Original Article

Institution of MECHANICAL ENGINEERS
Journal of AUTOMOBILE ENGINEERING

Proc IMechE Part D:
J Automobile Engineering
1–23

DOI: 10.1177/09544070211012553
journals.sagepub.com/home/pid
SAGE

Exploring the association of riders' physical attributes with comfortable riding posture and optimal riding position

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Abstract

In recent years, there has been a keen interest in the design improvisation of motorcycles. However, the theoretical model of association between motorcycle design attributes (like frame size/riding position) and rider's physical attributes (like anthropometry, range of motion (ROM), and comfort joint angles) are not well established. This study aims to estimate the relationship between rider's physical attributes and motorcycle design attributes. During this experimental study, the data was collected from 120 motorcyclists (aged between 19 and 44 years) belonging to 20 major states of India. A test-rig was fabricated to obtain the perceived comfort posture and position data using image processing technique. The anthropometry and ROM were manually measured and verified by reliability testing. The principal component analysis (PCA) and multiple linear regression were used to reduce the set of variables and estimate the relationship between 10 comfortable riding position and joint angles (as dependent variables), and the reduced set of 29 anthropometry and 20 ROM measurements (as the independent variables). These results indicate that the comfort joint angles and riding position were significantly associated with the anthropometrics and ROM of the riders. Highly significant regression models were formulated to examine the relationship between the comfort joint angles/riding position and the anthropometrics and ROM of the riders. The findings may support the motorcycle designers to design a comfortable motorcycle complying with Indian anthropometry and ROM.

Keywords

Riding comfort, riding posture, rider dimensions, ROM, motorcycle, ergonomics

Date received: 27 November 2020; accepted: 31 March 2021

Introduction

India, with 37 million motorcycles/scooters, is the country with the highest number of motorcyclists in the world.[1] Also, India has the largest motorcycle market as compare to other competing Asian countries like China, Indonesia, and Vietnam.[1] The motorcycle markets are mainly derived from cost competitiveness and user satisfaction. A recent survey of Sai Praveen and Ray[2] stated that Indian motorcycle manufacturers give more importance to riding comfort. Moreover, many research articles reported that the prevalence of riding discomfort is rather common among Indian motorcyclists.[3–8] Thus, improving riding comfort has long been of interest in motorcycle design-related research.

In general, research related to motorcycle design has been revolving around four key areas: (1) studies related to motorcycle seat design and (dis)comfort assessment,[4,9,10] (2) studies related to anthropometry of Indian motorcyclists,[11–13] (3) studies related to riding posture,[6–8,14](4) Motorcycle dynamic studies.[15] There are no studies which have estimated direct correlation among the motorcyclist's range of motion (ROM), posture and personal protective equipment/clothing (like jackets, boots).[16,17] Though motorcyclist's wearing

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tight clothing/suit might affect the motoring skill and ROM of the motorcyclist,[18,19] Indian motorcyclist usually wears simple clothing while riding. Arunachalam et al.[20] in their literature survey reviewed 124 research articles published from India and abroad. This literature survey highlighted about the factors associated with motorcycle riding posture. Altogether, the review revealed that no investigation has been done to understand the connection between rider's physical and motorcycle design attributes (like comfortable riding position). However, Grainger et al.[21] investigated the association between the anthropometry and comfortable posture (joint angles)/position of two-wheelers (bicycle) riders using multiple regression analysis. Though the regression model was moderate ($R^2 < 0.4$), they established a significant relationship between comfortable posture joint angle (like torso angle, arm angle, etc.) and riding position (like rise length, reach length dimensions of the bicycle) and anthropometry variables (like arm length, torso length, etc.).

Although the motorcycle industry follows Japanese standards[22–24] for motorcycle design, the ergonomic evaluation usually be conducted through Digital Human Modelling (DHM) tools in the early conceptualization stage of the motorcycle design process.[25] To perform virtual ergonomic evaluation (using DHM) of a newly designed motorcycle model, the research team usually built a mannequin (biomechanical CAD model) that resembles a simplified human skeleton with anthropometry, ROM measurements, and comfort joint angles of the target user population. Besides, some of the laboratory experiments are conducted to verify the riding comfort in the real-world.[26] However, according to the available literature, the association between the rider's physical attributes (anthropometry and ROM measurements) and motorcycle attributes (riding position/postures) have not been investigated by the researchers.

Since the relationship between the rider's physical attributes and motorcycle attributes are not yet established, it would have always been challenging for motorcycle designers to choose the appropriate anthropometry and ROM measurement to provide comfortable posture and comfortable riding experience. Moreover, the anthropometry dimensions are also being different for different countries. Thus, the present study tries to establish the relation between comfortable riding posture/position and corresponding anthropometry and ROM measurements. The overall aim of this study is to estimate the association between rider's physical attributes and motorcycle design attributes while riding for a shorter duration. The objectives of this study are: (1) To study the relationship between anthropometry and ROM and comfortable riding posture (CRP) variables; (2) To study the relationship between anthropometry and ROM and optimum/comfortable riding position (ORP).

Although a few research investigations established the link between the comfortable posture of (car/tractor/truck) drivers and seat position and body dimension (anthropometry),[27–30] similar type of investigation is still missing from the literature of motorcycle ergonomics. Also, to understand the importance of ROM in the user-centered design process of motorcycle, the relationship between the ROM and comfort posture is yet to be explored.[25,31] Based on the literature survey, two research questions were formulated:

RQ1: What common/principle factors (from a larger set) contain most of the information in explaining/representing CRP (joint angles) and ORP (position)?
RQ2: How is the association between CRP/ORP and rider's physical attributes (anthropometry and range of motion) of Indian motorcyclists?

Methods and materials

Subjects and experimental setup

Around 374 million (92%) Indian motorcyclists (aged between 19 and 44) are male.[32] Therefore, in the present study, the data collection and related measurements were focused on the dominating male users. Since the present research is the subsequent part of longitudinal research,[33] the same 120 arbitrarily selected male subjects were invited to participate. Subjects with clinical signs and symptoms of bone fractures, hypermobility, musculoskeletal discomfort, or other health problems were excluded. Male subjects in the age group of 19–44 years with least 1-year riding experience and a valid motorcycle license were included in the experiment.

The research objectives were achieved by conducting the experiment on an experimental set-up (in-house static simulator, see Figure 1). The test-rig was constructed using parts from a motorcycle (Make: Bajaj; year: 1999; Model: CT 100) to provide a realistic riding experience to the subjects. The equipment's (and their purpose) used in this static experimental set-up were listed in Table 1. Praveen and Ray[26] confirmed no significant difference between overall seating comfort in static and dynamic conditions (motorcycling on a flat road). Furthermore, many of the automotive postural studies were carried out in static-laboratory conditions for unbiased subjective evaluation.[21,29,34]

The limits of adjustability in the test-rig for handgrip, footrest, and seat were decided based on a previous study and Japanese standard.[22,35] Figure 2 explains the specific dimensions (like width, length, etc.) of the seat, handlebar/grip, and footrest and the dimensional adjustability provided in the test-rig. According to the survey (on 23 Indian standard motorcycles) by Arunachalam et al.[35,36] the mean value of the seat dimensions (front width, narrowest width, the distance between the front width and narrowest width, and the widest length) and handlebar

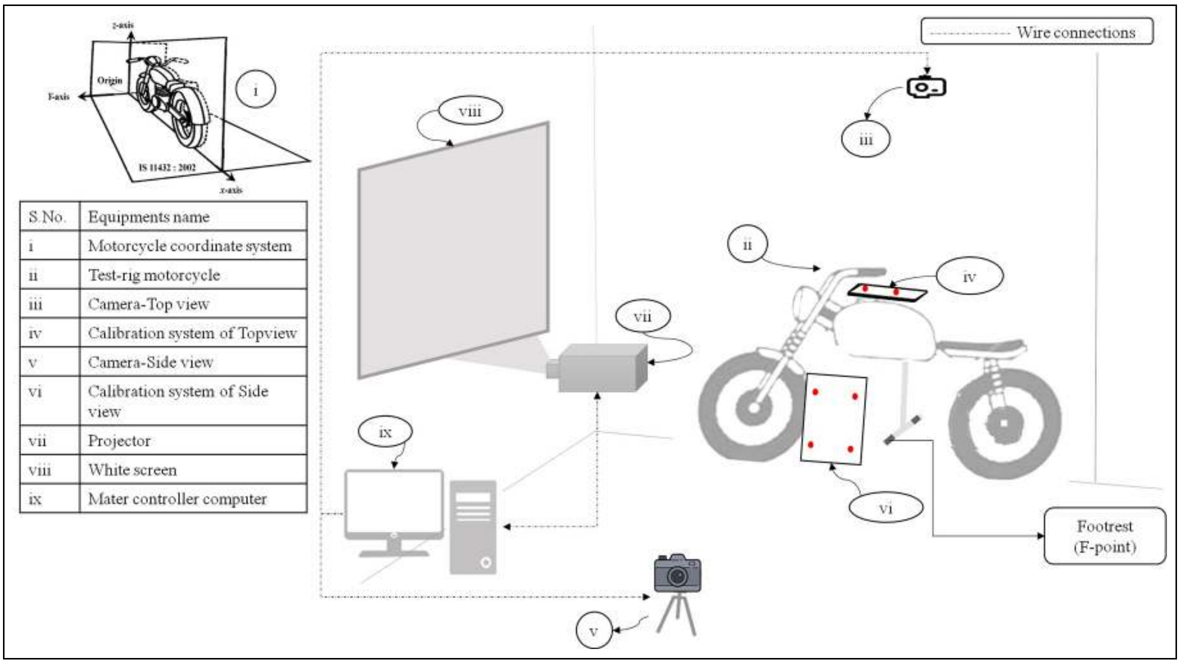

Figure 1. Experimental set-up.

