HIP AND LUMBOSACRAL JOINT CENTRE LOCATIONS IN ASIAN POPULATION: BIASES BY EXISTING REGRESSIONS AND DEVELOPMENT OF NEW METHODS

Natsuki Sado[1], Takeshi Edagawa[2], Toshihide Fujimori[2], Shogo Hashimoto[3], Yoshikazu Okamoto[4], Takahito Nakajima[4]

Faculty of Health and Sport Sciences, University of Tsukuba, Tsukuba, Japan[1]
Graduate School of Comprehensive Human Sciences, University of Tsukuba, Tsukuba, Japan[2]
School of Physical Education, Health and Sport Sciences, University of Tsukuba, Tsukuba, Japan[3]
Faculty of Medicine, University of Tsukuba, Tsukuba, Japan[4]

Accurate prediction of the lumbosacral and hip joint centres (LSJC, HJC) is crucial for the analysis of lumbo-pelvic-hip dynamics in various movements. Here we show that pre-existing regressions proposed by European research groups produce biased estimates of the LSJC and HJC in Japanese males and females (n = 23, 24), and that the biases in LSJC depend on sex. Whesn compared to locations directly measured by MRI, the pre-existing regressions estimated the LSJC to be more posterior in males and more inferior and posterior in females, and the HJC to be more medial for both sexes. We suggest the importance of considering racial and sexual differences in morphology. We propose new regressions for Asians and validate them using leave-one-out cross-validation. Our regression can be a powerful solution for accurate motion analysis in Asians.

KEYWORDS: MRI, MORPHOLOGY, SEX DIFFERENCE, MOTION ANALYSIS, PELVIS

INTRODUCTION: Accurate prediction of the lumbosacral and hip joint centres (LSJC and HJC) is crucial for the analysis of lumbo-pelvic-hip dynamics in various movements. Since LSJC and HJC cannot be palpated, prediction methods are necessary. Two types of methods exist for defining HJC: functional and regression methods. The functional method defines HJC as the common centre of rotation of thigh marker trajectories relative to the pelvis and is considered the gold standard (Camomilla et al. 2006). However, according to the guidelines of Camomilla et al. (2006), the functional method requires a range of motion (RoM) of at least 60° flexion-extension and 30° abduction-adduction. This may not be possible in some cases, such as studies on the recovery process from injuries that limit RoMs. In these cases, a regression method is necessary. The functional method cannot be applied to the LSJC because the spine is not a rigid object, and the centre of rotation cannot be calculated functionally. Therefore, regression methods for HJC and LSJC are necessary.

Several regression methods using pelvic dimensions have been proposed for the LSJC and HJC. A systematic review by Kainz et al. (2015) concluded that the method of Harrington et al. (2007) is the most reliable regression for HJC. For LSJC, Peng et al. (2015) proposed two methods: 1) regressions with revised coefficients from Murphy et al. (2011) and Reed et al. (1999), and 2) estimation of locations that satisfy the constancy of distances (estimated by regression) from multiple landmarks (ALs), and showed the smallest error in Murphy's revised coefficients (8.0 mm) compared to other methods (≥ 8.6 mm). These Harrington's and Peng's regressions are currently considered optimal for HJC and LSJC. However, although they are based on research by European groups, pelvic morphology varies by race. In forensic and skeletal anthropology, pelvic morphology can accurately discriminate race (88%), with pelvic width contributing significantly to the discrimination (Işcan, 1983). Thus, these pre-existing methods may produce biases in non-Europeans (e.g., Asians).

We measured LSJC and HJC in Japanese adults using Magnetic Resonance Imaging (MRI) and compared their estimated locations with the regression of LSJC with minimal error reported in Peng et al. (2015) and the regressions of HJC (Harrington et al., 2007). We hypothesized that the Peng’s and Harrington’s regressions produce biased estimations in Asians. Further we propose and validate new regression equations for LSJC and HJC in Asians.

