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Original article

Innominate movement patterns, rotation trends and range of motion in individuals with low back pain of sacroiliac joint origin

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ABSTRACT

Background: Innominate kinematic anomalies resulting in low back pain (LBP) of sacroiliac joint (SIJ) origin (SIJ-positive), has always been a topic of contention, owing to difficultly in its evaluation. Recent technique of electromagnetic palpation-digitization has been able to accurately quantify innominate kinematics in healthy individuals.

Objectives: The purpose of this study is to determine if participants with LBP of SIJ origin (SIJ-positive) demonstrate significantly different innominate kinematics than participants with LBP of non-SIJ origin (SIJ-negative).

Design: Single-blinded cross-sectional case–control study.

Method: Participants [n(122)] between the ages of 18 to 50 years, suffering from chronic non-specific LBP (≥3 months) volunteered in the study. An experienced musculoskeletal physiotherapist evaluated and classified participants into either SIJ-positive [n(45)] or SIJ-negative [n(77)] group, using the reference standard pain provocation tests [≥3 positive tests = SIJ-positive]. A research physiotherapist, blinded to clinical groups, conducted the innominate kinematic testing using a valid and reliable electromagnetic palpation-digitization technique, during prone lying incremental hip abduction-external rotation test positions.

Results: The results of the mixed model regression analyses demonstrated that SIJ-positive participants exhibited significantly different innominate movement patterns and trends of rotation, but not innominate ranges of motion, when compared with SIJ-negative LBP participants.

Conclusions: These findings demonstrate association between SIJ pain and altered innominate kinematics, and have led the groundwork for further exploration of clinical measurement, relevance, and management of these potentially important movement observations.

1. Introduction

Low back pain (LBP) is the most common, costly and disabling musculoskeletal condition of our age with point and lifetime prevalence of approximately 15% and 80% respectively (Krismer and van Tulder, 2007). Despite this high prevalence and wealth of literature, the causes of LBP are not well understood, resulting in a non-specific diagnosis in approximately 85% to 90% of the cases (Hoy et al., 2010; Balague et al., 2012). Although most people with LBP recover relatively rapidly, approximately 10% do not respond to treatment and eventually develop chronic LBP (Krismer and van Tulder, 2007; Briggs and Buchbinder, 2009). The most likely cause for this non-response to treatment is lack of specific diagnosis and inability to distinguish, in some people, pain arising from the sacroiliac joints (SIJs) or the lumbar spine (O'Sullivan, 2005; O'Sullivan and Beasles, 2007).

The SIJ have been identified as the source of low back and buttock pain for approximately 15% to 30% of the population (Schwarzer et al., 1995; Maigne et al., 1996). Pain resulting from mechanical disorders, including innominate positional and

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movement abnormalities appears to be the most commonly reported causes for non-specific LBP of SIJ origin (Hansen and Helm, 2003; Zelle et al., 2005; Al-khayer and Grevitt, 2007). Yet, presently there is a lack of accurate and reliable tests for assessing innominate movement anomalies in clinical populations (van der Wurff et al., 2000a, 2000b; Cattley et al., 2002; Stuber, 2007). Assessment of innominate motion is difficult owing to the complex anatomical orientation (McGrath, 2006; Vleeming et al., 2012), small ranges of three-dimensional motion (Goode et al., 2008), and the range of within- and between-participant variability (Bussey et al., 2009a, 2009b).

Several techniques have been used to accurately quantify the innominate bone kinematics, while using either multiple radiographs (Mens et al., 1999) or roentgen stereophotogrammetric analysis with implantation of radio-opaque markers (Sturesson et al., 1989; Kibsgard et al., 2012). While these techniques are highly accurate for investigating joint ranges of motion (ROM) between the two test positions, they are not appropriate for investigation of patterns or trends of joint motion as they cannot be performed in real time. Further, these techniques are cumbersome, expensive, and highly invasive which limits the total number of films that can be taken from one individual.

To overcome these limitations, Bussey et al. (2004) used an electromagnetic palpation-digitization technique of pelvic landmark identification, to non-invasively and accurately quantify innominate kinematics while loading the SIJ using prone hip abduction and external rotation (HABER) test positions. This technique of electromagnetic palpation-digitization of pelvic landmarks has previously demonstrated high levels of validity and reliability for measurement of innominate kinematics (Busssey et al., 2004; Adhia et al., 2012). However, although this technique has been shown to accurately define innominate kinematics in healthy population; its use in clinical population is still unknown. The current study therefore explored the use of the electromagnetic palpation-digitization technique in individuals clinically diagnosed with LBP of SIJ origin (SIJ-positive) and Non-SIJ origin (SIJ-negative) while applying HABER test positions. The aim of the study is to determine if the SIJ-positive individuals demonstrate significantly different innominate kinematic measures (movement pattern, ROM and trends of rotation) in the HABER test when compared with SIJ-negative individuals.

2. Method

2.1. Design

A laboratory based single-blinded cross-sectional case–control study using two groups of non-specific LBP participants (SIJ-positive and SIJ-negative) was conducted. Ethical approval for the study was obtained from Human Ethics Committee at University of Otago, NZ.

2.2. Participants

One hundred and twenty-two participants suffering from chronic (≥3 months) non-specific LBP were recruited from physiotherapy clinics and wider community for participation in the study. Any potential participants with past or current history of surgery or major trauma to spine, pelvis, lower limb, chest or abdomen in the past 12 months; lower extremity musculoskeletal disorders; known localised spinal pathology; known congenital anomalies of hip, pelvis or spine that limits mobility; known systemic arthropathy, neuropathy or metabolic disorder; diagnosed acute disc herniation/prolapse with or without radiculopathy; and pregnancy, less than 6 months post-partum, post-menopausal women; were excluded.