Table 1. Equipment's used in experimental set-up and its purpose.

S. no. (refer Figure 1)	Equipment name	Purpose
i.	Motorcycle coordinate system (origin)	*Origin point* was established at the distance of 1000 mm along *X* axis and 350 mm along *z*-axis and 0 mm along *y*-axis.[29,30,37]
ii.	Test-rig – motorcycle	Provided with the adjustability in handle grip, seat, and footrest. The level of dimensional adjustability in the test rig was disclosed in Figure 2.
iii.	Camera-top view (Make & Model: SonyA58 DSLR, Megapixel: 20 MP with max. resolution: 5456 × 3632 px)	To record joint angle from top view (in *xy* plane) Location – (1200 mm, 0 mm, 3660 mm) from origin point
iv.	Calibration system of top view	To calibrate top view images and extrapolate the images into real world measurements
v.	Camera-Side view (Make & Model: SonyA58 DSLR, Megapixel: 20 MP with max. resolution: 5456 × 3632 px)	To record joint angles from side view (in *xz* plane)
vi.	Calibration system of side view	To calibrate side view images and extrapolate the images into real world measurements Location – (800 mm, 4570 mm, 600 mm) from origin point
vii.	Projector	To play simulation videos during the experiment Location – 1830 mm from the test-rig
viii.	White screen	To project the simulation video from the projector Location – 1220 mm from the test-rig
ix.	Master controller computer (HP Desk with Intel i5-processor and windows 8.1)	To control the projector and cameras through USB/HDMI cables during experimentation

dimensions (handle grip length and handle grip width) were used in the test-rig. A flat (no curvature) seat (material: open-cell polyurethane; density: 82 kg/mm^3) was used to control the effect of the seat on overall discomfort.[10] A smaller fuel tank and standard footrest size were used in the test-rig for more flexibility in leg/thigh movement of the subjects while performing the experiment.

Figure 3 illustrates the study design of the present research. In this study, the CRP and ORP data were acquired by subjecting the subjects on the riding set up, and following the experimental protocol. The higher number of CRP and ORP variables were reduced using principal component analysis (PCA) technique. The reduced set of anthropometric and ROM variables were used from a prior study.[33] Multiple linear regression (MLR) was used to develop the regression models of comfortable riding position and joint angles, using the reduced set of anthropometric and ROM variables (as the independent variables).

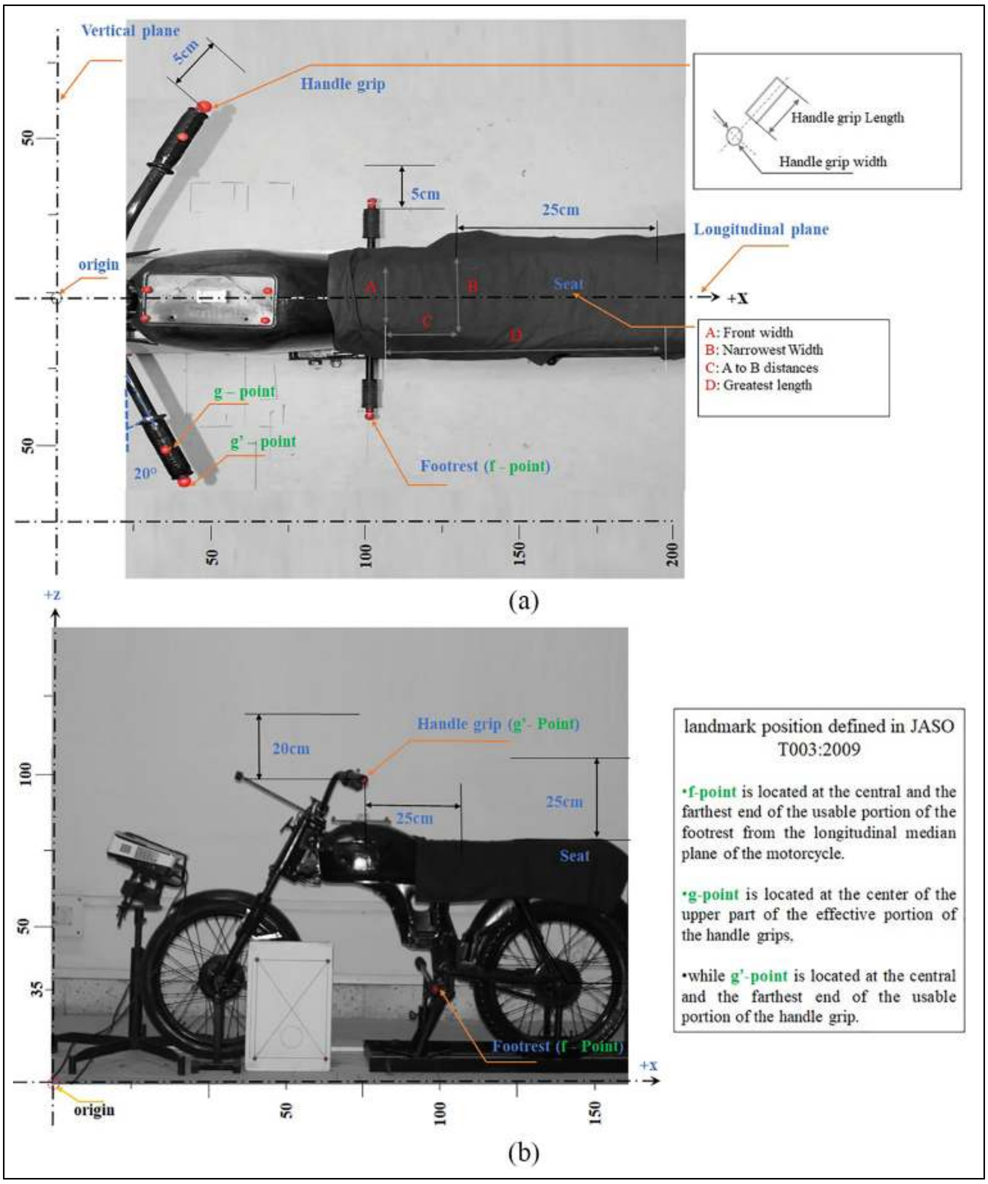

Figure 2. Adjustable ranges of seat, handle grip and footrest: (a) adjustability at *xy*-plan (top view) and (b) adjustability at *xz*-plan (side view).

Experimental procedure

The experiment was conducted in three subsequent stages: (1) fitting trials; (2) subjective discomfort and comfort evaluation and (3) estimation of weighted comfort joint angle.

Fitting trials. During this step, the subjects were asked to obtain a CRP and ORP on the test-rig. At first, subjects were instructed to sit on the test-rig and perceive degree of discomfort in their respective body joints. *They were asked to draw* their constant attention toward the simulation video projected on the white screen. After every 2 min, the subject was verbally asked for any discomfort in their body joints. If they report any discomfort in anybody joints, the component corresponding to that body joint (seat/handlebar/foot-rest) was regulated (up/down/back/forth) manually by the experimenter at discrete decrement/increment, in agreement with the procedure used in Porter and Gyi.[30] This process was repeatedly practiced until the subject felt comfortable or perceived as no discomfort while riding. Each subject took at least three fitting trials to obtain a comfortable posture and position. There was no time and trial limit to complete this process.

Subjective discomfort and comfort evaluation. Following the fitting trials, the subjects were asked to take a break for 10 min to avoid biases between the repeated experiments.[38] Afterward, the subject was asked to sit again on the test-rig, accepted as comfortable in "Fitting trials." Once the subject gets seated, the experimenter affixed the reflective markers on the subject's body and motorcycle landmarks (as shown in Figures 4 and 5).

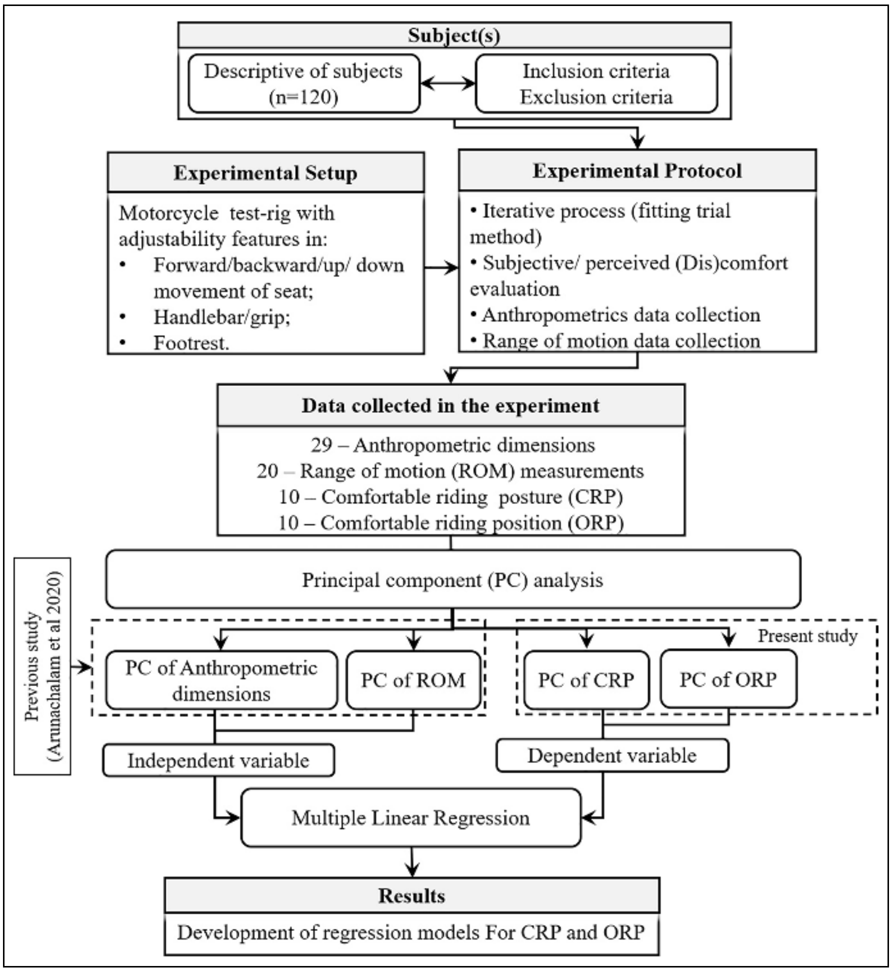

Figure 3. Study design – flow chart.
ROM: range of motion; CPR: comfortable riding posture; ORP: comfortable riding position.

