PELVIC OBLIQUITY AND ROTATION INFLUENCES FOOT POSITION ESTIMATES DURING RUNNING AND SIDESTEPPING: *"IT'S ALL IN THE HIPS"*

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Pelvic obliquity angles were hypothesised to influence mediolateral (ML) foot position estimates during sporting manoeuvres. Pelvic angles and ML foot position estimates during the weight acceptance phase of sidestepping and straight-line running tasks were obtained from 31 amateur Australian Rules Football players using three different kinematic models. ML foot position was calculated: *1)* in the global reference frame, *2)* in the pelvis reference frame and *3)* in the pelvis reference frame following correction for changes in pelvic obliquity. Significant differences in ML foot position were observed between all three models in both task conditions ($p < 0.05$). Correcting for changes in time varying pelvic obliquity during running and sidestepping tasks is an important modelling consideration for the reliable measurement of ML foot position when investigating injury and/or stability.

KEYWORDS: pelvis angle, change of direction, technique

INTRODUCTION: The extant walking gait literature uses a variety of dependent variables to characterise stable locomotion. Among these is foot position relative to whole body centre of mass (CoM) position (Bauby & Kuo, 2000; Hof, Gazendam, & Sinke, 2005; Winter, 1995; Winter, Patla, Ishac, & Gage, 2003) and while a clear mechanical relationship between foot position and whole body CoM is documented in the dynamic stability and balance literature, several surrogate or simplified foot position measurements have been proposed. These include; pelvis to stance foot displacement and; step and stride width and length (Bauby & Kuo, 2000; Nordin, Moe-Nilssen, Ramnemark, & Lundin-Olsson, 2010; Winter et al., 2003). The significant experimental and computational time to compute whole body CoM often precludes it calculation for pragmatic reasons. These simplified measures are, therefore, valuable but one needs to ensure that any dependent variable remains valid.
There are two general approaches employed to calculate pelvis to foot displacement: 1) measures are made in the global coordinate system (GCS) only (Collins & Kuo, 2013) or, 2) measures are referenced to the anatomical coordinate system of the pelvis segment (Dempsey et al., 2007; Kristianslund, Faul, Bahr, Myklebust, & Krosshaug, 2014). For the assessment of straight-line walking gait, there are few clinically or practically relevant differences between foot position estimates if measured using either approach, as most laboratories align the antero-posterior axis of the GCS with the antero-posterior axis of the pelvis anatomical coordinate system i.e. gross alignment remains consistent between the global and anatomical coordinate systems throughout the motion trial. However, during non-linear movements where the progression direction changes (e.g. sidestepping), Huxham and colleagues (2006) showed that estimating foot position relative to a global or anatomical coordinate system will produce clinically meaningful foot position estimates differences. The authors attributed this to time varying changes in the direction of travel and can be primarily characterised by pelvic rotation about the vertical axis. These differences are clinically meaningful as an athlete's mediolateral (ML) foot position has been positively correlated to peak valgus knee joint moments and subsequent classification of non-contact anterior cruciate ligament (ACL) injury risk (Dempsey, Lloyd, Elliott, Steele, & Munro, 2009; Kristianslund et al., 2014). It has been recommended that foot position estimates are made relative to a pelvis anatomical reference frame to account for scenarios when movement progression may be non-linear with the antero-posterior axis of the GCS (Huxham et al., 2006).
A limitation to the calculation of foot displacement relative to the pelvis segment during movement trials, is that rotation about the antero-posterior axis (pelvic obliquity) relative to the GCS is assumed to be zero at all times (pelvic obliquity is neutral). From the walking gait