The following descriptive information was collected from each participant: demographic information [age, sex, body mass index (BMI)], level of physical activity, level of disability (Modified Oswestry Low Back Pain Disability Questionnaire), duration of pain and current intensity of pain (visual analogue scale).

2.3. Procedure

Each participant underwent a standard musculoskeletal clinical examination performed by a qualified manual therapist (MPHTY) with considerable experience in diagnosing and treating LBP patients (>7 years). The clinical evaluation also included a comprehensive set of valid and reliable non-invasive SIJ symptom provocation tests (Laslett, 2008; Szadek et al., 2009). These included the Gaenslen's test, compression test, distraction test, thigh thrust test, sacral thrust test, and FABER's test, and were conducted in a randomized order to avoid rater-bias. The categorical clinical responses (familiar symptom reproduction) to each of these clinical tests were recorded by the clinician and the results were used to classify participants into clinical groups (familiar symptom reproduction in ≥3 pain provocation tests = SIJ-positive, and familiar symptom reproduction in <3 pain provocation tests = SIJ-negative) (Laslett et al., 2005; Laslett, 2008; Szadek et al., 2009). The SIJ-positive LBP participants were further divided into three clinical groups, namely right SIJ-positive (R-SIJ), left SIJ-positive (L-SIJ) and bilateral SIJ-positive (BL-SIJ) LBP, based on symptomatic side and results of SIJ symptom provocation tests (Fortin et al., 1994a, 1994b, 2003).

Immediately, following the clinical evaluation, each participant underwent an innominate kinematic testing session by a different tester, blinded to the outcome of their clinical evaluation. A valid and reliable [r(0.83), Intraclass Correlation Coefficient (ICC) (0.97), Standard Error of Measurement (SEM) (<1%, trial-to-trial = 0.5 mm, inter-rater = 2.0 mm)] Polhemus™ electromagnetic palpation-digitization technique was used to measure innominate kinematics of the participants (Bussey et al., 2004; Adhia et al., 2012). At a frequency of 240 Hz per sensor, this system had a static accuracy of 0.015 mm for a fixed position of source and repeated measurements using 3D digitizing stylus with respect to the local sensor (Adhia et al., 2012). The participants were positioned in prone-lying on a standardized testing table with the hip rotation frame (Fig. 1). A local system sensor was secured using adhesive tape over the 3rd lumbar spinous process. Each hip was moved in increments of 10° from a neutral position (0°) to the maximum available HABER test position (50°), with the side (right or left) to be tested first randomised for each participant. At each HABER increment, the four pelvic landmarks [left and right posterior superior iliac spine (PSIS) and anterior superior iliac spine (ASIS)] were palpated and digitized using the 3D digitizing stylus of Polhemus™ system.

2.4. Outcome measures

2.4.1. Innominate range of motion

The innominate ROM was defined as the angular displacement of innominate angle between the neutral hip test position and maximum HABER test position (Bussey et al., 2004). The innominate ROM were calculated about vertical (y) axis (individually for each innominate; for instance, right and left innominate in right HABER test) and about medio-lateral (z) axis (simultaneously for both innominates) (Fig. 2).

2.4.2. Innominate movement pattern

The innominate movement patterns were defined based on the direction of rotation of both innominate bones about y-axis when loaded from neutral hip test position to maximum HABER test