Now, a 5-min riding-simulation video was played on the white screen via the projector. During these 5 min, the subject was informed to perceive discomfort/comfort in different body joints/parts. The time duration (5 min) was opted based on earlier similar studies by Grainger et al.[21] and Barone and Curcio.[39] They have also evaluated the subjective discomfort while riding two-wheeler under static conditions.

At the end of each session, side and top viewed images of the subject were captured using side/top cameras. Later, these images were analyzed using the image process technique to extract the coordinates of the body landmarks for estimating body joint angles (explained in Appendix A1) and linear dimensions of the riding position. The image processing technique and arithmetic calculation involved in the study was explained in Appendices A2 and B.

After completing the session, the subjects were requested to leave the motorcycle test-rig and report the perceived discomfort and comfort (self-reported questionnaire) they experienced during the 5 min. This subjective rating assessment includes (1) Discomfort rating scale (as shown Appendix Figure C(a))[2]and (2) Comfort rating scale (as shown Appendix Figure C(b)).[35,40] The subjective rating scales are widely used in previous literature.[41–43] The present study adopted the procedure of using both comfort and discomfort scales (to evaluate the subject reliability) have also been proposed in many other studies.[41–43]

Estimation of weighted comfort joint angle. The weighted comfort joint angle can be referred to normalizing the body joint angles (adopted during comfortable riding position/posture) with respect to the perceived comfort rating, respectively. The weighted mean and standard deviations of comfort joint angle (θ_j and $\Delta\theta_j$) can be estimated using equations (1) and (2), and many earlier studies have referred θ_j to evaluate the comfortable riding posture.[48,49]

$$\theta_j = \frac{\sum_{n=1}^{120} \theta_{jn}\ w_{jn}}{\sum_{n=1}^{120} w_{jn}} \qquad (1)$$

where, $w_{jn} = C_n$ %; $n = 1,2,\ 3,\ldots..120$ and $j = 1,2,3\ldots.10$. θ_j is the weighted mean comfort joint angle of the (120) samples; θ_{jn} is measured comfort joint angle of the subject in the respective joint; w_{jn} is perceived comfort rating by the subject for the respective joint; C_n % is the percentage of comfort score

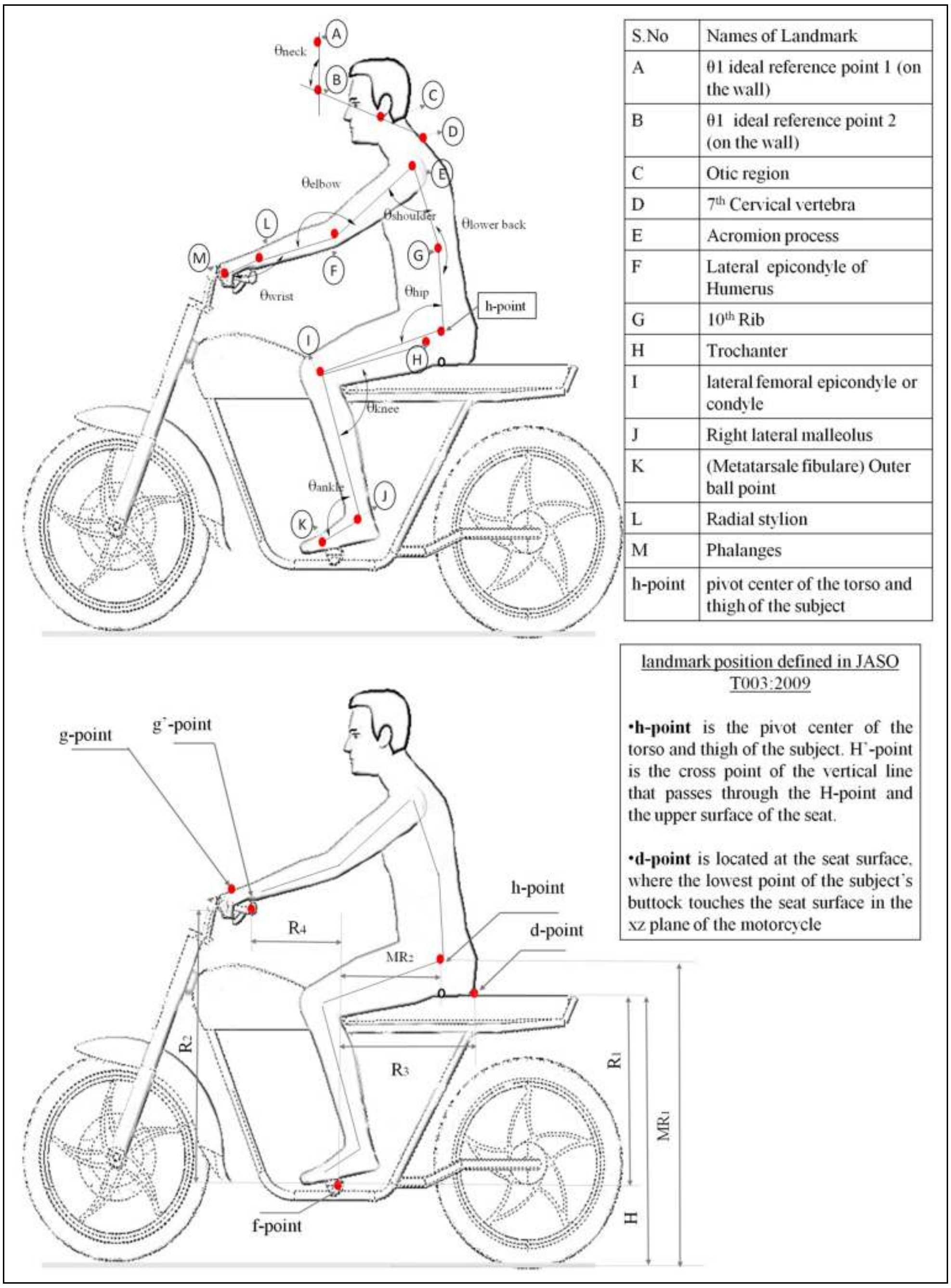

Figure 4. Reflective landmarks on motorcycle and rider at side view (Sagittal plane).

converted from the comfort rating of the individual joint of the subjects.

$$\Delta\theta_j = \frac{|\theta_j - (\theta_{nj})_{max}| + |\theta_j - (\theta_{nj})_{min}|}{2} \quad (2)$$

where, $\Delta\theta_j$ standard deviations or tolerance of weighted jth joint angle; $(\theta_{nj})_{max}$ and $(\theta_{nj})_{min}$ is the maximum and minimum values of the weighted comfort joint angle of the total subjects.

Reliability of measurements

Reliability assessment of joint angles and position measurements of the rider. Before the main experiment on 120 subjects, the reliability was examined on arbitrarily selected 10 subjects to evaluate the accuracy of the linear and angular measurements. As the subjects were different from the 120 subjects, the measurement information was not been included in the main experiment. During the evaluation, subjects were instructed to sit on the motorcycle test-rig comfortably. The measurement of riding position and joint angles was undertaken manually using a sliding caliper and static goniometer (Make & Model: Kristel-3278), respectively. After documenting the manual measurements, the red reflective markers were affixed (on the body landmarks) and images were captured. The linear and angular measurements from the image were calculated according to the

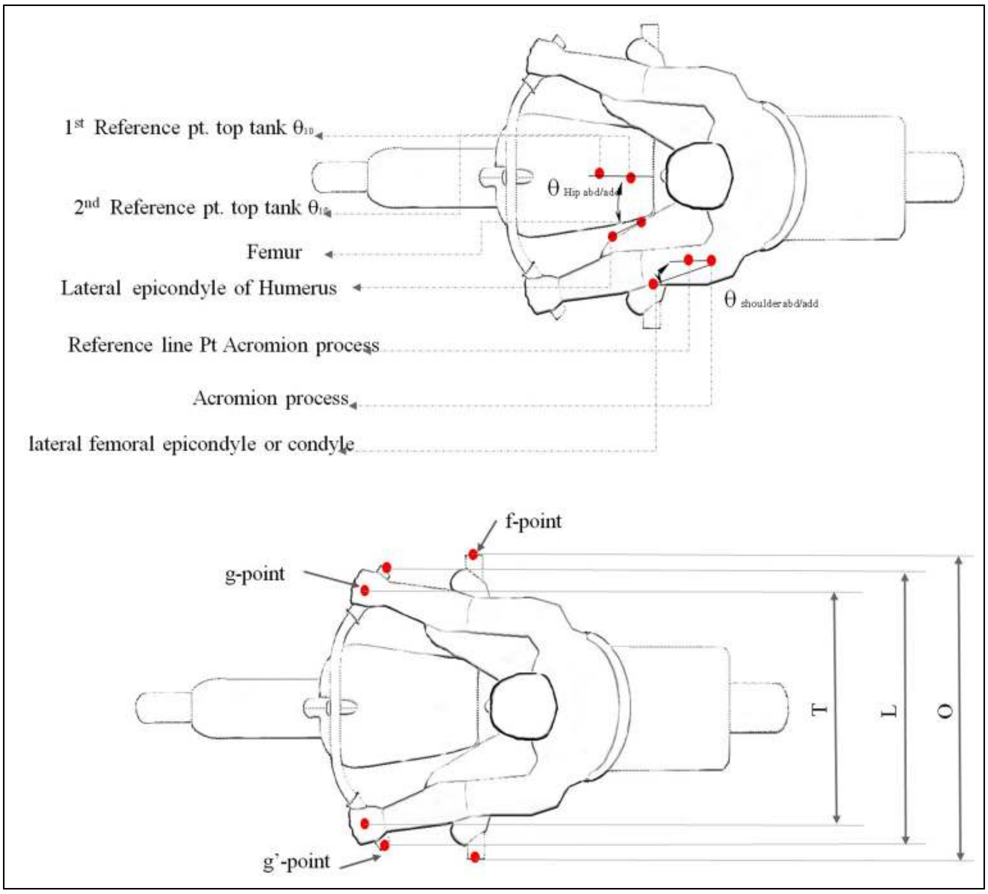

Figure 5. Reflective markers of motorcycle and rider at top view (Transverse plane).

