Inter-tester reliability of non-invasive technique for measurement of innominate motion

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ABSTRACT
Although the complex anatomical orientation and position of the sacroiliac joints (SIJ) has rendered their 3D kinematic evaluation difficult, recent techniques of palpation—digitization of pelvic landmarks using electromagnetic tracking device have been able to accurately and non-invasively quantify the subtle SIJ kinematics. While this technique demonstrates radiographic validity and high test-retest reliability, it is yet to be assessed with regards to inter-tester and trial-to-trial reliability. A single-group repeated measure design using 4 testers was conducted to evaluate the inter-tester and trial-to-trial reliability of palpation—digitization technique for innominate vector length measurements using the Polhemus electromagnetic tracking device. Fourteen young, healthy adults between the ages of 18–40 years participated in the study. The innominate vector length was calculated from 3D co-ordinates of palpated and digitized pelvic landmarks in two test positions of hip. A sensitivity analysis was conducted to determine how palpation—digitization errors for pelvic landmarks impacts on innominate angle calculation. Reliability indexes of Intraclass correlation coefficient (ICC) (≥0.97) and Standard error of measurement (SEM) (≤2.02 mm) demonstrated very high inter-tester and trial-to-trial reliability and accuracy of palpation—digitization technique for innominate vector length measurements, irrespective of the two test positions. A higher consistency of measurements was obtained within-testers as compared to between testers, and sensitivity analysis demonstrated a negligible influence of palpation—digitization errors on the innominate angle measurements. The results support clinical and research utility of this technique for non-invasive kinematic evaluation of SIJ motion for this population. Further research on the use of this palpation—digitization technique in symptomatic population is warranted.

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1. Introduction

The observation and quantification of movement is an essential part of musculoskeletal clinical assessment, helping to establish baseline ranges of motion (ROM), determine movement quality, monitor progress, and guide appropriate implementation of treatment strategies (Smith, 1982). While instruments such as goniometers and inclinometers can quantify planar movements of most joints (Smith, 1982), the complex anatomical structure and orientation of the SIJ (McGrath, 2006) makes accurate, non-invasive, three dimensional (3D) kinematic evaluation of this articulation difficult (Goode et al., 2008).

Quantification of both planar and 3D SIJ movements have been explored since the early 20th century, with some authors describing small but complex movements occurring about all three orthogonal axes (Sturesson et al., 1989, 2000; Jacob and Kissling, 1995; Smidt et al., 1995, 1997; Wilke et al., 1997). Numerous devices and techniques have involved both in-vitro and in-vivo procedures for quantifying SIJ movements. Some techniques, which appear capable of accurately measuring 3D kinematics, include roentgen stereophotogrammetric analysis (RSA) (Sturesson et al., 1989), computerised axial tomography (CAT) scan (Smidt et al., 1997) and Kirchner wires (Jacob and Kissling, 1995). Although these techniques are accurate, the nature and increased radiation exposure makes clinical utility of such invasive techniques impractical. While non-invasive potentiometers (Perret et al., 2001) and inclinometers (Freburger and Riddle, 1999) are incapable of measuring 3D SIJ motions (Goode et al., 2008), the Polhemus electromagnetic tracking system is a non-invasive
procedure capable of accurately measuring 3D SIJ kinematics (Bussey et al., 2004, 2009).

Bussey et al. (2004) used the digitizing stylus of the Polhemus 3Space Fastrak electromagnetic movement tracking device when palpating and identifying the anterior and posterior superior iliac spines (ASIS & PSIS) of the innominate bones. Following palpation and digitization of these landmarks the femur was abducted and externally rotated to load the innominate through the hip joint and thus create movement at the SIJ. Innominate rotation about the sacrum was defined by its displacement from a neutral to a stressed hip position of abduction and external rotation. However, the determination of such angular innominate rotational displacement depends on the precise palpation—digitization of pelvic landmarks, namely the ASIS and PSIS, the distance between which was defined as the innominate vector length. Measurement error in innominate vector from palpation—digitization errors of pelvic landmarks would influence calculation of innominate angular displacement.