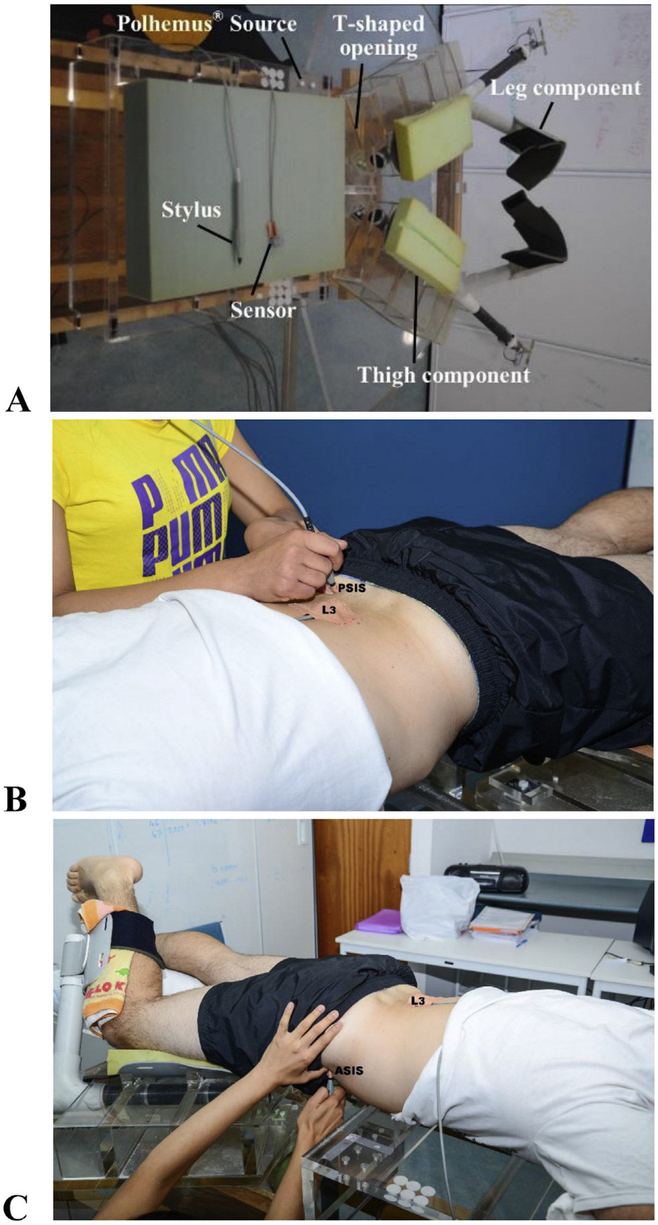

Fig. 1. Set-up of the procedure A) Hip rotation frame, B) Palpation-digitization of the PSIS in Neutral hip test position, C) Palpation-digitization of the ASIS in HABER test position. The top figure (A) presents a hip rotation frame which was used to standardize the HABER test positions across each participant regardless of their demographic parameters. The frame consists of a thigh and a leg component which allows for handling and standardization of the amount and direction of the anatomical stress applied to innominate bone through hip joint. The frame also consists of a T-shaped opening under the pelvis which allows exposure and palpation-digitization of the anterior pelvic landmarks. The structure of the frame and the gravity eliminated test position of prone lying, allows an unloaded position of the pelvis with minimal influence of muscle contraction on joint position. Further, the fixed position of the source of the Polhemus® system under the frame ensures adequate distance required between the sensor and source minimizing the measurement errors. The middle and the bottom figure (B and C) presents the palpation-digitization procedure of the pelvic landmarks in the Neutral and HABER test positions respectively. The pelvic landmarks, namely the left and right PSIS and the left and right ASIS were palpated in that order and the most prominent part of the palpated landmark was digitized using the 3D digitizing stylus pen of the Polhemus® system, at Neutral and each increment of the HABER test position.

position. Two innominate movement patterns, namely unilateral movement pattern and reciprocal movement pattern (Bussey et al., 2009b), were defined for each test side (right and left). The unilateral movement pattern was defined as rotation of both innominate bones in same direction and the reciprocal movement pattern was defined as rotation of both innominate bones in opposite direction (Fig. 2).

2.4.3. Innominate trend of rotation

The innominate trend of rotation (about y-axis and z-axis) was defined as the graphical pattern (linear or quadratic) that innominate rotations exhibited through increments of HABER's test (10°, 20°, 30°, 40°, and 50°). The innominate trend of rotation were calculated about vertical (y) axis (individually for each innominate; for instance, right and left innominate in right HABER test) and about medio-lateral (z) axis (simultaneously for both innominates) (Fig. 2).

2.5. Data analysis

To determine if the SIJ-positive participants demonstrates significantly different innominate movement patterns and ROM when compared with SIJ-negative LBP participants, a binary logistic regression and a linear regression analysis using mixed models were conducted respectively (Fitzmaurice et al., 2008; Field, 2009). The outcome variables for the mixed model binary logistic and linear regression analysis were innominate movement patterns [categorically classified as 0(Reciprocal pattern) and 1(Unilateral pattern)] and ROM [transverse plane (right and left innominate) and sagittal plane] respectively.

The independent variables included in the binary logistic and linear regression mixed model analysis were: clinical group [0(Non-SIJ), 1(R-SIJ), 2(L-SIJ), and 3(BL-SIJ)], HABER test side [0(Left) and 1(Right)], sex [0(Male) and 1(Female)], dominance [0(Left) and 1(Right)], and age (continuous). The independent variables were defined as fixed effects and participants were defined as a random effect. To avoid type-I error and adjust for multiple comparisons, a Bonferroni correction was applied and p value of ≤ 0.017 was considered as significant. The overall fit of the model was assessed using percentage prediction of model and R^2 value.

The association between clinical group and innominate trends of rotation was determined using linear mixed model regression analysis (Fitzmaurice et al., 2008; Field, 2009). Initial data exploration (i.e. statistical assumptions check, and best-fit lines for individual data on scatter plot) revealed that innominate trends of rotation for most participants were best defined using a quadratic polynomial curve. Thus, a quadratic curve (Equation (1))

$$y = \beta_0 + \beta_1 X_1 + \beta_2 {X_1}^2 \quad (1)$$

where y is outcome variable [i.e. innominate rotation (about y-axis and z-axis)], β_0 is intercept, β_1 is parameter estimate for linear term X_1 (i.e. HABER increment position) and β_2 is parameter estimate for quadratic term ${X_1}^2$ [i.e. (HABER increment position)^2] was fit individually for innominate rotations (about y-axis and z-axis) for each clinical group. The p value of the interaction term of clinical group and quadratic polynomial curve [i.e. Clinical group*HABER increment position*(HABER increment position)^2] was then interpreted to determine significance of association between clinical group and innominate trends of rotation. The covariates sex, age, and dominance, were initially considered in the model; however were removed as they did not demonstrate a significant association with innominate rotations.

3. Results

Fig. 3 presents flow of participants from recruitment to inclusion in study and their sub-division into clinical groups. Demographic details and clinical characteristics of participants included in each