procedure devised in Appendices A2 and B. Afterward, both manual and image measurements were tested for correlation (using spearman's rank method) to evaluate the alternate-form reliability. The results revealed that the correlation coefficients for (joint) angular measurement and linear (riding position) dimensions ranged between 0.92 to 0.99 and 0.94 to 0.99 (significant at 0.05 level), that can be considered trustworthy.[43–47]

Reliability assessment of subjective comfort/discomfort measurements. We measured alternate-form reliability to assess the reliability of subjective discomfort and comfort rating scores, as mentioned in the early studies.[41,46] While interpreting the relationship, the correlation coefficients of discomfort and comfort rating score ranged between −0.75 and −0.95 (significant at 0.05 level), that can be considered reliable for further analysis.[41,46]

Data analysis

The comfortable riding posture/position variables are intra-correlated (see Appendix Tables D1 and D2). As there are more extensive set of highly intra-correlated posture (joint angle $-\theta_j$) and position variables (R_i, MR_i, etc.), current study used Principal Component Analysis (PCA) to reduce them into a smaller subset and established appropriate relationship with anthropometry and ROM variables using regression. Also, the analysis helps to answer the first research question of the present research, that is, What common/principle factors (from a larger set) contain most of the information in explaining/representing CRP (joint angles) and ORP (comfortable riding position)?

PCA is typically recognized for dimensional reduction of a more enormous set of variables into a smaller subset.[50] This dimensional reduction method was applied on 10 joint angles (θ_1–θ_{10}) and riding position (R_1–R_4) variables to find the most influential components (contributing to maximum variance) from the original variables. This factor analysis was performed under the following consideration:

(1) Eigenvalues greater than 1,
(2) Extraction method as varimax rotation and,
(3) Factor loading coefficient greater than 0.4.

Before performing the PCA on the anthropometric and ROM variables, the data were checked for the following assumptions:

(1) Intra-correlation between all the variables using Pearson's correlation coefficient;

Table 2. Summary of principal components obtained from the anthropometric and ROM variables (Arunachalam et al.[33]).

Rider's physical attributes	Principal components (PC) – name	Variables
Anthropometry	Body length indicator	Stature, crotch height, buttock extension, cervical height–sitting, shoulder-elbow length, knee height, lower leg length, shoulder-elbow length, elbow-hand length, buttock-knee length, buttock-popliteal length, acromion grip length, ball of foot length, and hand length
	Volume indicator	Weight, BMI, elbow-elbow breadth, hip breadth, sitting, thigh circumference, calf circumference, upper arm circumference
	Body fat indicators	Triceps skinfold, subscapular skinfold, supraspinal skinfold, medial calf skinfold
	Sitting height indicator	Cervical height sitting, shoulder height sitting, elbow height, sitting, knee height
	Body bilateral length indicators	Femur breadth, humerus breadth, foot-breadth
ROM	Motion at Sagittal plane	Neck flexion, neck extension, wrist flexion, wrist extension, knee extension, elbow flexion, shoulder extension
	Motion at Transverse plane	Hip abduction, shoulder abduction, shoulder abduction
	Upper limb motions at Sagittal plane	Shoulder flexion, shoulder extension
	Lower limb motions at the Sagittal plane	Hip flexion, hip extension, ankle dorsiflexion
	Lower limb motion at Transverse plane	Hip abduction, ankle plantar flexion
	Spine motion at Sagittal plane	Lumbar flexion, lumbar extension
	Knee-elbow motion at Sagittal plane	Knee flexion, knee extension, elbow extension

(2) The adequacy of sample size (evaluated using Kaiser-Meyer-Olkin (KMO) and Bartlett's sphericity values) and;
(3) Identifying outliers (using box and whisker plot for each variable).

In a prior study,[33] the principal components (PC) of anthropometric and ROM variables were also obtained. They collected 29 anthropometric and 20 ROM measurements from 120 male subjects. The ROM measurement procedure has been explained in the Appendix E1. The descriptive statistics of 120 subject's anthropometric and ROM measurements were presented in Appendix E2 (Tables E1 and E2). After PCA, their results established that 7 ROM and 5 anthropometric measurements were the principal/influential components that can represent the physical attributes of male Indian motorcyclists. The PCs of ROM and anthropometry and their corresponding variables were tabulated in Table 2, which were utilized in the present research. The results from the PCs of joint angles and riding position (present study) and the PCs of ROM and anthropometric measurements were used to answer the second research question. Based on the question, the following hypotheses have been constructed.

H_{1a}: Comfortable riding posture (CRP) is significantly predictable by anthropometric and ROM variables of motorcyclist
H_{2a}: Optimum/comfortable riding position (ORP) is significantly predictable by anthropometric and ROM variables of motorcyclist

While testing the hypothesis, the PCs of posture (joint angles) and riding position (as dependent variables) were predicted by PCs of anthropometric and ROM variables (as independent variables, Table 2).

Stepwise multiple linear regression (SMLR) analysis was used to establish a regression model between the PCs of response variables (i.e. postural joint angles and riding position) and the PCs of independent ones (i.e. anthropometric and ROM variables). Unlike other MLR, in this iterative regression model, the selection of predictor variables is done one at a time based on statistical threshold/criteria. In every step, independent variables have been involved for addition or subtraction to obtain the best fitting regression model. Before performing regression analysis, the SMLR assumptions were examined, in the following order: (1) Multivariate Normality test (Shapiro-Wilk test); (2) Multicollinearity among the variable (see Appendix D–D1 and D2 for Pearson correlation coefficient); and (3) Homoscedasticity (Bartlett's method). The statistical analyses were performed at a chosen confidence level set to 0.05 and 0.01. All statistical analyses were performed using SPSS 23.0 software.

Results and discussion

Descriptive analysis of the comfort joint angles and riding position variables

Table 3 shows the descriptive statistics in terms of mean (M), standard deviation (SD), minimum (Min), and maximum (Max) for the riding position variables and weighted comfort joint angles.

Table 3. Descriptive of weighted joint angles and riding position (units: mm; unless specified).

Comfort joint angles/ riding position variables	Mean	SD	Min	Max
θ_{neck} (°)	17.80	5.10	4.10	27.50
$\theta_{shoulder}$ (°)	32.60	12.80	10.30	58.50
θ_{elbow} (°)	109.60	28.60	52.40	167.60
$\theta_{lowerback}$ (°)	119.70	42.10	35.90	193.20
θ_{hip} (°)	80.60	22.30	36.80	125.10
θ_{knee} (°)	61.80	13.40	37.90	88.20
θ_{ankle} (°)	84.50	16.20	50.60	119.40
θ_{wrist} (°)	128.50	38.10	52.60	185.40
$\theta_{shoulder\ abd/add}$ (°)	39.60	14.80	9.60	70.20
$\theta_{hip\ abd/add}$ (°)	33.20	19.60	1.80	73.20
R_1	476.00	33.00	343.00	544.00
R_2	683.00	33.00	613.00	765.00
R_3	392.00	54.00	293.00	541.00
R_4	221.00	45.00	69.00	313.00
MR_1	912.00	45.00	794.00	96.00
MR_2	264.00	52.00	153.00	375.00
T	722.00	11.00	673.00	758.00
L	779.00	12.00	721.00	816.00
H	808.00	19.00	693.00	889.00
O	594.00	13.00	521.00	602.00

R_1: vertical distance between *f*-point and *d*-point; R_2: vertical distance between *f*-point and *g′*-point; R_3: horizontal distance between *f*-point and *d*-point; R_4: horizontal distance between *f*-point and *g′*-point; MR_1: vertical distance between *h*-point and floor; MR_2: horizontal distance between *h*-point and *f*-point; *T*: the distance between *g*-points on left and right handle grips; *L*: the distance between *g′*-points on left and right handle grips; O: the distance between *f*-points on the left and right footrest.

Dimensional reduction using principal component analysis (PCA)

PCA of comfortable riding posture (CRP). The statistical method yielded three PCs from the 10 CRP (joint angles) variables. The potential PCs were recognized graphically using the scree plot (see Figure 6). This plot implied effective PCs (PC1–PC3) that have eigenvalues greater than 1. The KMO measure of sampling adequacy was obtained as 0.71 (ranged between 0.70 and 0.79). It can be interpreted as a "middling" sample size for the research.[51] Bartlett's test was also found to be significant at $p < 0.001$, which indicates an adequate sample size.[52] The intra-correlation coefficients between all the postural (joint angles) variables are presented in Appendix Table F1. Even though the table shows significant correlations, low intra-correlation coefficients were found among the majority of postural (joint angles) variables. However, the evidence of a moderate relationship between elbow and shoulder joint angles; lower-back and hip joint angles.