This non-invasive procedure is thus capable of quantifying SIJ 3D kinematics, and its use is considered an important advancement that can be used by clinicians as well as researchers. Measurement of innominate rotation has demonstrated radiological validity and excellent intra-tester reliability (Bussey et al., 2004) but has yet to be challenged for its inter-tester properties. In order to demonstrate clinical and research utility it is obvious that this method needs to be reliable across different examiners. Thus the primary aim of this study is to determine inter-tester and trial-to-trial reliability of innominate bone vector length measurements using the Polhemus electromagnetic tracking system, and to determine whether alteration of hip position impacts on measurement reliability. The secondary aim of this study is to determine how variance in palpation—digitization of pelvic landmarks for innominate vector length measurement impacts on calculation of innominate rotations about the sacrum.

2. Methods

2.1. Study design and settings

A single-group, repeated measures design, using four independent testers was conducted in the Biomechanics laboratory of School of Physical Education, at the University of Otago in Dunedin, NZ. This study was approved by the School of Physiotherapy Human Ethics Committee, University of Otago, NZ.

2.2. Participants

A sample size of 14 healthy individuals was considered adequate for this study design to predict an ICC of 0.9 ± a 95% confidence interval of 0.1 (Giraudeau and Mary, 2001; Karamicolas et al., 2009). A convenience sample of 7 males and 7 females aged between 18 and 40 years were voluntarily recruited from the staff and students at the University of Otago. Any potential participants who had a current or past history of low back or hip disorders, lumbar/sacral nerve root compromise, lower extremity joint disorders, known spinal pathology (viz., tumour, infection, fracture and inflammatory disease), spinal surgery or if pregnant were excluded from the study.

2.3. Testers and training

Four physiotherapists with varying levels of clinical experience (ranging from 1 to 10 years) but no prior electromagnetic palpation—digitization experience volunteered to take part in the study. Instrument familiarization, tester training and technique standardization are considered important for minimizing tester variability (Smidt et al., 1992). A researcher (MDB), with expertise in palpation—digitization with the Polhemus electromagnetic tracking device provided familiarization and training to all four testers for 2 one-hour sessions, 3 weeks prior to the start of study. Based on consensus between the testers and the expert (MDB), the palpation—digitization technique for pelvic landmarks was standardized to palpating and identifying the iliac crest followed by tracing this landmark posteriorly and anteriorly to reach the highest prominence of PSIS and ASIS respectively. Following training of the testers the expert (MB) took no further part in observation, measurement or analysis. The order of the testers was randomized and each tester was blinded to the measurements taken by the remaining testers.

2.4. Test positions

Pelvic landmarks (ASIS and PSIS) were palpated and digitized in prone-lying. Two hip positions (Fig. 1), neutral hip (Neu) and combined hip abduction-external rotation (ER + AB), were required to determine the angular rotations of the innominate (Bussey et al., 2004). To ensure standardization across all testers, a single tester (DBA) positioned the participants in the desired test position using the hip rotation frame (Bussey et al., 2004). The ER + AB test position was achieved by moving the right hip through 20° of abduction followed by 20° of external rotation. The positional order was block randomized with each tester reversing the sequential hip test position order of the previous tester.

2.5. Instrumentation

Kinematic data were collected from each participant using the six degree of freedom Polhemus Liberty™ (Colchester, VT, US) electromagnetic tracking device, consisting of a system electronic unit, one source, one sensor and a 3D digitizing stylus. At a frequency of 240 Hz per sensor, this system has a resolution of 0.004 mm for position and 0.001° for orientation. At a 300 mm

![Fig. 1. Two test positions of hip.](image-url)
range the static accuracy of the global system is 0.79 mm. The global system (i.e., the source), mounted to the standardizing frame, was transformed as the local reference sensor, which was attached to the skin over the 3rd lumbar spinous process of each participant. As the present study outcome is heavily reliant upon the accuracy of the local Polhemus system (i.e., position measure between two sensors as opposed to the source and sensor), a study was conducted to measure the static accuracy of the local system. This was done by taking ten measures at ten different known distances within our calibration volume and calculating the range of difference across the measures. From this study the static accuracy of the Polhemus local reference system was found to be 0.015 mm.