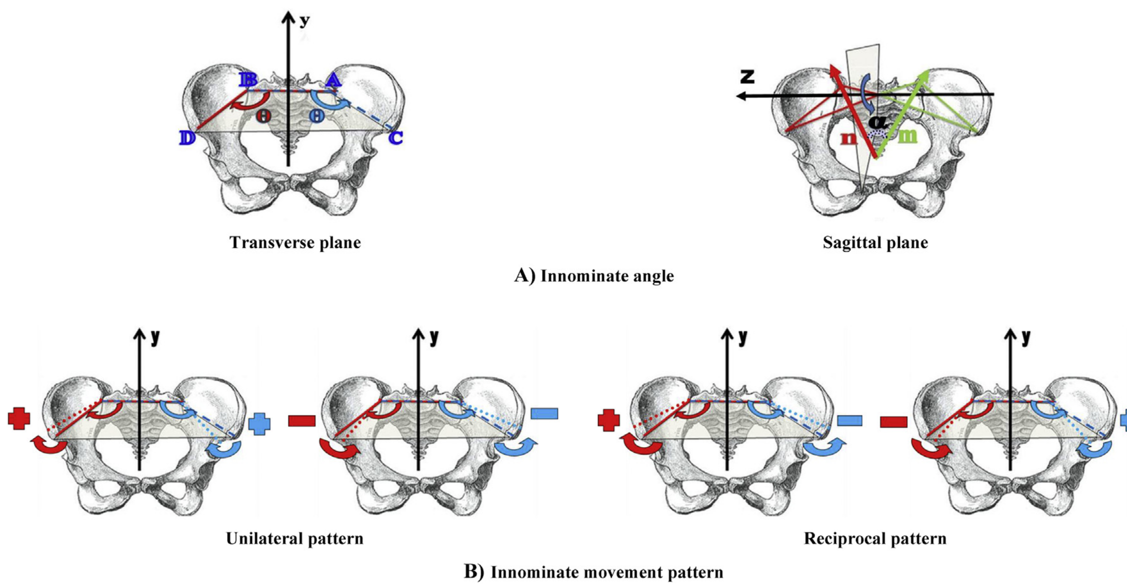

Fig. 2. Defining innominate outcome variables. A) Innominate angle: The figure on the left top presents the transverse plane innominate angles used to calculate the innominate rotation about y-axis. The transverse plane innominate angles (θ) of each side (right and left innominate) were calculated from the respective PSIS and innominate vector using the formula (Bussey et al., 2004)

$$\theta = \cos(-\hat{1})\ (\text{PSIS vector} \cdot \text{Innominate vector})/(\|\text{PSIS vector}\| * \|\text{Innominate vector}\|)$$

θ (red): Right innominate angle calculated from innominate vector (V_{BD}) and PSIS vector (V_{BA}); θ (blue): left innominate angle calculated from innominate vector (V_{AC}) and PSIS vector (V_{AB}). The figure on the right top presents the sagittal plane innominate angle (α) used to calculate the innominate rotation about z-axis. A plane was defined for each innominate bone (right and left) using the respective PSIS vector and innominate vector of that side. A vector normal to each plane (right and left) was calculated as the cross product of the respective PSIS and innominate vector. The innominate sagittal angle (α) was defined as the angle between the two planes and was calculated as the angle between the two normal vectors using the formula (Bussey et al., 2004)

$$\alpha = \cos(-\hat{1})\ (\text{Right normal vector} \cdot \text{Left normal vector})/(\|\text{Right normal vector}\| * \|\text{Left normal vector}\|)$$

The blue arrow shows the rotation about the z-axis; the red triangle shows the right plane and the green triangle shows the left plane; n: right normal vector; m: left normal vector; α: Sagittal innominate angle calculated from right and left normal vector. The transverse plane right and left innominate angles and the sagittal plane innominate angle were calculated for the neutral hip test position (0 deg) and for each increment (10 deg, 20 deg, 30 deg, 40 deg, and 50 deg) of the HABER test positions. The innominate rotation was then defined as the change in innominate angle between the neutral hip test position and the HABER test position. These innominate rotations were then used to define the innominate ranges of motion and trend of rotation. B) Innominate movement pattern: The figure describes the innominate movement pattern when the SIJ is stressed in the right HABER test position. The plus sign (+) indicates the movement of the innominate bone to the same side as that of the loaded hip (viz., right hip in this figure) and the negative sign indicates the movement of the innominate bone to the opposite side as that of the loaded hip. The dotted line on the respective sides (red on right and blue on left) demonstrates the displacement of the innominate angle during the stressed position of the hip. The arrows near the PSIS indicate the neutral position of the innominate and the arrows near the ASIS demonstrates the direction of innominate bone rotation in the maximal HABER test position. If both the innominate bones rotated in one direction either towards loaded hip or towards unloaded hip, then the innominate movement pattern was defined as unilateral. If both the innominate bones rotated in opposite directions either away from each other (i.e. external rotation) or towards each other (i.e. internal rotation), then the innominate movement pattern was defined as reciprocal. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

clinical group are presented in Table 1. Descriptive statistics for innominate movement pattern and ROM are presented in Table 2. The frequencies for innominate movement pattern demonstrate that unilateral innominate movement pattern was more common in SIJ-positive individuals compared with SIJ-negative individuals. The mean and standard deviation for innominate rotations (right, left and sagittal) demonstrated small (≤4.5°) ROM irrespective of clinical group and HABER test side.

Table 3 presents results of associations between clinical group and innominate movement patterns and ROM. A significant positive association was demonstrated between clinical group and unilateral innominate movement pattern. This association was independent of HABER test side [clinical group*HABER test side: *p*(0.861)]. The covariates sex, dominance, and age did not demonstrate a significant association with innominate movement patterns.

No significant association was demonstrated between clinical group and transverse plane (right and left innominate) and sagittal plane innominate ROM, irrespective of HABER test side [clinical group*HABER test side: *p*(0.343, 0.700, and 0.480 respectively)]. The covariates of sex and dominance did not demonstrate a significant association with right, left and sagittal innominate ROM. While age had a significant association with right innominate ROM, the beta statistics revealed a very weak association [B(0.03)].

The innominate trends of rotation for each clinical group during incremental HABER test positions are presented in Fig. 4. The SIJ-positive individuals exhibited significantly different innominate trends of rotation (in one or more planes) when compared with SIJ-negative individuals [R^2(0.34 to 0.82)].

4. Discussion

The present study is the first to compare innominate kinematics in two groups of non-specific LBP populations during incremental as well as maximal HABER test positions. The results of present study demonstrate that the SIJ-positive individuals exhibit significantly different innominate movement patterns and trends of rotation in the HABER test when compared to SIJ-negative individuals.