literature, pelvic obliquity range of motion (ROM) is known to deviate ±5 degrees from a neutral parallel position (Gard & Childress, 1997; Kadaba, Ramakrishnan, & Wootten, 1990; Molina-Rueda et al., 2014). It is unknown however what influence, if any, this assumption has on downstream ML foot position calculations. Especially consider that during the weight acceptance (WA) phase of sidestepping while walking, peak pelvis obliquity angles have been reported to be as large as -12.9 ± 2.7° during planned sidestepping (PSS) and -9.8 ± 2.6° in unplanned sidestepping (UPSS) (Houck, Duncan, & De Haven, 2006). With the range of uses for ML foot position in the sporting and clinical domains (Bauby & Kuo, 2000; Dempsey et al., 2009; Donnelly, et al., 2012), it is imperative that modelling standards are continually tested and implemented to ensure they can be reproduced between motion capture laboratories.
The purpose of the study was to: *1)* estimate and compare pelvis obliquity angles during planned straight line running (PSLR), PSS, and UPSS tasks, *2)* determine the influence pelvis obliquity angles have on current methods of calculating ML foot position in PSLR, PSS and UPSS sporting tasks and, 3) if required, propose a new model for the reliable measurement of ML foot position during running and sidestepping manoeuvres. It was hypothesised that: 1) the largest mean pelvic obliquity angle during the WA phase of all three tasks would be observed during PSS, 2) correcting for time varying pelvic obliquity would change ML foot positions estimates during the PSS and UPSS tasks and 3) pelvic obliquity would be positively correlated to ML foot position estimates during both PSS and UPSS sporting tasks.

METHODS: From a laboratory specific data base of 115 mixed characteristic male and female team sport athletes, 31 male athletes (22 ± 4.2 yrs, 1.8 ± 5.94 m, 80.6 ± 9.55 kg) were selected for further analyses. All data were collected using the same sidestepping protocol, marker sets and kinematic model (Donnelly, et al., 2012). During biomechanical testing, athletes were asked to perform a series of planned and unplanned straight-line running and sidestepping sporting tasks (Besier, Lloyd, Cochrane, & Ackland, 2001; Dempsey et al., 2009; Donnelly, et al., 2012). A 12 camera Vicon MX system (Oxford Metrics, UK) recording at 250 Hz synchronized with an AMTI force platform (AMTI, Massachusetts, USA) capturing at 2,000 Hz, captured 3D marker trajectory and ground reaction force data respectively. Kinematic data, using a custom lower body kinematic model were used to calculated pelvis, ankle and foot kinematics (Dempsey et al., 2007; Donnelly, et al., 2012). Ground reaction force data was used to define the WA phase of stance (Dempsey et al., 2007). During WA for the PSLR, PSS and UPSS tasks, mean pelvic angles were measured relative to the global coordinate system and ML foot positions were calculated using three kinematic models:

- **Model 1** (No-correction): ML displacement of ankle joint centre relative to the mid-pelvis within the global coordinate system.
- **Model 2** (Rotation-correction): ML displacement of the ankle joint centre relative to the mid-pelvis within the anatomical co-ordinate system of the pelvis. Accounts for participant progression angle in global coordinate system.
- **Model 3** (Rotation/Obliquity-correction): ML displacement of the ankle joint centre relative to the mid-pelvis within the anatomical co-ordinate system of the pelvis, and corrected for time varying pelvic obliquity.

A one-way ANOVA and Sidăk *post hoc* test was used to compare global estimates of pelvis angles between sporting tasks (PSLR, PSS, UPSS). A negative obliquity value indicated that the iliac crest of the pelvis was higher on the ipsilateral side to stance foot. Differences in ML foot position between the three sporting tasks and three models were assessed using a 3x3 repeated measures ANOVA. A Pearson's correlation between pelvic obliquity angles and changes in ML foot position between Model 2 and Model 3 for all three sporting tasks was also performed. All analyses were conducted in SPSS 21.0.1 (SPSS Inc, IBM, Chicago, Illinois) at an alpha of 0.05.

RESULTS: Mean pelvis obliquity angle was higher during PSS (-14.8 ± 4.4 °) when compared to UPSS (-7.4 ± 5.2 °), with both greater than the PSLR (-2.7 ± 2.7 °) task ($p<0.001$) (Table 1).
During the PSLR task, mean ML foot position estimates for the rotation-correction model (Model 2) (-3.0 ± 5.2 cm) were significantly lower and in the opposite direction to the mean