Following varimax orthogonal rotation, three PCs accounted for 62.97% of the total variance in the original variables (see Table 4). PC 1 includes 3 variables (see Table 5), and accounts 37.12% of the total variance (Eigenvalue = 3.7). These factors were labeled as "*Comfort hip joint angles*" because these joints movements take place in the hip joint regions (i.e. Hip flexion/extension, hip adduction/abduction, and Lower back joint angle). Since the lower back joint is connected with hip joint (tailbone), we considered it in the

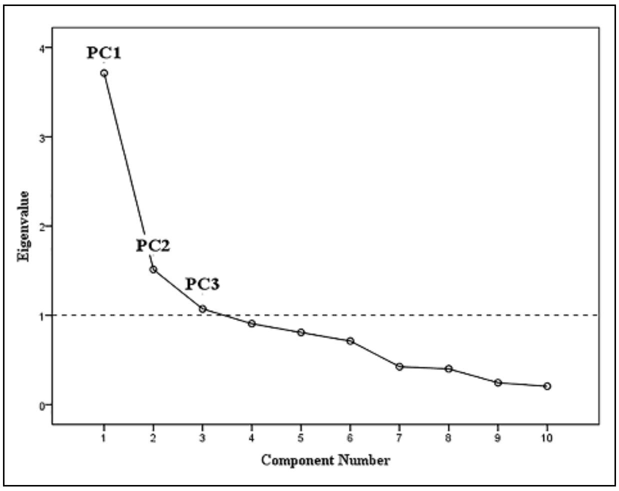

Figure 6. Scree plot of CRP (joint angles).

"hip joint angle." PC 2 was comprised of four variables and labeled as the "*Comfort joint angles of upper limbs*" since its accommodated joint angle related to the upper part/limbs of the human body. It accounted for 15.13% of the total variance (Eigenvalue = 1.5). PC 3 consisted of three variables (10.17% of the total variance; Eigenvalue = 1.07) and labeled as "*Comfort joint angles of lower limbs*" (the joint angles of lower limbs/parts of the human body).

The PCA results interpret that the comfort joint angles could be classified into three major principal components, which will effectively represent all the 10 joint angles. The first component represents the joint

Table 4. Total variance explained for CRP joint angles.

Principal component (PC)	Initial Eigenvalues			Rotation sums of squared loadings		
	Total	% Of variance	Cumulative %	Total	% Of variance	Cumulative %
1	3.71	37.12	37.12	2.21	22.12	22.12
2	1.51	15.13	52.25	2.19	21.89	44.02
3	1.07	10.71	62.97	1.89	18.95	62.97
4	0.90	9.05	72.03			
5	0.80	8.08	80.11			
6	0.71	7.12	87.23			
7	0.42	4.25	91.48			
8	0.40	4.00	95.49			
9	0.24	2.45	97.94			
10	0.20	2.05	100.00			

Table 5. Results of factor analysis for CRP joint angles.

	Principal component (PC)		
	1	2	3
θ_{neck}		0.82	
$\theta_{shoulder}$		0.75	
θ_{elbow}		0.68	0.59
$\theta_{lowerback}$	0.65	0.41	
θ_{hip}	0.79		
θ_{knee}			0.77
θ_{ankle}			0.43
θ_{wrist}		0.44	
$\theta_{shoulder\ abd/add}$			0.73
$\theta_{hip\ abd/add}$	0.81		

Eigenvectors values < 0.4 suppressed for display in the table.

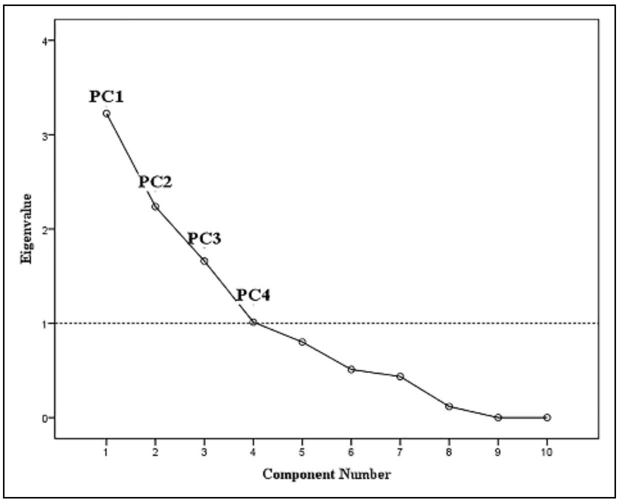

Figure 7. Scree plot of riding position variables.

angles of the hip and lower back. The second component represents the joint angles of upper limbs like neck, shoulder, arms, and hand/wrist. Whereas, the third component represents the joint angles of lower limbs like the knee, foot. Moreover, these three principal components may represent the 10 originals variables (more than 62% of the variance explained).

In line with our results, the study by Vergara and Page[53] on automotive male drivers also revealed that the hip-related joints expressed higher joint angle characteristics than other joint angles. Also, JASO T003:2009 recommends that the hip joint angles can be considered as the key measurements while designing motorcycles.

PCA of comfortable riding position (ORP). Four PCs were yielded from the 10 ORP variables. The potential PCs (PC1–PC4) were recognized graphically using the scree plot (see Figure 7). This plot implied that the effective PCs were having an Eigenvalues larger than 1. The KMO measure of sampling adequacy was obtained as 0.64 (ranged between 0.60 and 0.69). It can be interpreted as a "mediocre" sample size for the research.[51] Bartlett's test was also found to be significant at $p < 0.001$, which indicates that the sample size was adequate.[52] The intra-correlation coefficients between all the ORP variables are presented in Appendix Table F2. The majority of the ORP variables showed low but significant intra-correlation. However, the strong correlation among R_1, MR_1, and H is understandable. The dimensions (R_1 and H) are likely to be fixed and the variation in MR_1 may not be much among the subjects. Likewise, the intra-correlation among R_3, MR_2, and MR_1 and H, L, and T were also found to be high.

Following varimax orthogonal rotation, four PCs of the joint angles accounted for 81.5% of the total variance in the original variables (see Table 6). PC 1 includes four variables (see Table 7), and accounts 32.26% of the total variance (Eigenvalues = 3.2). These factors were labeled as "*Vertical dimensions at Sagittal plane*" because it accommodates the dimensions in the longitudinal side (i.e. R_1, R_2, MR_1, and H). PC 2 was comprised of two variables and labeled as the "*Dimensions at Transverse plane*" since it accommodated variables related to the axial/top plane of viewing. It accounted for 22.37% of the variance (Eigenvalues = 2.2). PC 3 consisted of three variables (16.59% of the variance; Eigenvalues = 1.6) and labeled as "*Horizontal dimensions at Sagittal plane*" because it accommodates dimensions related to the frontal side of viewing (i.e. MR_2, R_3, and R_4). PC 4 consisted of one variable (10.12% of the variance; Eigenvalues = 1.01) and labeled as "*Footrest*

Table 6. Total variance explained for riding positions variables.

Principal component (PC)	Initial Eigenvalues			Rotation sums of squared loadings		
	Total	% Of variance	Cumulative %	Total	% Of variance	Cumulative %
1	3.22	32.26	32.26	2.73	27.35	27.35
2	2.23	22.37	54.63	2.28	22.81	50.16
3	1.65	16.59	71.22	2.09	20.93	71.10
4	1.01	10.12	81.34	1.02	10.24	81.34
5	0.80	8.01	89.36			
6	0.51	5.10	94.46			
7	0.43	4.35	98.82			
8	0.11	1.17	100.00			
9	0.01	0.46	100.00			
10	0.01	0.51	100.00			

Table 7. Results of factor analysis for ORP variables.

	Principal component (PC)			
	1	2	3	4
R_1	0.96			
R_2	0.44			
R_3			0.89	
R_4		−0.53	−0.55	
MR_1	0.80			
MR_2			0.94	
H	0.96			
G		0.97		
D		0.97		
F				0.98

Eigenvectors values < 0.4 suppressed for display in the table.

dimensions at Transverse plane" (the footrest dimension in the transverse plane).

The PCA results interpreted that the ORP could be classified into four major principal components, which will efficiently represent all the 10 riding position variables. The first PC1 represents the vertical dimensions at Sagittal plane like R_1, R_2, MR_1, and H. The second PC2 represents dimensions at the Transverse plane like L, T. The PC3 component represents the horizontal dimensions at the Sagittal plane like MR_2, R_3, R_4. Whereas, PC4 represents the footrest dimension. Moreover, these four principal components may represent the 10 originals variables (more than 81% of the variance explained). In line with our results, the JASO T003:2009 recommends that the vertical dimensions were key dimensions of motorcycles. Whereas, some of the motor vehicle standards were also suggested that the vertical dimensions were key dimensions of the vehicle design.[54]

Prediction of comfortable riding posture (CRP)

The present section describes the association of CRP with the PCs of anthropometry and ROM.[33] Also, it includes the prediction models of three PC of CRP (comfort hip joint angles, comfort joint angles of upper limbs, and comfort joint angles of lower limbs) based on anthropometry and ROM data.

Table 8 shows the SMLR analysis. The predicted model explained 22.8% of variance the variables related to "*comfort hip joint angles*." A high significant SMLR analysis was found (F (4, 115) = 8.482, $p < 0.01$), with an R^2 of 0.228. The multiple correlations (R) between comfort hip joint angles and the five predictors (PCs of ROM and anthropometry were moderate (0.47). Motion at Sagittal plane ($\beta = 0.335$, $p < 0.01$), motion at Transverse plane ($\beta = -0.213$, $p < 0.01$), lower limb Motion at Transverse plane ($\beta = -0.193$, $p < 0.01$), Upperlimb Motions at Sagittal plane ($\beta = 0.182$, $p < 0.01$), and volume indicators ($\beta = -0.281$, $p < 0.01$) were associated with higher *comfort hip joint angles*. In other words, the slender subject who is usually having greater ROM than the obese subject are likely to sit in the erect posture rather than the collapsed/slumped posture.[55] The *comfort hip joint angles* increase with higher flexion movement of upper limb joints and lower adduction/abduction movement of lower limb joints.

