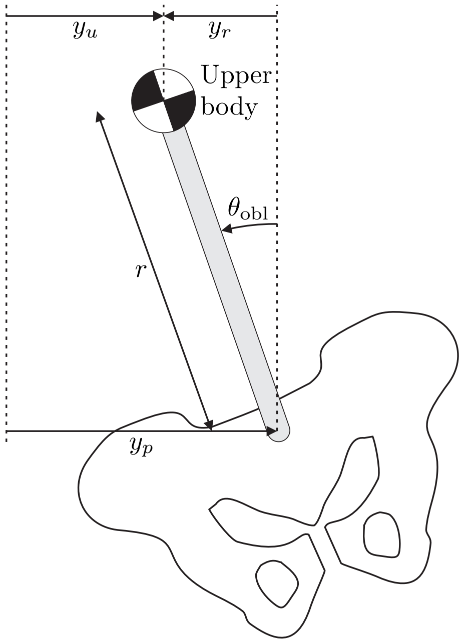


Fig. 3. Proposed role of pelvic obliquity in reducing lateral excursion of the upper body.

Subject	Gender	Mass (kg)	Height (cm)
A	M	57	170
B	M	72	180
C	M	65	192
D	F	75	182

TABLE II
SUBJECT CHARACTERISTICS.

Movements in six degrees of freedom were measured at the pelvis and upper body using two devices located at different positions on the body. The sensor corresponding to the pelvic level was mounted at the sacrum, while the upper body sensor was attached at the T4 vertebra level. The recordings allowed calculation of the levels of pelvic obliquity, tilt and lateral translation at each time point. The overall experimental setup is shown in figure 4.

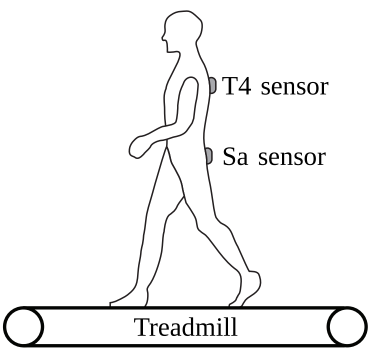


Fig. 4. Experimental setup. Subjects walk uncontrained or in a robotic orthosis device (not shown) at different step widths, with movements in six degrees of freedom measured at T4 and Sa levels.

Condition	Step width	Robotic Orthosis
1	Narrow	No orthosis
2	Normal	No orthosis
3	Wide	No orthosis
4	Narrow	Orthosis
5	Normal	Orthosis
6	Wide	Orthoses

TABLE III
DESCRIPTION OF EXPERIMENTAL CASES.

D. Hardware

The treadmill employed was a Mercury model (h/p cosmos, Nussdorf-Traunstein, Germany). This treadmill is equipped with two Kistler force plates, which each have four force sensors, allowing the centre of pressure (CoP) to be computed for each step [11]. The robotic orthosis device used in this study was a research version of the Lokomat (Hocoma, Volketswil, Switzerland) [12]. The Lokomat provides support in the sagittal plane through an exoskeleton powered by linear actuators which control the angles at the hip and knee joints. In the specific research version of the device used in this study, lateral translation of the pelvis is permitted along with abduction and adduction of the hip joint, but pelvic rotations are constrained. Movements in six degrees of freedom at the pelvis and upper body were measured using two Valedo units (Hocoma, Volketswil, Switzerland).

E. Data Analysis

All data analysis was performed using MATLAB (Mathworks, Natick, MA, U.S.). Using the centre of pressure recordings, the data were partitioned into individual step cycles using the peak values of the longitudinal position of the CoP [13]. For each gait cycle, the range of the given variable (such as pelvic obliquity) within that gait cycle was evaluated, allowing the mean range of the variable to be calculated for that condition. This is illustrated in figure 5.

Acceleration data were transformed into the inertial frame, and was then integrated in two stages to produce the lateral positions of the pelvis and upper body. In order to remove high frequency noise and drift effects, the resulting position data were filtered with a second order Butterworth filter of bandpass 0.5 to 25 Hz.