ML foot position estimates of both the uncorrected (Model 1) (2.8 ± 3.2 cm, p<0.001) and rotation/obliquity-corrected (Model 3) models (0.7 ± 4.7 cm, p=0.004) (Figure 1). During the PSS tasks, the mean ML foot position estimates of the rotation/obliquity-corrected model (Model 3) (40.1 10.1 cm) were significantly higher than the rotation-corrected model (Model 2) (21.7 ± 11.2 cm, p<0.001) and uncorrected model (Model 1) (32.6 ± 5.7 cm, p=0.006). The mean ML foot position estimates for the uncorrected model (Model 1) were significantly greater than the rotation-corrected model (Model 2) (p<0.001). During the UPSS task, the mean ML foot position estimates of the rotation/obliquity-corrected model (Model 3) (42.1 ± 10.6 cm) were significantly greater than the rotation-corrected (Model 2) (33.0 ± 10.6 cm, p=0.001) and uncorrected (Model 1) (35.3 ± 6.9 cm, p=0.18) models.
A strong positive correlation was observed between pelvic obliquity angle and the change in ML foot position displacement between the rotation-corrected and rotation/obliquity-corrected models for all three movement conditions (PSLR, r=1.000; PSS, r=0.996; UPSS, r=0.999).

Table 1. Mean pelvis angles (stdev) during WA for planed straight line run (PSLR), planned sidestep (PSS) and unplanned sidestep (UPSS) tasks. A positive value indicates: tilt – anteriorly rotated; obliquity – rotated upwards towards the contralateral side to the stance leg; rotation – rotated towards the intended direction of travel.

	Movement Condition		
Pelvis Angle	PSLR	PSS	UPSS
Tilt (°)	16.4 (6.80) ^{T}	12.4 (6.47)	12.5 (6.67)
Obliquity (°)	-2.7 (2.74) $^{\wedge, T}$	-14.8 (4.41) ^{*,T}	-7.4 (5.18) $^{*,\wedge}$
Rotation (°)	-2.8 (5.29) $^{\wedge, T}$	9.2 (10.00) *	9.0 (9.95) *

* significantly different to PSLR condition (p<0.05)
$^{\wedge}$ significantly different to the PSS condition (p<0.05)
^{T} significantly different to the UPSS condition (p<0.05)

Distance from mid pelvis to ankle joint centre (cm)

Figure 2. ML foot position calculated using the three models measured during the WA phase of PSLR, PSS and UPSS tasks. A positive value indicates that the foot is placed laterally away from the intended direction of travel. *Denotes a significant difference between models (p < 0.05).

DISCUSSION: Results from this study show that if changes in pelvic obliquity are not accounted for in deriving outputs during running and sidestepping tasks, researchers will underestimate ML foot position. The observed differences in ML foot positon between model 2 and model 3 were positively correlated (r ≥ 0.996) to pelvic obliquity angles across all three task conditions (PSS, UPSS, PSLR). Between model differences in ML foot position estimates were most pronounced during the PSS task, which also reported the highest levels of mean pelvic obliquity across WA. In support of hypothesis one, this finding confirms that the largest pelvic obliquity angles would be observed during PSS. These results are in alignment with Houck et al. (2006), who reported larger pelvis obliquity angles during low velocity PSS (-12.7 ± 2.9 °) when compared with UPSS (-9.8 ± 2.6 °). Additionally, Marshall et al. (2014) found that athletes displayed a pelvis obliquity angle of 5.2 ± 3.3 ° when performing a PSS of 75° at maximum speed. This was characterised by a contralateral pelvic drop relative to the stance foot. As sidestepping requires a large amount of control of the stance leg, Marshall et al. (2014) postulated that this position of the pelvis to be higher on the side of the leg in contact with the ground, is necessary for a fast and successful change of direction. The lower mean pelvis obliquity observed during UPSS may be attributed to a lack of planning time and the subsequent inability to adequately prepare their movement.
In partial confirmation of hypotheses two and three, correcting for time vary pelvic obliquity changes during PSS and UPSS tasks were positively correlated with changes in ML foot position estimates. Contrary to our second hypothesis, the same findings were observed for the PSLR task. For all three movement conditions, correcting for only pelvic rotation resulted in smaller ML foot position estimates, while correcting for pelvic rotation and obliquity resulted in larger ML foot position estimates when compared to an uncorrected pelvis (Model 1). These findings are not meant to disregard ML foot position as an important ACL injury risk classifier, rather highlight that developed standards must be considered for measurement of ML foot position within the injury prevention and motor control literature.

CONCLUSION: Pelvic obliquity was shown to influence ML foot position estimates during the WA phase of PSLR, PSS and UPSS tasks. To obtain, reliable, clinically meaningful and standardised ML foot position estimates during sidestepping and running, researchers should consider adopting modelling methods that accounts for time varying changes in both pelvis rotation and obliquity.

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