2.6. Procedures

Following written informed consent, each participant attended a 2 h testing session diurnally standardized from 9:00am to 11:00am. Demographic and anthropometric data (age, sex, height, weight, skin fold measurements) were gathered from each participant by the principal investigator (DBA). Skin fold measurements were taken from the chest, abdomen and thigh of males; and the triceps, supra-ilium and thigh of females (Jackson and Pollock, 1985). All participants were positioned in prone-lying on the standardized testing table with the source of the electromagnetic tracking device attached. The local system sensor was secured using adhesive tape over the 3rd lumbar spinous process for each participant. Each participant was positioned in the desired block randomized test position using the standardized hip rotation frame (Bussey et al., 2004). The same test-procedure was performed independently by each tester in their random order. The test-procedure involved palpating and identifying the right PSIS and ASIS in that order. The most prominent part of the palpated landmark was digitized using the 3D digitizing stylus pen of Polhemus system. The tip of the stylus pen was kept perpendicular to landmark in order to standardize the digitization method. Each tester re-palpated and digitized the landmarks independently and consecutively for 5 trials in the two different test positions. In order to minimise for a creep response at the joint, a rest period of about 10 min was provided between each tester and each position.

2.7. Data reduction and analysis

The 3D spatial co-ordinates for each pelvic landmark with respect to the local coordinate system were obtained from the proprietary written computer software (LibCtrl developed by the School of Physical Education, University of Otago, Dunedin, NZ) connected to the electromagnetic tracking system. Two vectors were defined based on the digitized landmarks; one vector (VOD) pointing from L3 (O) to ASIS (D) and another vector (VOB) pointing from the L3 (O) to PSIS (B) (Fig. 2). The vector length of the innominate bone was defined as the difference between the two vectors [VBD = (VOD − VOB)]. The vector length of the innominate bone in both test positions was calculated from the available 3D pelvic co-ordinates using a transformation matrix embedded in Matlab™. The 5 individual trials of innominate vector lengths measured by each tester for each participant in both the test positions were used for trial-to-trial reliability analysis. The mean of the 5 trials, as calculated in the data sheet, was used for inter-tester reliability analysis.

All statistical analyses were performed using SPSS version 16.0 for Microsoft Windows™. Following the calculation of mean and standard deviations of all demographic data and innominate vector lengths, relative reliability was determined by use of the ICC (Shrout and Fleiss, 1979). The ICC2,3 and ICC2,5 (two-way random effects model) together with their 95% confidence intervals (CIs) were used for analysing trial-to-trial and inter-tester reliability respectively. Absolute reliability was determined by the SEM and its percentage (SEM%) (Beckerman et al., 2001). The calculated inter-tester SEM was then used for the secondary aim (sensitivity analysis) of the study.

2.8. Sensitivity analysis

To determine the influence of palpation—digitization variance in calculated innominate vector length on angular displacement about the SIJ, five subjects were randomly selected from the sample of 14. These five subjects underwent a further palpation—digitization procedure by a single tester (DBA) in a neutral test position. The pelvic landmarks of right ASIS and PSIS, and left PSIS were palpated and digitized for 5 trials. The innominate angle was calculated from the two vector lengths, namely the PSIS vector (VBA) and innominate vector (VBD) using the equation:

$$\theta = \cos^{-1}\left(\frac{\|V_{BA} \cdot V_{BD}\|}{\|V_{BA}\| \cdot \|V_{BD}\|}\right)$$

Assuming normal distribution of measurement error and the SEM being the standard deviation of measurement errors, the probability of the original measurement to fall within 1 SEM and 2 SEM is 68% and 96% respectively (Domholdt, 2005). In order to determine the 96% probability of the influence of measurement