In order to assess the effects of the orthoses and step width on pelvic obliquity, a two-way analysis of variance (ANOVA) was performed. Secondly, to determine the relationships between the pelvic rotations and translations and upper body lateral translation, a linear regression on upper body translation was carried out.

III. RESULTS

Results concerning the ANOVA are presented in table IV. A significant effect of the orthoses on pelvic obliquity is present, whilst the step width factor did not significantly influence the degree of obliquity. Figure 6 illustrates the levels of obliquity observed at different levels of step width, for walking performed with and without the robotic orthosis platform.

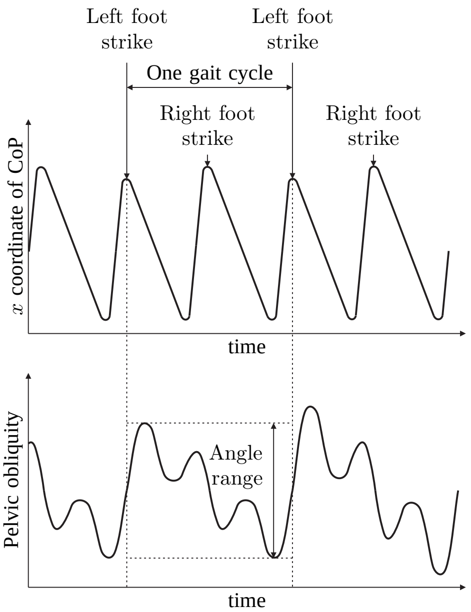


Fig. 5. Data partitioning into individual gait cycles using the center of pressure (CoP) to compute angle ranges.

Factor	p-value
Step width	0.490
Presence of orthoses	< 0.001
Interaction: step-width $\times$ orthoses	0.654

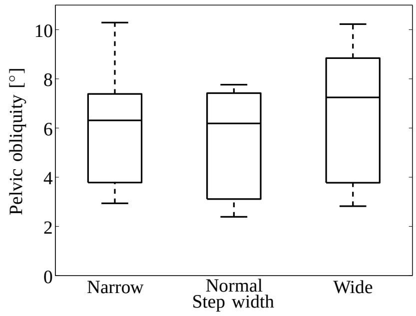
TABLE IV
ANOVA RESULTS: p-VALUES FOR STEP WIDTH AND PRESENCE OF ROBOTIC ORTHOSES.

Results from the linear regression analysis are provided in table V. The regression coefficients for the relationships between the lateral movement of the upper body and the movements of the pelvis - lateral translation and the three rotational degrees of freedom - are provided, along with 95% confidence intervals (CI). Only the lateral translation of the pelvis was significantly related to the lateral movement of the upper body at the 95% confidence level.

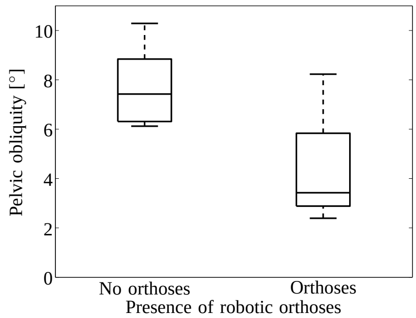
Variable	Regression coefficient	CI lower bound	CI upper bound
Intercept	2.72×10^{-2}	1.92×10^{-3}	5.26×10^{-2}
y_p	1.08×10^{0}	4.65×10^{-1}	1.69×10^{-1}
θ_{obl}	-6.55×10^{-3}	-1.33×10^{-2}	2.75×10^{-3}
θ_{tilt}	-4.75×10^{-4}	-3.70×10^{-3}	2.75×10^{-3}
θ_{rot}	2.23×10^{-3}	-1.85×10^{-3}	6.40×10^{-3}

TABLE V
REGRESSION ON UPPER BODY LATERAL TRANSLATION, y_u: COEFFICIENTS AND 95% CONFIDENCE INTERVALS (CI) FOR LATERAL TRANSLATION OF THE PELVIS, y_p, OBLIQUITY, θ_{obl}, TILT, θ_{tilt} AND TRANSVERSE ROTATION, θ_{rot}.