The innominate trends of rotation graphs (Fig. 4) suggest between-group differences in motion coupling of innominate bones with increments of the HABER test. For instance, in the left

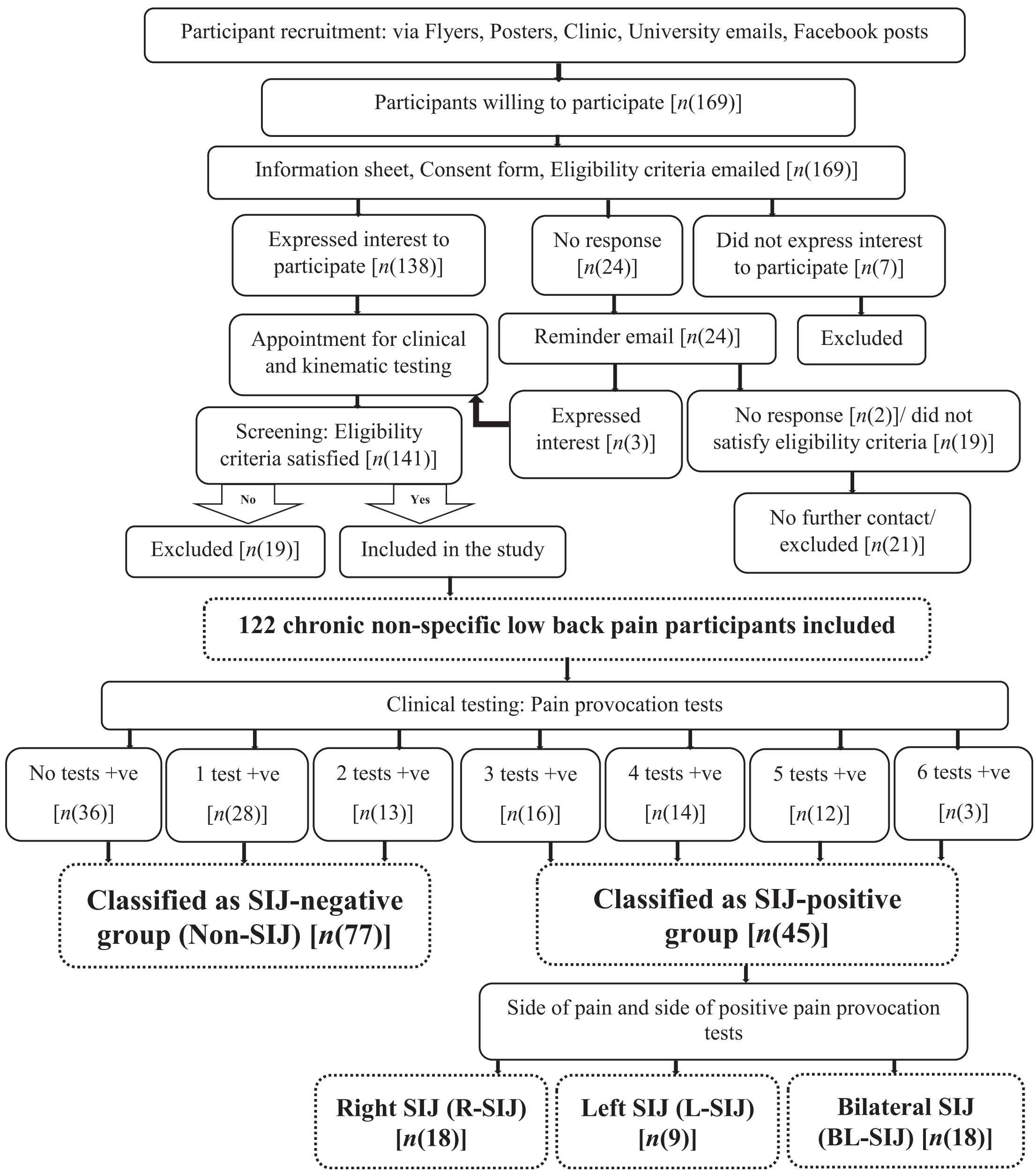

Fig. 3. Participants flow from recruitment to classification into clinical groups.

HABER test, the SIJ-negative individuals appear to display more linear trends that are dominated by motion in sagittal plane. However, SIJ-positive individuals tend to have polynomial trends in the sagittal plane. For R-SIJ individuals the trend implies less movement in sagittal plane and greater movement in transverse plane to 30° of hip rotation when the movement in transverse plane declines with a concurrent increase in sagittal plane movement. Similar between planes trading is seen in the L-SIJ and BL-SIJ

Table 1
Demographic details and clinical characteristics of participants.

Characteristics	SIJ-negative	SIJ-positive		
	Non-SIJ (n = 77)	R-SIJ (n = 18)	L-SIJ (n = 9)	BL-SIJ (n = 18)
Age (years) (Mean ± SD)	30.2 ± 9.8	35.1 ± 10.6	35.7 ± 7.2	28.6 ± 10.3
Sex (Females:Males)	49:28	12:6	6:3	16:2
Dominance (Right:Left)	65:12	16:2	8:1	17:1
BMI (kg/m^2) (Mean ± SD)	25.0 ± 4.2	27.2 ± 6.8	27.8 ± 5.3	23.2 ± 4.0
Physical activity (h/week) (Mean ± SD)	9.1 ± 7.0	7.1 ± 5.4	5.3 ± 2.4	10.7 ± 6.3
Pain duration (years) (Mean ± SD)	7.6 ± 11.4	7.1 ± 6.6	5.9 ± 6.1	5.4 ± 5.0
VAS score (mm) (Mean ± SD)	10.8 ± 15.6	10.8 ± 8.1	14.4 ± 13.3	19.2 ± 19.9
Modified Oswestry LBP disability score (%) (Mean ± SD)	12.0 ± 8.8	12.1 ± 8.6	11.1 ± 10.7	14.1 ± 5.1

R = right, L = left, BL = bilateral, n = sample size, SD = standard deviation, VAS = visual analogue scale, LBP = low back pain.

Table 2
Descriptive statistics of the innominate movement patterns and ranges of motion for each clinical group in the maximal HABER test position.