![Fig. 2. Innominate vector length Point O = Local sensor at 3rd lumbar spine, Point B = Digitized posterior superior iliac spine, Point D = Digitized anterior superior iliac spine, VOD = vector from 3rd lumbar spine to ASIS, VOB = vector from 3rd lumbar spine to PSIS, VBD = Innominate vector length determined using VOD and VOB (VBD = VOD − VOB).](image-url)
error, the 3D co-ordinates of pelvic landmarks (ASIS and PSIS) for each subject were manipulated to add or subtract 2 SEM (inter-tester SEM) to the obtained x (medial–lateral axis), y (superior–inferior axis) and/or z (anterior–posterior axis) co-ordinates of pelvic landmarks. The 3D co-ordinates of each landmark were manipulated independently (±2SEM) as well as simultaneously (±1SEM to each landmark) in various combinations to determine the worst case scenario. The manipulated 3D co-ordinates of pelvic landmarks were then used for innominate angular calculations about the sacrum, and the difference between obtained original and manipulated angles determined.

3. Results

The 7 males and 7 females had a mean age of 26.14 (±SD of 6.28) and 26.86 (±6.91) years; a mean BMI of 23.05 (±3.44) and 21.20 (±1.21) kg/m²; and a mean percent body fat composition (PBF) of 11.03 (±3.52) and 19.73 (±4.9%) respectively. The mean innominate segment length measurements ranged between 158.10 (±14.67) mm and 160.50 (±8.42) mm for males and females respectively.

The trial-to-trial and inter-tester ICCs (±95% CI) and SEMs are presented in Table 1. Trial-to-trial and inter-tester ICC along with narrow 95% CIs acquired in this study demonstrates very high reliability (Munro, 2005) independent of both the test positions. The mean SEM value ranged from 0.53 to 0.55 mm for individual testers and 1.99–2.02 mm for between testers. The percentage SEM relative to innominate length was less than 1.3% for individuals as well as between testers.

The differences between the original and manipulated innominate angles about the sacrum of the 5 subjects used for sensitivity analysis are presented in Table 2. The worst case scenarios were found when the co-ordinates of pelvic landmarks were manipulated simultaneously in y and/or z axis. The maximum difference (2.29°) in innominate angle measurements was found when the ASIS and PSIS co-ordinates changed by ±1SEM each (4.04 mm in total) in y and z axis respectively (Table 2) and the mean difference of this manipulated combination was 2.04° resulting in a mean measurement difference between the original and manipulated innominate angle of 1.84%.

4. Discussion

The results of this study demonstrate very high inter-tester and trial-to-trial reliability of palpation–digitization technique for innominate vector length measurements using the Polhemus electromagnetic tracking device across 4 testers. Similar reliability statistics (ICC = 0.972 and SEM = 2.02 mm) were observed in both Neu as well as ER + AB hip test positions and thus demonstrate no influence of test position on measurement reliability. These results are in accordance with previous research by Smidt et al. (1992) and Bussey et al. (2009). Bussey et al. (2009) reported intra-tester test-retest ICCs of 0.977 (95% CI = 0.941–0.992) and 0.971 (95% CI = 0.941–0.994) for loaded (ER + AB hip) and unloaded (Neu hip) innominate positions respectively. Smidt et al. (1992) also reported high intra- and inter-rater ICCs of 0.86–0.99 for palpation–digitization of pelvic landmarks in normal individuals. While Smidt et al. (1992) demonstrated a high relative reliability; the reported error magnitude was comparatively much larger (5.7 mm) than the current study (2.02 mm) and those reported by Bussey (2010) (0.3 mm for each landmark). This can be partly attributed to use of Metrecom Skeletal Analysis System (MSAS) with the high positional error of 2.7 mm identified by Smidt et al. (1992) compared to the 0.76 mm static positional error in the Polhemus device used in the present study.