The relationships between the different variables are illustrated in figure 7. As may be expected, a close relationship between the lateral movements of the upper body and pelvis is clear. Furthermore, there is a trend of decreasing upper body lateral translation with increasing pelvic obliquity.



(a) Step width factor



(b) Orthoses factor

Fig. 6. Box plots for the influence of step width and the presence of the robotic orthosis on the degree of pelvic obliquity.

IV. DISCUSSION

At the 95% confidence level, no significant relationship between pelvic obliquity and upper body lateral translation was found. However, a trend was present indicating decreasing levels of lateral excursion of the upper body for increasing ranges of pelvic obliquity. Indeed, at the 90% confidence level, the CI of the regression coefficient relating upper body lateral excursion with pelvic obliquity is -1.22×10^{-2} to -9.31×10^{-4} m/°. Nevertheless, though pelvic rotations may indeed play a minor role in determining the upper body orientation, other degrees of freedom (e.g. movements of the spine) are also likely to have a large influence on the kinematics of the upper body.

One weakness of this preliminary study is the small number of subjects. Moreover, the presence of the robotic exoskeleton on the subjects' legs could have affected the underlying gait mechanics such that the normal relationships between the pelvic and upper body degrees of freedom were distorted; therefore, the results presented here concerning the relationship between pelvic obliquity and upper body movement may not accurately reflect that in actual, unconstrained overground walking.

The strong effect of the presence of the robotic orthosis on the rotational degrees of freedom indicates the relevance of this aspect of gait kinematics to the design of robot-driven orthoses. In future work, this study will be extended by providing a greater range of walking conditions and subject number in

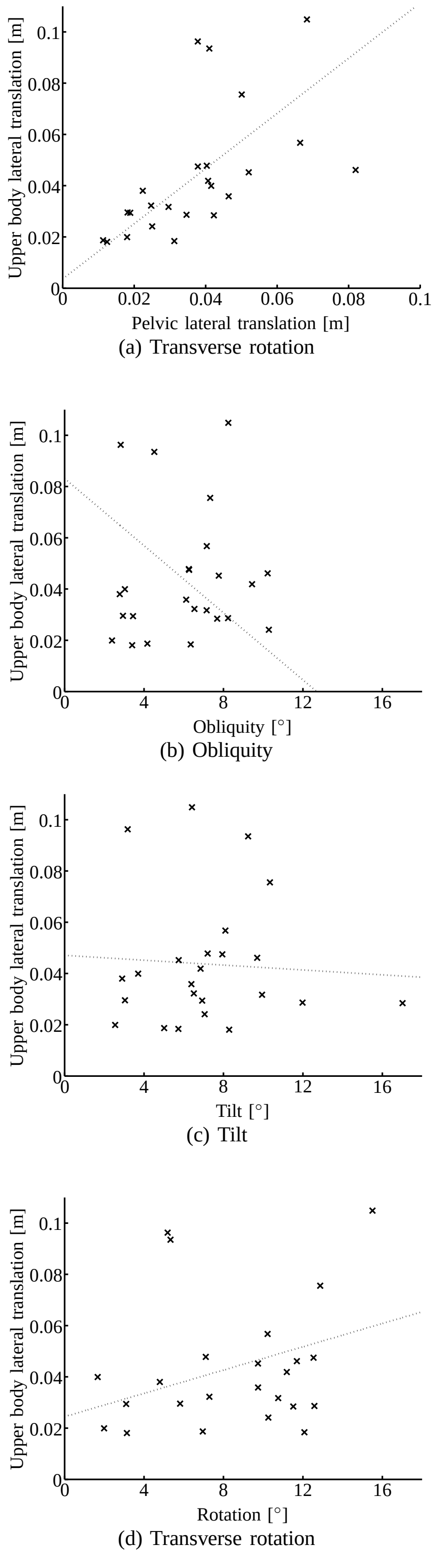


Fig. 7. Relationships between upper body lateral translation, pelvic translation and pelvic rotations.

order to yield further insight into the roles of the different degrees of freedom of the pelvis, and the implications of limiting their range of motion within robotic gait rehabilitation devices.