METHODS: We recruited a total of 47 (23 males and 24 females) healthy Japanese adults (Table 1), which satisfies the sample size of 17 for each sex based on a power analysis for the multiple one-sample *t*-tests with α = 0.0015 [33 tests with overall α = 0.05], 1-β = 0.80, and *d* = 1.2 [very large (Sawilowsky, 2009)]. The Human Research Ethics Committee at University of Tsukuba approved the experimental protocol (PE021-140).
We measured body height (BH) and mass to the nearest 1 mm and 50 g, respectively. Axial MRIs of the pelvis in the supine position (Fig. 1A) were obtained using a 3.0-T MRI scanner (Philips Medical Systems, Netherlands) with a 3D mDIXON sequence (TE: 2.37 ms, TR: 3.16 ms, thickness: 4 mm with 50% overlap [2 mm inter-slice], field of view: 500 × 500 mm, matrix: 512 × 512). To derive the 3D coordinates of joint-related points (the anterior inferior 5th lumbar spine [$L5_{AI}$], the posterior superior 1st sacral spine [$S1_{PS}$], and 30 points on the femoral head surfaces) and the points closest to the anterior and posterior superior iliac spines [ASIS, PSIS] on the skin, an examiner (N.S.) digitised those points using OsiriX v.13 (Pixmeo, Geneva, Switzerland). The same process was performed by another examiner (T.E.) on 18 randomly selected participants (nine in each sex) to confirm the reliability of manual digitising.
LSJC was defined as the midpoint between $L5_{AI}$ and $S1_{PS}$ (Peng et al., 2015). HJC was defined using a least-squares calculation for a sphere fitting of 30 points on the right and left femoral head surfaces (Harrington et al., 2007). We defined a right-handed orthogonal pelvic coordinate system ($\boldsymbol{\Sigma}_{\mathbf{Pel}}$; Fig. 1B) using the 3D coordinates of the ASISs and PSISs (Sado et al. 2020). The unit vectors $\boldsymbol{i}_{\mathbf{Pel}}$, $\boldsymbol{j}_{\mathbf{Pel}}$ and $\boldsymbol{k}_{\mathbf{Pel}}$ defined the positive directions of $\boldsymbol{x}_{\mathbf{Pel}}$ (right) $\boldsymbol{y}_{\mathbf{Pel}}$ (forward) and $\boldsymbol{z}_{\mathbf{Pel}}$ (upward) axes**,** respectively. The position vectors from ASISs' midpoint to LSJC and to HJCs were calculated and expressed on $\boldsymbol{\Sigma}_{\mathbf{Pel}}$. We calculated the pelvic width (PW: the distance between the right and left ASISs) and depth (PD: the distance between midpoints of ASISs and PSISs) (Fig. 1B). We confirmed interrater reliability in these 3D position vectors and the pelvic dimensions using intra-class correlation coefficients (ICCs). ICCs were classified based on Landis and Koch (1977). Using the pelvic dimensions, we calculated the estimated HJC and LSJC locations by the regression methods (Harrington et al., 2007; Peng et al., 2015). Peng et al. (2015) exhibited two equations with revised coefficients of Murphy et al. (2011) for LSJC height ($\hat{z}_{\mathrm{LSJC}}$) (reported a single absolute error) but did not explain how those two should be used separately. Thus, we tested both regressions. The normal distribution of variables was confirmed using Shapiro-Wilk test. We developed new equations for LSJC and HJC predictions as the following form:

$$\boldsymbol{r}_{\overline{\mathbf{ASIS_{MID}} \to \mathbf{LSJC}}} = \hat{y}_{\mathrm{LSJC}}\boldsymbol{j}_{\mathbf{Pel}} + \hat{z}_{\mathrm{LSJC}}\boldsymbol{k}_{\mathbf{Pel}}, \text{ and}$$
$$\boldsymbol{r}_{\overline{\mathbf{ASIS_{MID}} \to \mathbf{HJC}}} = \hat{x}_{\mathrm{HJC}}\boldsymbol{i}_{\mathbf{Pel}} + \hat{y}_{\mathrm{HJC}}\boldsymbol{j}_{\mathbf{Pel}} + \hat{z}_{\mathrm{HJC}}\boldsymbol{k}_{\mathbf{Pel}}. \quad (1)$$

To predict those coefficients ($\hat{x}_{\mathrm{Jnt}}$, $\hat{y}_{\mathrm{Jnt}}$, $\hat{z}_{\mathrm{Jnt}}$), we used least absolute shrinkage and selection operator (LASSO) regression, instead of stepwise multiple-regression, as it is a more robust method for variable selection, and less prone to overfitting. To select the best LASSO model, the regularization parameter was chosen based on the minimal mean squared error in leave-one-out cross-validation (LOOCV). LOOCV involves selecting one out of n participants, as the target and using the remaining $n-1$ participants as the training set. This process is repeated for all n participants, so that each participant serves as the target exactly once. The independent variables were PW, PD, BH, and SEX (a dummy variable, 1 for males and 0 for females). Some studies have used pelvic height (Reed et al., 1999) or leg length (Hara et al. 2016) as predictors for LSJC or HJC, but we decided not to use them for our analysis. Pelvic height measurements via palpation of the pubic symphysis is not practical for clinical and motion capture purposes. Leg length measurements have low inter-rater reliability (Harrington et al., 2007). As an

Table 1 Participants parameters.