Regarding the *comfort joint angles of upper limbs*, a high significant SMLR analysis was found (F (4,115) = 8.932, $p < 0.01$), with an R^2 of 0.237. The multiple correlations (R) comfort joint angles of upper limbs and the four predictors (PCs of ROM and Anthropometry) were moderate (0.48). The combination of these predictors accounts for nearly 25% of the *comfort joint angles of upper limbs*. Dimensions at the Transverse plane ($\beta = -0.358$, $p < 0.01$), horizontal dimensions at Sagittal plane ($\beta = -0.273$, $p < 0.01$), sitting height indicators ($\beta = 0.235$, $p < 0.01$), and Motions at Sagittal plane ($\beta = 0.183$, $p < 0.01$) were associated with higher *comfort joint angles of upper limbs*. It can be inferred that the lightweight rider feels comfortable with outstretched upper limb joints (arms/neck/shoulder). Also, an underweight rider prefers lower and shorter handlebar positions (lower values of R_2 and R_4) was for better control.

While analyzing *comfort joint angles of lower limbs*, a high significant SMLR analysis was found (F (2, 117) = 12.58, $p < 0.01$), with an R^2 of 0.177. The predicted model explained 17.7% of the *comfort joint angles of lower limbs*. The multiple correlations (R) between *comfort joint angles of lower limbs* and the two predictors

Table 8. Comfortable riding posture (joint angles) regression models.

F	R^2	Regression model		p
		Explanatory variables[a]	β	
Comfort hip joint angles F (4, 115) = 8.48	0.22	Motion at Sagittal plane[c]	0.33	< 0.001
		Motion at Transverse plane	−0.21	
		Lower limb motion at Transverse plane	−0.19	
		Upper limb motions at Sagittal plane	0.18	
Comfort joint angles of upper limbs F (4, 115) = 8.93	0.23	Dimensions at Transverse plane	−0.35	< 0.001
		Horizontal dimensions at Sagittal plane	−0.27	
		Sitting height indicator[b]	0.23	
		Motion at Sagittal plane	0.18	
Comfort joint angles of lower limbs F (2, 117) = 12.58	0.17	Body length indicator[b]	−0.29	< 0.001
		Spine motion at Sagittal plane[c]	0.22	

[a]Refer Table 2.
[b]Anthropometry variables.
[c]ROM variables.

Table 9. Comfortable riding position regression models.

F	R^2	Regression model		p
		Explanatory variables[a]	β	
Vertical dimensions at Sagittal plane F (2, 117) = 8.58	0.12	Motion at Sagittal plane[b]	−0.27	< 0.001
		Body fat indicators[c]	−0.22	
Dimensions at Transverse plane F (2, 117) = 41.16	0.41	Body bilateral length indicator[c]	−0.52	< 0.001
		Upperlimb motions at Sagittal plane[b]	0.25	
Horizontal dimensions at Sagittal plane F (2, 117) = 7.85	0.11	Body length indicator[c]	0.23	< 0.001
		Comfort angles of upper limbs	−0.23	
Footrest dimensions at Transverse plane F (2, 117) = 5.71	0.08	Motion at Transverse plane[b]	0.21	< 0.001
		Lower limb motion at Transverse plane[b]	0.20	

[a]Refer Table 2.
[b]ROM variables.
[c]Anthropometry variables.

(PCs of ROM and Anthropometry) were moderate (0.42). Body length indicator ($\beta = -0.292$, $p < 0.01$) and Spine Motion at Sagittal plane ($\beta = 0.226$, $p < 0.01$) were associated with higher comfort *joint angles of lower limbs*. Needless to say, while riding, shorter subjects need to stretch their knee/foot to reach the footrest. This makes the subject move forward from the original sitting position and increases the flexion of the spine for reaching the handlebar. In line with these results, a study by Porter and Gyi,[30] found that shorter drivers prefer outstretched arms while driving.

Although the independent variables (PCs of anthropometry and ROM) were moderately predicted the PCs of comfortable riding postures (joint angles), the regression models were highly significant ($p < 0.001$). In support of our results, the study by Grainger et al.[21] on bicycle riders also adopted a similar procedure and revealed that the comfortable (bicycle) riding postures were moderately predicted by the anthropometry of riders. Altogether, it can be said that CRP significantly correlated with anthropometric and ROM variables of the motorcyclist.

Prediction of comfortable riding position (ORP)

This section describes the association of ORP with the PCs of anthropometry and ROM.[33] Also, it includes the prediction models of four PCs ORP (Vertical dimensions at Sagittal plane, dimensions at Transverse plane, Horizontal dimensions at Sagittal plane, Footrest dimensions at Transverse plane) based on anthropometry and ROM data.

Table 9 shows the SMLR analysis, the predicted model explained 12.8% variances of the *Vertical dimensions at Sagittal plane*. A high significant SMLR analysis was found (F (2, 117) = 8.581, $p < 0.01$), with an R^2 of 0.128. The multiple correlations (R) between *vertical dimensions at Sagittal plane* and the two predictors (PCs of ROM and Anthropometry) were moderate (0.35). Motion at the Sagittal plane ($\beta = -0.272$, $p < 0.01$), and body fat indicators ($\beta = -0.224$, $p < 0.01$) were associated with higher dimensions at the Sagittal plane. It can be inferred that the overweighed subjects preferred to keep their riding position dimensions (R_1, R_2, MR_1, and H) lower, which may help them to keep lesser flexion movements of joints at the Sagittal plane.

Regarding the *dimensions at Transverse plane*, a high significant SMLR analysis was found (F (2,117) = 41.16, $p < 0.01$), with an R^2 of 0.413. The multiple correlations (R) between *Dimensions at Transverse plane* and the two predictors (PCs of ROM and Anthropometry) were strong (0.64). The combination of these predictors accounts for nearly 41.3% of the *dimensions at Transverse plane*. Body bilateral length indicator (β = −0.52, $p < 0.01$), and Upper limb Motions at Sagittal plane (β = 0.256, $p < 0.01$) were associated with higher *dimensions at Transverse plane*. In other words, the slender subjects preferred the handlebar away as their comfortable riding position, that in turn increased their joint movements (upper limb).

About the *horizontal dimensions at Sagittal plane*, a high significant SMLR analysis was found (F (2, 117) = 7.85, $p < 0.01$), with an R^2 of 0.118. The predicted model explained 34.4% of the *horizontal dimensions at Sagittal plane*. The multiple correlations (R) between *horizontal dimensions at Sagittal plane* and the two predictors (PCs of comfort joint angle and anthropometry) were moderate (0.344). Body length indicator (β = 0.233, $p < 0.01$), and comfort angles of upper limbs (β = −0.239, $p < 0.01$) were associated with higher *horizontal dimensions at Sagittal plane*. Perhaps the taller subjects preferred the handlebar away for better anthropometric compatibility while riding. Also, if the *horizontal dimensions* (i.e. the horizontal distance between the F-point and D-point, and horizontal distance between the F-point and G'-point) increases, the discomfort in upper limbs was evident.

For the *footrest dimensions at Transverse plane*, a high significant SMLR analysis was found (F (2, 117) = 5.71, $p < 0.01$), with an R^2 of 0.089. This predicted model explained 29.8% of the *footrest dimensions at Transverse plane*. The multiple correlations (R) between *footrest dimensions at Transverse plane* and the two predictors (PCs of Motion at Transverse plane and Lower limb motion at Transverse plane) were moderate (0.298). Motion at the Transverse plane (β = 0.214, $p < 0.01$), and lower limb motion at the Transverse plane (β = 0.208, $p < 0.01$) were associated with higher *footrest dimensions at Transverse plane*. Though explanatory variables moderately predicted the comfortable riding position, the regression models were highly significant ($p < 0.001$). In line with our results, the study by Park et al.[29] on passenger car driver revealed that association was moderate/low between the seating dimensions and anthropometry of the drivers. Thus, the results clearly establish that ORP has a significant relationship with anthropometric and ROM variables of the motorcyclist.

Study recommendations

The study discussed the association between the physical characteristics (anthropometry/ROM) and ORP/CRP of the riders. These findings could be considered as a vital information in motorcycle design to decide on the design limits (handlebar, seat, and footrest dimensions) of the motorcycle. The following recommendations presents the major contributions of the study:

I. While deciding on vertical dimensions of the motorcycle (e.g. $R1$, $R2$, MR1, and H; refer Figures 4 and 5) in the design process, body fat indicators (i.e. triceps skinfold, subscapular skinfold, supraspinal skinfold, medial calf skinfold), and Motion at Sagittal plane (i.e. flexion/extension of the neck, wrist, knee, elbow, and shoulder) of the target population should be considered.

II. The dimensions at transverse plane (e.g. T and L; refer Figures 4 and 5) have to be decided based on body bilateral length indicator (i.e. femur breadth, humerus breadth, foot-breadth) and Upper limb Motions at Sagittal plane (i.e. shoulder flexion, shoulder extension) of the target population.

III. The dimensions at the transverse plane (i.e. T and L) and horizontal dimensions at the sagittal plane (i.e. MR2, $R3$, and $R4$) inversely affects the comfort joint angles of upper limb (i.e. comfort joint angles of the neck, shoulder, arms and hand/wrist). Therefore, these dimensions need to be selected carefully.