Measurement error between testers is influenced by tester, procedure and participant-related variability. The minimal inter-tester palpation–digitization innominate measurement error obtained in this study can be attributed to the standardized methodology. First, a single tester positioned the participant in the desired test positions. Second, the palpation–digitization technique was standardized for all testers and the testers were clearly instructed to palpate–digitize the bony landmark as firmly as could be tolerated by the participant. Third, the mean of 5 trials per participant was taken in order to obtain the most accurate identification of the 3D landmark co-ordinates. Finally, the passive nature of the test procedure minimized the error effect of muscle contraction on joint position.

The mean inter-tester length measurement error (2.02 mm) was greater than the within-tester trial-to-trial error (0.55 mm), logically revealing a greater consistency of measurements within-testers than between testers. This indicates that some tester-related factors contributed to this difference in consistency. The variable range of measurement error (0.36–0.85 mm) possibly reveals differing levels of manual dexterity skills amongst the testers and may be due to the differences in clinical experience (ranging from 1 to 10 years). Higher sensory function of the fingers is one of the major components determining manual dexterity. Variability in higher sensory functions, namely two point discrimination and stereognosis, is shown to exist between different fingers, its surfaces and age groups (Nolan, 1982). Although such variability cannot be inferred from this study, it may be that testers used different fingers and surfaces for palpation. Moreover the test-procedure in this study involved manually collecting 3D co-ordinates of landmarks by digitizing the palpated landmark. Hence the varying levels of force applied or depth attained during palpation–digitization of landmarks can also be liable for inter-tester variability (Fryer, 2006). Although these factors would have contributed to tester-related variability, no attempts were made to control these factors, resembling a true clinical situation and hence strengthening the external validity of the study.

Error in the location and measurement of bony landmarks has shown to result in measurement discrepancy of 3D angular movements of a joint (Moriguchi et al., 2009). As the innominate angle was dependent on accurate palpation–digitization of pelvic landmarks, any errors in palpation–digitization of pelvic

<table>
<thead>
<tr>
<th>Reliability</th>
<th>Tester</th>
<th>ICC (95% CIs)</th>
<th>SEM (mm)</th>
<th>SEM %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Neu ER + AB</td>
<td>Neu ER + AB</td>
<td></td>
</tr>
<tr>
<td>Trial-to-trial reliability</td>
<td>T1</td>
<td>0.998 (0.995–0.999)</td>
<td>0.998 (0.995–0.999)</td>
<td>0.53 0.55</td>
</tr>
<tr>
<td></td>
<td>T2</td>
<td>0.999 (0.998–1.000)</td>
<td>0.999 (0.997–1.000)</td>
<td>0.38 0.40</td>
</tr>
<tr>
<td></td>
<td>T3</td>
<td>0.996 (0.991–0.999)</td>
<td>0.995 (0.989–0.998)</td>
<td>0.85 0.73</td>
</tr>
<tr>
<td></td>
<td>T4</td>
<td>0.998 (0.995–0.999)</td>
<td>0.997 (0.997–1.000)</td>
<td>0.36 0.51</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>0.998 (0.995–0.999)</td>
<td>0.998 (0.995–0.999)</td>
<td>0.53 0.55</td>
</tr>
<tr>
<td>Inter-tester reliability</td>
<td>All</td>
<td>0.972 (0.919–0.991)</td>
<td>0.971 (0.924–0.990)</td>
<td>2.02 1.99</td>
</tr>
</tbody>
</table>

lands marks for innominate vector length measurements across testers poses a threat to accurate innominate angular measurements. Although this study demonstrated low inter-tester measurement errors for palpation-digitization of pelvic landmarks for innominate vector length measurements, a sensitivity analysis was essential to determine how much this measurement error influenced the innominate angular measurements. The results of the sensitivity analysis (Table 2) demonstrated a negligible (1.84%) influence of palpation-digitization errors of pelvic landmarks on innominate angular measurements. This result further supports a high level of accuracy and reliability for intra- and inter-rater innominate angular measurements using this palpation-digitization technique of pelvic landmarks.