	Male (n = 23)			Female (n = 24)		
	Mean	±	SD	Mean	±	SD
Age [yrs]	24	±	2	23	±	3
BH [mm]	1718	±	61	1600	±	59
Mass [kg]	69.45	±	9.50	55.59	±	6.64
PW [mm]	230.4	±	11.9	226.6	±	17.1
PD [mm]	163.8	±	10.6	163.5	±	8.8
$\hat{y}_{\mathrm{LSJC}}$	-80.2	±	8.0	-81.0	±	6.2
$\hat{z}_{\mathrm{LSJC}}$	26.2	±	6.5	33.6	±	7.9
$\hat{x}_{\mathrm{HJC}}$	88.1	±	4.2	87.4	±	3.8
$\hat{y}_{\mathrm{HJC}}$	-50.6	±	5.8	-47.8	±	5.9
$\hat{z}_{\mathrm{HJC}}$	-81.4	±	5.0	-79.9	±	5.5

BH: body height; PW, PD: pelvic width and depth; $\hat{x}_{\mathrm{Jnt}}$, $\hat{y}_{\mathrm{Jnt}}$, $\hat{z}_{\mathrm{Jnt}}$: lateral, anterior, and superior distances from the midpoint of ASISs; LSJC, HJC: lumbosacral and hip joint centres.

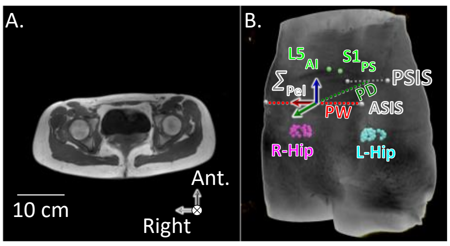

Figure 1 MRI (a) and 3D maximum intensity projection (B).

alternative to leg length, we used BH, a simple and reliable method that does not require special skills for palpation. In addition, an interaction term between SEX and each dimensional variable was added to the model to consider the possibility that the influence extent of each dimension may differ between sexes. To evaluate the biases in the pre-existing regression and in our regressions, we used one-sample *t*-test to determine if each of directional components of the relative positions from the measured to the predicted LSJC and HJC (LOOCV for our regression) was significantly different from zero. The alpha level of each one-sample *t*-test was adjusted via Bonferroni inequality (i.e., 0.0015 [0.05/33] for each *t*-test), with a total of 33 tests of the biases in 6 pre-existing regressions ($\hat{y}_{\mathrm{LSJC}}$, $\hat{z}_{\mathrm{LSJC}}$ [two regressions], $\hat{x}_{\mathrm{HJC}}$, $\hat{y}_{\mathrm{HJC}}$, $\hat{z}_{\mathrm{HJC}}$) in 3 groups (male, female, pooled) as well as in 5 LOOCVs of our regressions ($\hat{y}_{\mathrm{LSJC}}$, $\hat{z}_{\mathrm{LSJC}}$, $\hat{x}_{\mathrm{HJC}}$, $\hat{y}_{\mathrm{HJC}}$, $\hat{z}_{\mathrm{HJC}}$) in 3 groups. We used a paired *t*-test to compare the absolute error in each direction between our LOOCV and the pre-existing method applied to our data. Cohen's *d* was calculated as an effect size for each of *t*-tests. The alpha level was set to 0.05.

RESULTS AND DISCUSSION: The interrater reliability was 'almost perfect' for the LSJC's and HJCs' locations, as well as pelvic dimensions (ICC(2,1) $\geq$ 0.90). When compared to the directly measured locations, Peng's regressions estimated LSJC to be significantly more posterior for males and more posterior and inferior for females ($p < 0.001$, Table 2). Harrington's regressions estimated HJC to be significantly more medial for both sexes ($p < 0.001$, Table 2). In this study, the averages and SDs of BH and body mass were well similar to those in 20–24 years old Japanese in 2021 Government statistics (Government of Japan, 2022); our data would reflect the Japanese adults. Thus, we suggest that pre-existing regressions on Europeans (Harrington et al., 2007; Peng et al., 2015) lead to biased estimation of LSJC and HJC locations in Asians and that considering racial differences in morphology can improve accuracy in joint centre definitions for analysing lumbo-pelvic-hip dynamics. However, we were not able to measure Europeans directly, and we cannot discuss whether the pre-existing regressions had some biases for Europeans, which is a limitation of this study. The bias in the pre-existing regression for the HJC was similar between sexes; however, the bias in pre-existing regression for LSJC differed by sex. Furthermore, the better pre-existing regression of $\hat{z}_{\mathrm{LSJC}}$ differed by sex, with the PW-basis being better for males and the PD-basis being better for females, (Table 2). Thus, sexual difference should also be considered for accurate LSJC estimations. Meanwhile, our data are only from young adults. Age-dependency is an issue for the future.