IV. The comfort joint angles of lower limbs (e.g. knee angle, ankle/foot angle) is significantly associated with body length indicator (i.e. stature, crotch height, buttock extension, cervical height–sitting, shoulder-elbow length, knee height, lower leg length, shoulder-elbow length, elbow-hand length, buttock-knee length, buttock-popliteal length, acromion grip length, ball of foot length and hand length). As the body dimensions changes over time,[56] the designer must consider the most recent anthropometric database of the targeted population.

V. In line-with JASO recommendations,[22–24] the present research also highlights higher influence of comfort hip joint angles (i.e. lower back and hip joint angles) over the other two joint angles (comfort joint angles of upper/lower limbs) in defining the riding posture.

Limitations and future scope of the present research

The parameters related to ORP and CRP are vital while designing motorcycles. Understanding their association with ROM and anthropometry can be useful while deciding some of the important dimensions like handlebar/seat dimensions. For example, while deciding the vertical dimensions of the motorcycle (i.e. R_1, R_2, MR_1, and H), *Body fat indicators* (i.e. somatotype) and flexion/extension of joints need to be taken into account. Though the sample size was estimated as per the ISO recommendation, the limitations of a study could be limiting the sample size to 120. It is difficult to infer about a large motorcyclist population using a small sample. At present, Indian males are dominant motorcycle users. Nevertheless, we recommend including female subjects in future research. Although this is a laboratory study, we are planning to investigate the same in the dynamic riding condition (riding on a flat road).

Conclusion

It can be established from the results of PCA that out 10 comfortable joint angles, only three variables (joint angles of hip and lowers back) and out of 10 riding position only four variables (R_1, R_2, MR_1, H) were identified as the principal components explaining most variance in CRP and ORP. This is the first attempt to establish the link between the comfortable riding posture/position and rider's physical attributes (anthropometry and ROM). It was noticed that the ROM and anthropometry of riders were significantly associated with their CRP/ORP. Moreover, CRP/ORP can be predicted using rider ROM and anthropometry. It can be concluded that the ROM and anthropometry of riders are equally important in the motorcycle design process. Therefore, it is suggested to establish a wide anthropometric and ROM database of Indian motorcycle users. Also, the research methods presented in this research can be utilized by other similar two-wheeler design (like sport, cruiser, scooter, etc.) in order to explore the CRP and ORP. The finding of this study may lead to the need of attention among electric-motorcycle manufacturers/start-ups trying to develop new ergonomic design. The present work significantly contributes to the knowledge-base, and motorcycle design methodology to ensure comfortable riding experience in the context of ergonomic design and development of standard motorcycles in India.

Acknowledgements

The authors would like to thank the Ministry of Human Resource Development (*MHRD*) *and research under the* Design Innovation Centre (DIC) project. Also, the authors would like to thank all the participants who participated in this time-consuming experimental measurement survey.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

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Appendix I

Notation

DSLR	digital single-lens reflex
MP	Megapixel
USB	Universal Serial Bus
HDMI	High-Definition Multimedia Interface
DHM	Digital Human Modelling
ROM	Range of motion
PC	Principal Component
PCA	Principal Component Analysis
SMLR	Stepwise multiple linear regression
MLR	Multiple linear regression
ORP	Optimum/comfortable riding position
CRP	Comfortable riding posture
KMO	Kaiser-Meyer-Olkin
w_{jn}	Perceived comfort rating by the subject for the respective joint
Cn %	Percentage of comfort score converted from the comfort rating of the individual joint of the subjects.
F	*F*-test value is any statistical test in which the test statistic has an Fisher–Snedecor distribution
R^2	coefficient of determination
P	probability of obtaining test results
R_1	vertical distance between *f*-point and *d*-point
R_2	vertical distance between *f*-point and g'-point
R_3	horizontal distance between *f*-point and *d*-point
R_4	horizontal distance between *f*-point and g'-point
MR_1	vertical distance between *h*-point and floor
MR_2	horizontal distance between *h*-point and *f*-point
T	distance between *g*-points on left and right handle grips
L	distance between g'-points on left and right handle grips
O	distance between *f*-points on the left and right footrest

Greek symbols

β	slope of the line through a regression of data points
θ_j	Weighted mean comfort joint angle of the (120) samples
θ_{jn}	Measured comfort joint angle of the subject in the respective joint
$\Delta\theta_j$	standard deviations or tolerance of weighted *j*th joint angle
$(\theta_{nj})_{max}$	The maximum values of the weighted comfort joint angle of the total subjects
$(\theta_{nj})_{min}$	The minimum values of the weighted comfort joint angle of the total subjects.
θ_{neck}	Estimated neck angle using ideal reference point 1 (on the wall), otic region and ideal reference point 2 (on the wall)
$\theta_{shoulder}$	Estimated shoulder angle using the coordinates of lateral epicondyle of the humerus, acromion process, and 10th rib
θ_{elbow}	Estimated elbow angle using the coordinates of the acromion process, lateral epicondyle of the humerus, and radial styloid
$\theta_{lowerback}$	Estimated lowerback angle using the coordinates of trochanter, 10th rib, and acromion process
θ_{hip}	Estimated hip angle using coordinates of 10th rib, trochanter, and lateral femoral epicondyle
θ_{knee}	Estimated knee angle using coordinates of trochanter, lateral femoral epicondyle, and right lateral malleolus
θ_{ankle}	Estimated ankle angle using coordinates of lateral femoral epicondyle, right lateral malleolus, and metatarsale fibulare
θ_{wrist}	Estimated wrist angle using coordinates of phalanges, radial styloid, and lateral epicondyle of the humerus
$\theta_{shoulder\ abd/add}$	Estimated shoulder adduction/abduction angle using coordinates of lateral epicondyle of the humerus, acromion process, and extended point of acromion process
$\theta_{hip\ abd/add}$	Estimated hip adduction/abduction angle using ideal reference point 1 (on the seat), lateral epicondyle of the humerus and ideal reference point 2 (on the seat)

Appendix A

Digital image processing (DIP)

Procedure adopted in DIP. These coordinates were identified through a code programmed in the MATLAB R2016a. The algorithm adopted for MATLAB program follows below steps:

Input: Image (I), ʈ (threshold), *p* -› connected components, *M* (number of images)
Output: Co-ordinates (x, y)
Step – I: Read the Image I

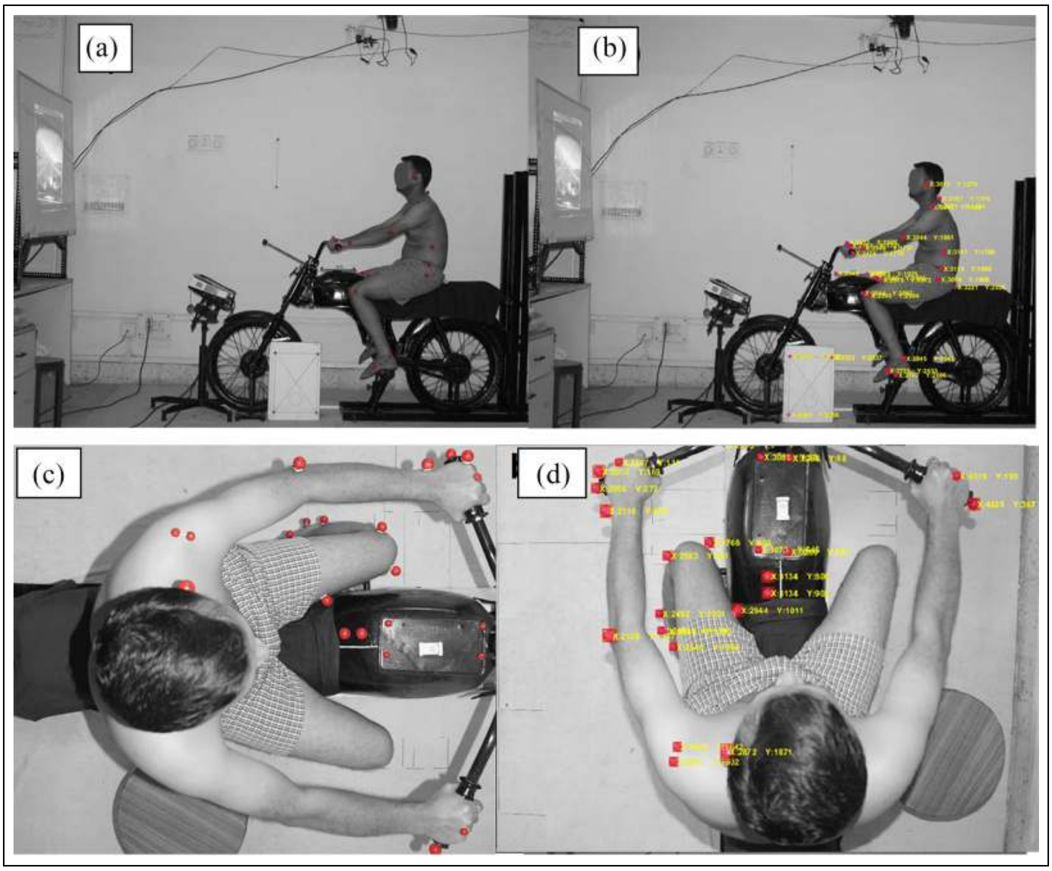

Figure A1. (a) Side view image of participant with red-reflective markers, (b) image processing – performed on side view image, (c) top view image of participant with red-reflective markers, and (d) image processing – performed on top view image.