Variable	HABER test side	SIJ-negative	SIJ-positive		
		Non-SIJ (n = 77)	R-SIJ (n = 18)	L-SIJ (n = 9)	BL-SIJ (n = 18)
Innominate movement pattern [Unilateral (%)]	Right	44	83	89	72
	Left	47	83	89	83
Right innominate range of motion (degrees) (Mean ± SD)	Right	1.6 ± 1.2	2.2 ± 1.7	1.2 ± 0.7	2.0 ± 1.4
	Left	1.4 ± 1.0	1.4 ± 0.9	2.0 ± 1.2	1.8 ± 1.7
Left innominate range of motion (degrees) (Mean ± SD)	Right	2.0 ± 1.4	1.5 ± 1.4	1.2 ± 1.1	1.5 ± 1.3
	Left	2.1 ± 1.6	1.9 ± 1.8	1.7 ± 1.5	1.5 ± 1.2
Sagittal innominate range of motion (degrees) (Mean ± SD)	Right	2.8 ± 2.6	3.2 ± 2.2	4.5 ± 4.6	2.5 ± 2.6
	Left	3.5 ± 2.1	3.7 ± 2.3	3.6 ± 3.0	2.9 ± 2.0

R = right, L = left, BL = bilateral, n = sample size, SD = standard deviation.

individuals where sagittal plane motion is decreasing at the 30° point while transverse plane motion is increasing. Bussey and Milosavljevic (2013), demonstrated similar coupling trends in persons with ankylosing spondylitis (AS) compared to healthy controls. They suggested the likely reason for such findings was physiological joint restriction related to the disease. Thus putatively, the trading pattern identified in the current study is linked to a physiological joint restriction involving either intra-articular or extra-articular structures. For instance, involvement (degeneration/inflammation) of the superior short articular surface of the SIJ may restrict the arthrokinematic (i.e., superior glide) movement during the sagittal plane innominate posterior rotation (Bogduk, 2005; Vleeming et al., 2007), which may thus call upon for compensatory coupled movement in transverse plane to accommodate the incremental load applied to the joint.

The findings of the present study indicate significant between-group differences in innominate movement patterns. The SIJ-positive individuals predominantly exhibited a unilateral pattern of innominate movement (Fig. 2). Putatively, the unilateral innominate movement pattern is indicative of a particular model of physiological restriction, which derives from an asymmetric stiffness between the pelvic joints in SIJ-positive individuals.

Table 3
Results of mixed model regression analyses for association of clinical group and innominate movement patterns and ranges of motion.

Independent variables included in the model for each outcome variable	**Outcome variable**			
	Unilateral innominate movement pattern	**Innominate range of motion**		
		Right (y-axis)	**Left (y-axis)**	**Sagittal (z-axis)**
Clinical group: R-SIJ vs. Non-SIJ	B = 1.63, $p < 0.001$, Exp (B) = 5.13 (2.07, 12.69)	B = 0.38 (-0.08, 0.84), p = 0.103	B = -0.41 (-1.00, 0.18), p = 0.169	B = 0.30 (-0.76, 1.36), p = 0.580
Clinical group: L-SIJ vs. Non-SIJ	B = 2.28, p = 0.003, Exp (B) = 9.82 (2.16, 44.72)	B = 0.02 (-0.60, 0.63), p = 0.956	B = -0.37 (-1.16, 0.42), p = 0.358	B = 0.80 (-0.62, 2.22), p = 0.270
Clinical group: BL-SIJ vs. Non-SIJ	B = 1.45, p = 0.001, Exp (B) = 4.28 (1.79, 10.24)	B = 0.40 (-0.07, 0.87), p = 0.091	B = -0.29 (-0.89, 0.30), p = 0.334	B = -0.07 (-1.15, 1.00), p = 0.894
HABER test side: Right vs. Left	B = -0.16, p = 0.578, Exp (B) = 0.86 (0.49, 1.48)	B = -0.18 (-0.46, 0.10), p = 0.212	B = -0.01 (-0.35, 0.34), p = 0.788	B = -0.86 (-1.48, -0.25), p = 0.006
Sex: Female vs. Male	B = 0.05, p = 0.881, Exp (B) = 1.05 (0.58, 1.90)	B = -0.17 (-0.51, 0.18), p = 0.336	B = 0.30 (-0.13, 0.74), p = 0.173	B = -0.29 (-1.09, 0.50), p = 0.465
Age	B = -0.00, p = 0.760, Exp (B) = 1.00 (0.97, 1.02)	B = 0.03 (0.01, 0.04), p = 0.002	B = 0.02 (-0.00, 0.04), p = 0.122	B = -0.01 (-0.04, 0.03), p = 0.751
Dominance: Right vs. Left	B = -0.57, p = 0.180, Exp (B) = 0.57 (0.25, 1.30)	B = 0.41 (-0.05, 0.88), p = 0.083	B = -0.63 (-1.23, -0.04), p = 0.038	B = -0.46 (-1.54, 0.63), p = 0.408
Model Fit	$R^2 = 0.39$ Percentage prediction = 65%	$R^2 = 0.06$	$R^2 = 0.16$	$R^2 = 0.17$

B: beta statistics, Exp (B): exponential beta, vs.: versus, R: right, L: left, BL: bilateral. The red highlighted values indicate a significant association with $p < 0.017$. Each column within the outcome variable represents a separate mixed regression model that was fit to the respected innominate kinematic variable. A binary logistic mixed model with independent variables of clinical group, HABER test side, sex, age, and dominance was fit to the innominate movement pattern (outcome variable). Three linear mixed models each with the independent variables of clinical group, HABER test side, sex, age, and dominance were fit individually to the right, left and sagittal innominate ranges of motion (outcome variable).