Assessment of SIJ motion using palpation of pelvic landmarks is a common clinical practice. Several studies evaluating reliability assessment using palpation have consistently shown poor reliability. However, the major component of those assessment procedures relies on a subjective outcome measure which may be more susceptible to rater bias. In contrast, the use of the palpation-digitization technique using Polhemus electromagnetic tracking device provides an objective outcome measure which should be less susceptible to rater bias. The manual digitization of the pelvic landmark in each of the test positions minimizes error caused by the skin movement or position, thus avoiding the “palpatory illusion” created by subcutaneous and extra-articular soft tissue tension (Cattley et al., 2002). The non-invasive nature, small measurement error and very high levels of inter(& intra)-rater reliability amongst testers unfamiliar to the use of an electromagnetic tracking device strongly suggests easy use and adaptation of this technique by clinicians or researchers with a musculoskeletal background.

4.1. Study limitations

Inter-rater reliability of innominate vector length measurements were performed on a relatively small sample of young healthy individuals without any history of low back pain. Hence the reliability of this test-procedure cannot be generalised to SIJ pain patients or to either older or younger subjects whose anthropometric measurements are disparate from the sampled group. Further studies are required to assess the SIJ mobility and reliability of subjects whose age, anthropometric and clinical features were not accounted for in this study. The second limitation includes the use of research based (Matlab™) software to calculate the innominate vector length measurements from the obtained 3D coordinates. The Matlab™ programming may not be well understood by clinicians and further “clinician-friendly” software may need to be developed. Although each tester was not allowed to observe the palpation identification of the other testers, the 5 intra-tester trials of palpation—digitization of bony landmarks were done consecutively with minimal time between palpations, with only a 10 min break between testers. Cutaneous visual (pressure) impressions from the firm palpation technique may have added a bias for consecutive testers using the previous landmark identification. This bias may have influenced the results, however, the randomized design should minimise this effect in the final analysis.

5. Conclusion

The palpation—digitization of the ASIS and PSIS pelvic landmarks with the digitizing stylus of the Polhemus electromagnetic tracking device demonstrated very high inter-tester and trial-to-trial reliability for innominate vector length measurements irrespective of the two test positions. The small innominate vector length measurement errors and its negligible influence on the innominate angle measurements demonstrates clinical and research utility of this technique with high levels of accuracy and reliability, and supports and gives credence to the previously published data.

Acknowledgements

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Table 2
Influence of pelvic landmark (ASIS and PSIS) positional errors on innominate angle measurements.

<table>
<thead>
<tr>
<th>Subjects</th>
<th>Original # (degrees)</th>
<th>Manipulated # (degrees)</th>
<th>Difference in # (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ASIS y+ - PSIS y-</td>
<td>ASIS z - PSIS z+</td>
<td>ASIS y+ - PSIS y-</td>
</tr>
<tr>
<td>1</td>
<td>108.76</td>
<td>110.07</td>
<td>110.08</td>
</tr>
<tr>
<td>2</td>
<td>110.18</td>
<td>111.53</td>
<td>111.87</td>
</tr>
<tr>
<td>3</td>
<td>108.43</td>
<td>109.90</td>
<td>109.88</td>
</tr>
<tr>
<td>4</td>
<td>110.80</td>
<td>112.08</td>
<td>112.51</td>
</tr>
<tr>
<td>5</td>
<td>114.97</td>
<td>116.25</td>
<td>116.95</td>
</tr>
<tr>
<td>Mean</td>
<td>110.63</td>
<td>111.97</td>
<td>112.26</td>
</tr>
</tbody>
</table>

ASIS: Anterior superior iliac spine, PSIS: Posterior superior iliac spine, y: Innominate angle, y axis: superior—inferior axis, z axis: anterior—posterior axis, ASIS y+ - PSIS y-: ASIS moves superiority and PSIS moves inferiorly, ASIS z - PSIS z+: ASIS moves posteriorly and PSIS moves anteriorly, ASIS y+ PSIS z+: ASIS moves superiority and PSIS moves anteriorly.