We developed regression equations for locating LSJC and HJC from anatomical landmarks on skin (Table 3). LOOCV revealed that the biases produced in our model were negligible in any direction for LSJC (≤ 0.5 mm, $p > 0.61$) and for HJC (≤ 0.5 mm, $p > 0.88$). LOOCV had significantly smaller absolute errors for $\hat{y}_{\mathrm{LSJC}}$, $\hat{x}_{\mathrm{HJC}}$, and $\hat{z}_{\mathrm{HJC}}$ than those produced by pre-existing regressions and similar errors for other parameters (Table 3). In particular, the absolute error in $\hat{y}_{\mathrm{LSJC}}$ of our model was less than half of that in Peng's regression. In general, errors in the anteroposterior joint location induce critical errors in the sagittal kinetics (Stagni et al. 2000). Motor tasks requiring large hip extension torque involve large lumbosacral extension torque (Sado et al., 2020). The improved accuracy in LSJ position leads to accurate assessment of lumbo-pelvic-hip dynamics, thereby contributing to future studies in Sports Biomechanics for injury prevention and motor performance. However, note that regression methods cannot eliminate errors due to individual variations in pelvic morphology. In particular for HJC, the gold standard is a functional method. When analysing individuals with sufficient RoM, the functional method should be used. The use of regression methods should be accompanied by an understanding of the limitations.

Table 2 3D biases of the estimated locations by pre-existing regressions.

	Bias [mm]			
	Prev. regress.			
	Male	Female	Pooled	
	Mean ± SD	Mean ± SD	Mean ± SD	
$\hat{y}_{\mathrm{LSJC}}$	**-13.2 ± 7.1**	**-12.2 ± 4.1**	**-12.7 ± 5.7**	
$\hat{z}_{\mathrm{LSJC}}$	-0.9 ± 6.8	**-8.7 ± 7.9**	**-4.9 ± 8.3**	†PW
	3.3 ± 7.2	-4.2 ± 7.2	-0.5 ± 8.1	†PD
$\hat{x}_{\mathrm{HJC}}$	**-4.8 ± 4.9**	**-5.3 ± 5.6**	**-5.1 ± 5.2**	
$\hat{y}_{\mathrm{HJC}}$	1.4 ± 4.4	-1.3 ± 5.0	0.0 ± 4.9	
$\hat{z}_{\mathrm{HJC}}$	1.4 ± 6.3	1.0 ± 7.3	1.2 ± 6.7	

Significant differences from 0 (i.e., bias) were shown in bold. †PW and †PD mean PW- and PD-basis regression in Peng et al. (2015) revising Murphy et al. (2011). $\hat{x}_{\mathrm{Jnt}}$, $\hat{y}_{\mathrm{Jnt}}$, $\hat{z}_{\mathrm{Jnt}}$: lateral, anterior, and superior distances from the midpoint of ASISs; LSJC, HJC: lumbosacral and hip joint centres.

Table 3 Regressions for LSJC and HJC locations and their errors' evaluations.

	Regression equation (in mm)	R^2	Absolute error [mm] LOOCV Mean ± SD	Absolute error [mm] Prev. regress. Mean ± SD		Comparison P	Comparison d
Pooled							
$\hat{y}_{\mathrm{LSJC}}$	-19.652-0.372PD	0.36	4.5 ± 3.8	12.7 ± 5.7		**< 0.01**	**1.29**
$\hat{z}_{\mathrm{LSJC}}$	17.180+(0.099-0.042SEX)PD	0.24	6.1 ± 4.3	7.3 ± 6.3	†PW	0.14	0.22
				6.3 ± 4.9	†PD	0.61	0.07
$\hat{x}_{\mathrm{HJC}}$	54.807+0.005BH+0.059PW+0.064PD	0.17	3.3 ± 2.3	5.8 ± 4.4		**< 0.01**	**0.53**
$\hat{y}_{\mathrm{HJC}}$	9.155-0.018BH+0.136PW-0.360PD-0.958SEX	0.53	3.5 ± 2.9	4.0 ± 2.7		0.19	0.19
$\hat{z}_{\mathrm{HJC}}$	-5.795-0.069BH+(0.105+0.027SEX)PW+0.075PD	0.47	3.6 ± 2.2	5.7 ± 3.7		**< 0.01**	**0.59**

SEX = 1 (males) or 0 (females). †PW and †PD mean PW- and PD-basis regression in Peng et al. (2015) revising Murphy et al. (2011). $\hat{x}_{\mathrm{Jnt}}$, $\hat{y}_{\mathrm{Jnt}}$, $\hat{z}_{\mathrm{Jnt}}$: lateral, anterior, and superior distances from the midpoint of ASISs; LSJC, HJC: lumbosacral and hip joint centres.