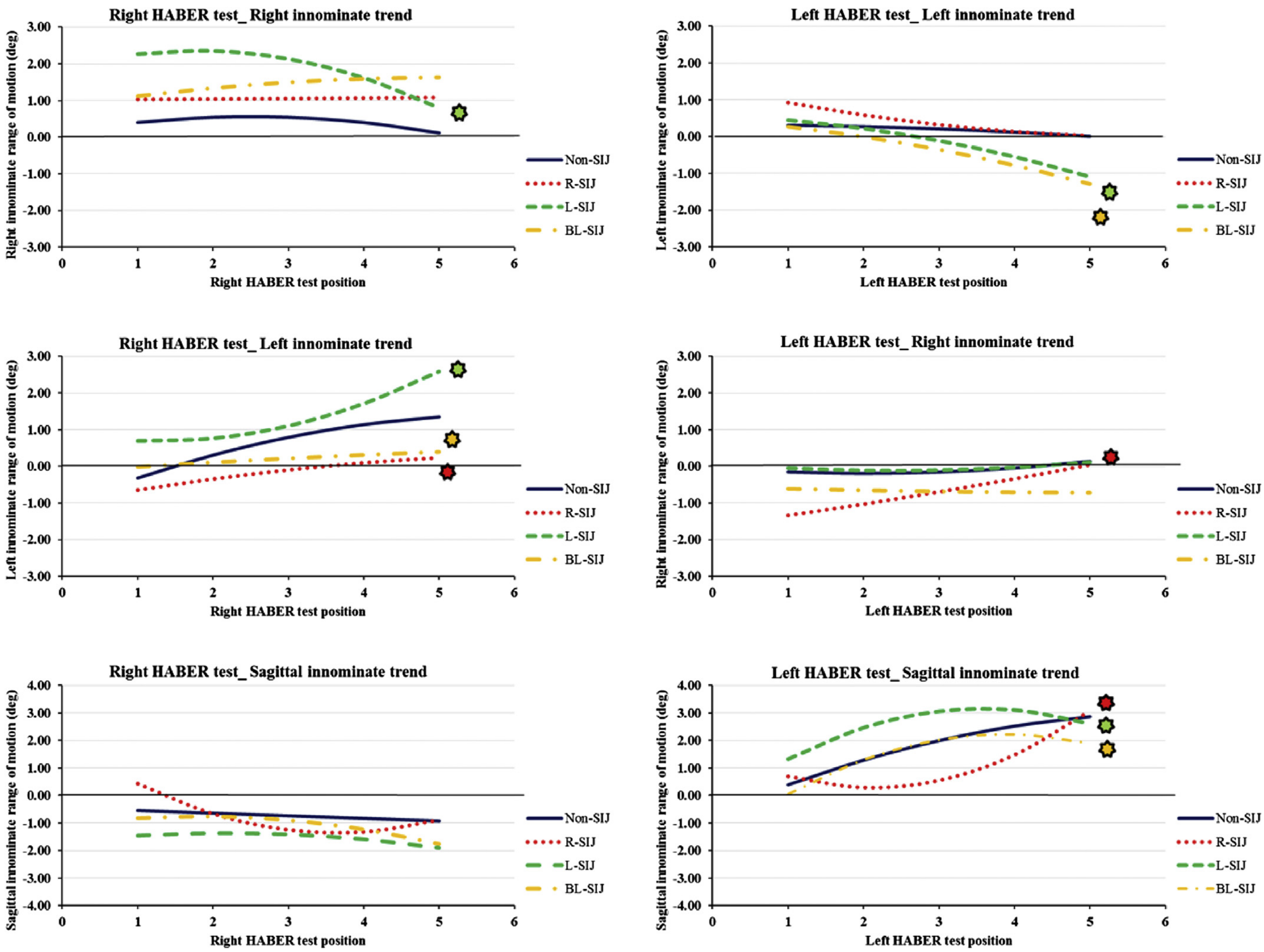

Fig. 4. Innominate trend of rotation in the HABER test positions. The x-axis of the graphs presents the increments of the HABER test positions (thus 1 = 10 deg, 2 = 20 deg, 3 = 30 deg, 4 = 40 deg and 5 = 50 deg). The star indicates a significant ($p < 0.017$) between-group difference in the innominate trend of rotation of the respective SIJ-positive group when compared with the SIJ-negative (Non-SIJ) group. The positive value for the right and left innominate (transverse plane) indicates rotation in the same direction viz. right innominate rotates towards right (i.e. external rotation), whereas the negative value will indicate rotation in the opposite direction viz. right innominate rotates towards left (i.e. internal rotation). The increase in the sagittal innominate range of motion will indicate an increase in sagittal torsion of pelvis with the loaded innominate bone (right innominate in right HABER's test) rotating posteriorly and the unloaded innominate bone (left innominate in right HABER's test) rotating anteriorly. The above graphs presents several interesting findings, 1) The innominate trend of rotations of the SIJ-positive and SIJ-negative individuals demonstrated significant differences in the transverse plane during the right HABER test positions, especially the unloaded (left) innominate. While the transverse plane rotation of the left innominate demonstrated a positive slope with each increment of right HABER test in Non-SIJ individuals, the BL-SIJ positive LBP individuals demonstrated a flat slope, the R-SIJ positive LBP individuals demonstrated a negative slope (until 30 deg) and the L-SIJ positive LBP individuals demonstrated a positive slope (after 30 deg). 2) The innominate trend of rotations of the SIJ-positive and SIJ-negative individuals demonstrated significant differences in the sagittal plane during the left HABER test positions. While Non-SIJ individuals demonstrated a positive slope of the sagittal plane innominate rotations with each increment of left HABER test, the L-SIJ positive and BL-SIJ positive LBP individuals demonstrated a positive slope until 30 deg followed by a negative slope after 30 deg of HABER test, and the R-SIJ positive LBP individuals demonstrated a negative slope until 30 deg followed by a positive slope after 30 deg of HABER test. 3) The SIJ-positive LBP individuals also demonstrated between-plane motion trading (i.e. a decrease of innominate rotations in one plane (viz., transverse plane) was accompanied by an increase in another plane (viz., sagittal plane) and vice-versa). For instance, the R-SIJ positive individuals in the left HABER test positions demonstrated a decrease in transverse plane innominate rotations and an increase in sagittal plane innominate rotations, specifically after 30 deg of Left HABER test position; and the L-SIJ positive and BL-SIJ positive individuals demonstrated a decrease in sagittal plane innominate rotations and an increase in transverse plane innominate rotations, specifically after 30 deg of Left HABER test position.