V. CONCLUSIONS

A role of pelvic obliquity in reducing lateral movement of the upper body has been proposed, and the relationships between pelvic rotations and excursion of the upper body have been explored using a robotic orthosis device. The degree of pelvic obliquity is reduced when walking in the robotic device. A trend of decreasing lateral movement with increasing pelvic obliquity is evident, which may have implications for future design of robots for gait rehabilitation, but no significant linear relationship between the variables was found in the data. Though the rotational movements of the pelvis may have a minor influence on upper body translation, other factors such as the kinematics of the spine could play a strong role.

ACKNOWLEDGMENT

The authors would like to thank the subjects who participated in this study. This work was developed under funding from the Commission for Technology and Innovation (CTI) of Switzerland.

REFERENCES

[1] J. Saunders, V. Inman, and H. Eberhart, "The major determinants in normal and pathological gait," *Journal of Bone and Joint Surgery*, vol. 35, no. 3, pp. 543–558, 1953.

[2] V. Inman, "Human locomotion," *Canadian Medical Association Journal*, vol. 94, no. 20, pp. 1047–1054, 1996.

[3] S. Gard and D. Childress, "The effect of pelvic list on the vertical displacement of the trunk during normal walking," *Gait & Posture*, vol. 5, no. 3, pp. 233–238, 1997.

[4] ——, "What determines the vertical displacement of the body during normal walking?" *Journal of Prosthetics and Orthotics*, vol. 13, no. 3, pp. 64–67, 2001.

[5] U. Croce, P. Riley, J. Lelas, and D. Kerrigan, "A refined view of the determinants of gait," *Gait & Posture*, vol. 14, no. 2, pp. 79–84, 2001.

[6] R. Neptune, F. Zajac, and S. Kautz, "Muscle mechanical work requirements during normal walking: the energetic cost of raising the body's center-of-mass is significant," *Journal of Biomechanics*, vol. 37, no. 6, pp. 817–825, 2004.

[7] J. Ortega and C. Farley, "Minimizing center of mass vertical movement increases metabolic cost in walking," *Journal of Applied Physiology*, vol. 99, no. 6, pp. 2099–2107, 2005.

[8] K. Gordon, D. Ferris, and A. Kuo, "Metabolic and mechanical energy costs of reducing vertical center of mass movement during gait," *Archives of Physical Medicine and Rehabilitation*, vol. 90, no. 1, pp. 136–144, 2009.

[9] M. Kadaba, H. Ramakrishnan, and M. Wootten, "Measurement of lower extremity kinematics during level walking," *Journal of Orthopaedic Research*, vol. 8, no. 3, pp. 383–392, 1990.

[10] R. Baker, "Pelvic angles: a mathematically rigorous definition which is consistent with a conventional clinical understanding of the terms," *Gait & Posture*, vol. 13, no. 1, pp. 1–6, 2001.

[11] F. Dierick, M. Penta, D. Renaut, and C. Detrembleur, "A force measuring treadmill in clinical gait analysis," *Gait & Posture*, vol. 20, no. 3, pp. 299–303, 2004.

[12] S. Jezernik, G. Colombo, T. Keller, H. Frueh, and M. Morari, "Robotic Orthosis Lokomat: a rehabilitation and research tool," *Neuromodulation*, vol. 6, no. 2, pp. 108–115, 2003.

[13] A. Pennycott, D. Wyss, H. Vallery, and R. Riener, "Effects of added inertia and body weight support on lateral balance control during walking," in *12$^{\text{th}}$ IEEE International Conference on Rehabilitation Robotics (ICORR)*, Zürich, Switzerland, 2011.