CONCLUSION: Pre-existing regression models for LSJC and HJC, proposed by European research groups, produce biased locations in Asians. We suggest the need to consider racial and sexual differences in morphology to locate LSJC and HJC. The new regressions for Asians considering sex differences can lead to a more accurate biomechanical analysis of lumbar-pelvic-hip dynamics in all cases for LSJC and in cases of motion assessment under limited RoM, such as rehabilitation from injury, for HJC.

REFERENCES

Camomilla, V., Cereatti, A., Vannozzi, G., & Cappozzo, A. (2006). An optimized protocol for hip joint centre determination using the functional method. *Journal of Biomechanics*, *39*(6), 1096–1106. https://doi.org/10.1016/j.jbiomech.2005.02.008

Government of Japan. (2022). *e-Stat: Portal Site of Official Statistics of Japan*. https://www.e-stat.go.jp/en

Hara, R., McGinley, J., Briggs, C., Baker, R., & Sangeux, M. (2016). Predicting the location of the hip joint centres, impact of age group and sex. *Scientific Reports*, *6*, 1–9. https://doi.org/10.1038/srep37707

Harrington, M. E., Zavatsky, A. B., Lawson, S. E. M., Yuan, Z., & Theologis, T. N. (2007). Prediction of the hip joint centre in adults, children, and patients with cerebral palsy based on magnetic resonance imaging. *Journal of Biomechanics*, *40*(3), 595–602. https://doi.org/10.1016/j.jbiomech.2006.02.003

Işcan, M. Y. (1983). Assessment of race from the pelvis. *American Journal of Physical Anthropology*, *62*(2), 205–208. https://doi.org/10.1002/ajpa.1330620210

Kainz, H., Carty, C. P., Modenese, L., Boyd, R. N., & Lloyd, D. G. (2015). Estimation of the hip joint centre in human motion analysis: A systematic review. In *Clinical Biomechanics* (Vol. 30, Issue 4, pp. 319–329). https://doi.org/10.1016/j.clinbiomech.2015.02.005

Landis, J. R., & Koch, G. G. (1977). The Measurement of Observer Agreement for Categorical Data. *Biometrics*, *33*(1), 159. https://doi.org/10.2307/2529310

Murphy, A. J., Bull, A. M. J. J., & McGregor, A. H. (2011). Predicting the lumbosacral joint centre location from palpable anatomical landmarks. *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine*, *225*(11), 1078–1083. https://doi.org/10.1177/0954411911416859

Peng, J., Panda, J., Van Sint Jan, S., & Wang, X. (2015). Methods for determining hip and lumbosacral joint centers in a seated position from external anatomical landmarks. *Journal of Biomechanics*, *48*(2), 396–400. https://doi.org/10.1016/j.jbiomech.2014.11.040

Reed, M. P., Manary, M. A., & Schneider, L. W. (1999). Methods for Measuring and Representing Automotive Occupant Posture. *SAE Technical Paper*. https://doi.org/10.4271/1999-01-0959

Sado, N., Yoshioka, S., & Fukashiro, S. (2020). Three-dimensional kinetic function of the lumbo-pelvic-hip complex during block start. *PLoS ONE*, *15*(3), e0230145. https://doi.org/10.1371/journal.pone.0230145

Sawilowsky, S. S. (2009). New Effect Size Rules of Thumb. *Journal of Modern Applied Statistical Methods*, *8*(2), 597–599. https://doi.org/10.22237/jmasm/1257035100

Stagni, R., Leardini, A., Cappozzo, A., Grazia Benedetti, M., & Cappello, A. (2000). Effects of hip joint centre mislocation on gait analysis results. *Journal of Biomechanics*, *33*(11), 1479–1487. https://doi.org/10.1016/S0021-9290(00)00093-2

ACKNOWLEDGEMENTS: This work was supported by JSPS KAKENHI (21K17592) and JST Moonshot R&D (JPMJMS2295).