Asymmetric stiffness has been demonstrated previously in patients experiencing pregnancy related pelvic girdle pain (Damen et al., 2001, 2002). Moreover, Bussey and Milosavljevic (2013), also found a similar unilateral pattern in AS participants. They postulated this pattern may be related to SIJ structural changes in the AS group, but lacked radiographic evidence to support this notion.

While SIJ-positive individuals' demonstrated predominantly unilateral innominate movement patterns, the SIJ-negative individuals' demonstrated equal amounts of unilateral, as well as reciprocal innominate movement patterns. It is important to highlight that SIJ-positive participants were diagnosed based on the criterion standard of ≥ 3 positive pain provocation tests. Participants that did not meet this threshold were classified as SIJ-negative LBP, however a significant proportion (58%) of these individuals did demonstrate at least 1 positive pain provocation test. We believe that there are two likely scenarios for the significance of unilateral pattern in SIJ-negative group. Firstly, the unilateral pattern might suggest a secondary SIJ dysfunction in these SIJ-negative LBP participants, probably due to increased mechanical stress on the SIJ through faulty load transfer across the lumbo-pelvic complex. Secondly, the unilateral pattern might have a predictive role for SIJ pain in SIJ-negative participants under the threshold of 3 positive pain provocation tests (O'Shea et al., 2010; Madani et al., 2013), where individuals exhibiting such unilateral movement patterns could be at a higher risk of developing SIJ pain when compared with individuals exhibiting reciprocal movement patterns. Either way, the unilateral innominate movement pattern is putatively an outcome of the SIJ component of LBP, and the relationship of innominate movement patterns with the LBP of Non-SIJ origin needs further investigation via a prospective follow-up design of healthy controls.

The maximal innominate ROM did not demonstrate a significant association with the clinical groups. This non-significant association could be likely due to the smaller magnitudes of innominate ROM ($<4°$) along with larger amounts of intra- and inter-individual variability present, irrespective of clinical groups, a finding consistent with previous studies (Sturesson et al., 1989; Jacob and Kissling, 1995). Moreover, a non-linear relationship was observed between magnitude of innominate rotations and the standardised increments of HABER test (Fig. 4). Such non-linear trends imply that the greatest motion within the joints is not necessarily found at end point of hip movement, particularly in populations with SIJ pain.

The sagittal plane maximal innominate ROM, although demonstrated no significant between-group differences, were significantly associated with the HABER test side. The sagittal innominate ROM were greater when the left hip was stressed in HABER test position compared with the right hip, a finding consistent with previous study, albeit in healthy population (Bussey et al., 2009b). Similarly, the innominate trends of rotation also demonstrated a side effect, with different innominate motion coupling observed between the right and left HABER test positions. These findings support two previously described notions for SIJs. Firstly the two SIJ are not the mirror image of each other (Brunner et al., 1991; Boulay et al., 2006), and thus their movements not only possess a great deal of variability between-individuals, but also within-individuals (Bussey et al., 2009a, 2009b). Secondly, these findings are also suggestive of a differing axis of rotation for each innominate (Lavignolle et al., 1983; Plochocki, 2002). These notions, call into question the various clinical tests that a) are designed to diagnose innominate kinematic anomalies based on asymmetry between the two sides, and b) aims to stress the bilateral SIJs simultaneously.

The findings of present study are encouraging, although not without some limitations. Firstly, the participants evaluated included only a small sample of SIJ-positive LBP participants, primarily right dominant (97%) females (68%), with mild to moderate levels of pain and disability (Table 2). Thus the findings of present study cannot be generalized to populations with disparate clinical characteristics. Secondly, innominate bone deformations that may result from application of incremental load (Pool-Goudzwaard et al., 2012) would have affected the innominate kinematic measurements. However, an ad hoc analysis demonstrated no significant differences between the innominate vector lengths[2] at each increment of HABER test. Furthermore, the palpation-digitization measurement errors were $<2SEM$ (4.0 mm), and as determined in the sensitivity analysis by Adhia et al. (2012) will not have a significant influence on the innominate kinematic measurements.

The findings of the present study indicate that SIJ-positive LBP is not associated with the magnitude of innominate motion, but is significantly associated with the innominate movement patterns and trend of rotation. Future research studies evaluating the clinical assessment of innominate movements for diagnosis of SIJ-positive LBP, could thus allow a focus on direction of innominate movements and treatment strategies that would aim at restoring these movement direction anomalies. Further, the findings of the innominate trends of rotation suggest alterations in the trends and couplings at the end ranges, specifically after 30° of the HABER test. The treatment strategies could therefore be specifically targeted at those test positions instead of neutral position.

[2] The innominate vector length (for the purpose of the present study) is defined as the vector joining the highest point of the posterior superior iliac spine and the highest point of the anterior superior iliac spine (Adhia et al., 2012).

5. Conclusion

These investigations of innominate movements in two groups of non-specific chronic LBP participants indicate relationships between innominate kinematic anomalies and LBP of SIJ origin. While this cross sectional design does not allow discrimination of cause and effect relationship between innominate kinematics and SIJ pain, these findings are closely linked to the SIJ pain reproduction in people with clinically diagnosed LBP. These findings thus have led the groundwork for further exploration of clinical measurement, relevance, and management of these potentially important movement observations. Future prospective studies will seek to link increased risk of occurrence of clinical SIJ pain with specific baseline innominate movement patterns and trends of rotation.

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