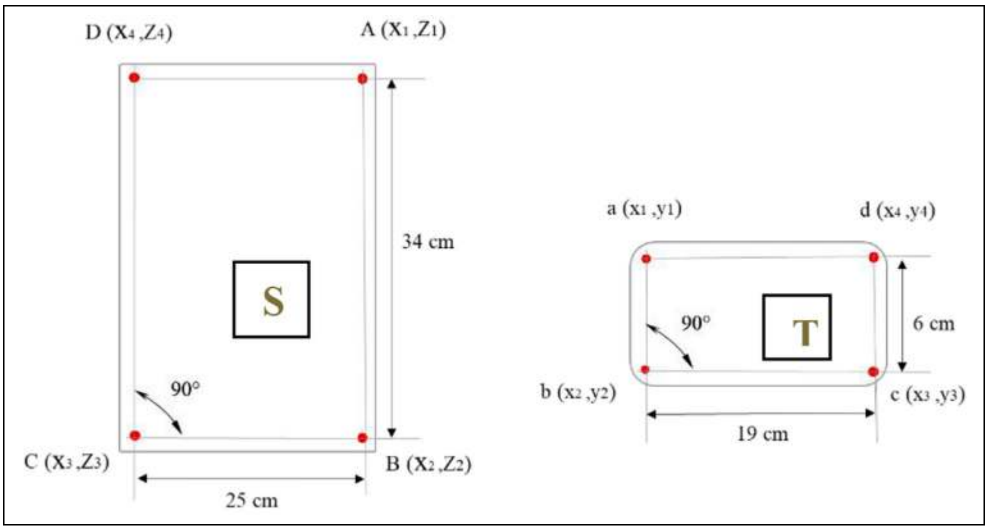

Figure A2. Calibration system of the image with known size: (S) side view and (T) top view.

Step – II: Convert the image to grayscale format
Step – III: Use the ɩ to covert the grayscale Image to binary image
Step – IV: Contract the center pixel of all black points in a binary image
Step –V: Create the label matrix with *p* connected components
Step –VI: Label all the co-ordinates with red colors

Image calibration system. The actual dimensions of the side and top view rectangular board are disclosed in Figure A2. The red reflective markers (Ø 12 mm) were placed in all the corners (ABCD and abcd points) of the rectangular boards. These red reflective markers were considered as reference points in the process of image calibration. The 2-dimesional coordinators ((X_1 Z_1), (X_2 Z_2), ($x_1 y_1$), ($x_2 y_2$), and so on) from the images were used to estimate the pixel's DPI (Dot per Inch).

Further, they were also used to compute the percentage of error deviation in angular (AEd%) and dimensional (Ed%) measurement between the actual (known size) and image measurement (coordinates) of the rectangular board.

The DPI (in centimeters), Ed%, and AEd% were calculated for both images (side and top view) using equations (a.1)–(a.3), respectively, which were referenced from the previous literature (Gavan et al., 1952[57]; Hsiao et al., 2015[58]; Hung et al., 2004[59]).

$$\text{DPI (in cm)} = \begin{cases} \dfrac{(Z_1 - Z_2)_{\text{AB image distances in pixels}}}{\text{Actual Distance of A to B points (34 cm)}} & \text{; if side view} \\ \dfrac{(y_1 - y_2)_{\text{ab image distances in pixels}}}{\text{Actual Distance of a to b points (6 cm)}} & \text{; if top view} \end{cases} \tag{a.1}$$

$$\text{Ed\%} = \begin{cases} \dfrac{\text{Actual Distance of B to C point} - \text{Calculated BC}}{\text{Actual Distance of B to C points (25 cm)}} \text{X } 100; \text{if side view} \\ \dfrac{\text{Actual Distance of b to c point} - \text{Calculated bc}}{\text{Actual Distance of a to b points (19 cm)}} \text{X } 100; \text{if top view} \end{cases} \tag{a.2}$$

where,

$$\text{Calculated BC} = \frac{(X_2 - X_3)_{B\ to\ C\ pixels\ distance\ in\ the\ image}}{DPI\ of\ side\ view\ image}$$

$$\text{Calculated bc} = \frac{(x_2 - x_3)_{b\ to\ c,\ pixels\ distance\ in\ the\ image}}{DPI\ of\ Top\ view\ image}$$

$$\text{AEd\%} = \begin{cases} \dfrac{(\angle ABC = 90^\circ) - (\text{Estimated } \angle ABC)}{(\angle ABC = 90^\circ)} \text{X } 100; \text{if side view} \\ \dfrac{(\angle abc = 90^\circ) - (\text{Estimated } \angle abc)}{(\angle abc = 90^\circ)} \text{X } 100; \quad \text{if Top view} \end{cases} \tag{a.3}$$

where estimated ∠ABC and ∠abc computed using the coordinates of these points in equation (1).

The resolution of each side view image was 5456 × 3064 pixels. With actual dimension of 34 × 25 cm, the average estimated resolution of calibration rectangular board (side view) was 389.59 × 280.88 pixels (SD = 11.93 × 8.5 pixels) for all the 120 images (for 120 subjects). Therefore, each pixel of the side view image estimated as 0.087 cm. Further, the mean and SD of Ed% and AEd% calculated as 1% (±1.96) and 0% (±0.26), respectively, for the side view images.

Similarly, the resolution of the top view image was 3872 × 2176 pixels. The top calibration rectangular board of 6 × 19 cm was on the size of 121.83 × 393.38 pixels (SD = 24.02 × 70.69 pixels owing to focus deviation). Therefore, each pixel of the side view image estimated as 0.049 cm. The mean and SD of Ed% and AEd% calculated as −1% (±3.24) and 1.74% (±1.42), respectively, for the top view images. Overall, the calibration results (Ed% and AEd%) of both image views were found to be precise enough and within the recommended maximum error tolerance of ±3.24%, in-line with the previous literature (Gavan et al., 1952; Hsiao et al., 2015; Hung et al., 2004).

Appendix B

Angular estimation

The 10 body-joint angles (θ_1–θ_{10}) in riding posture were defined through the subject's body landmark (as shown in Figure B), which were also predominantly used in the similar type of previous studies (Grainger et al.[21]; Hsiao et al., 2015[58]; Young et al., 2012[60]). Red spherical reflective markers (Ø 19 mm) were affixed on the respective body locations to highlight the coordinate of

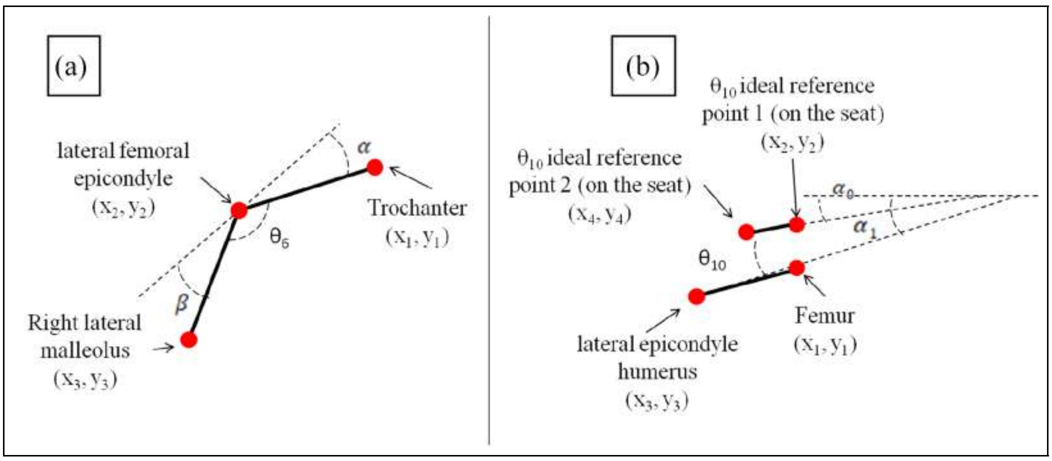

Figure B. Representation of (a) application of equation (b.1) for estimating knee angle (θ_6) and (b) application of equation (b.2) for estimating hip abduction/adduction angle (θ_{10}).

the landmarks. The 2D coordinate (x, y) of these spherical reflective markers of the body landmarks were substituted in the equations (b.1) and (b.2) to obtain the joint angles. These equations (b.1) and (b.2) were referenced from the previous studies (Hsiao et al., 2015; Chou and Hsiao[48]) and tangent rules (for estimating intersection angle between two lines). The application of equation (2) for estimation of the hip abduction/adduction angle (θ_{10}). Figure B(a) and (b) illustrates the estimation of knee angle (θ_6) utilizing the respective coordinates for computing the slopes ($\tan \alpha$ and $\tan \beta$). Similarly, Figure B(b) has been used to illustrate the application of equation (2) for estimation of the hip abduction/adduction angle (θ_{10}).

$$\theta = \tan^{-1}\frac{(\tan\alpha + \tan\beta)}{(\tan\alpha\cdot\tan\beta) - 1} \tag{b.1}$$

where, $\tan\alpha = \frac{y_1 - y_2}{x_1 - x_2}$

$$\tan\beta = \frac{y_3 - y_2}{x_2 - x_3}$$

$$\theta = (\alpha_1 - \alpha_0) \times \frac{180}{\pi} \tag{b.2}$$

where,

$$\alpha_0 = atan2(y_3 - y_1, x_3 - x_1)$$

$$\alpha_1 = atan2(y_4 - y_2, x_4 - x_2)$$

Alternative cases:

$$\mathrm{atan2}(\Delta y, \Delta x) = \begin{cases} \tan^{-1}\left(\frac{\Delta y}{\Delta x}\right) & ; if\ \Delta x > 0 \\ \tan^{-1}\left(\frac{\Delta y}{\Delta x}\right) + \pi & ; if\ \Delta y \geqslant 0,\ \Delta x < 0 \\ \tan^{-1}\left(\frac{\Delta y}{\Delta x}\right) - \pi & ; if\ \Delta y < 0,\ \Delta x < 0 \\ +\frac{\pi}{2} & ; if\ \Delta y > 0,\ \Delta x = 0 \\ -\frac{\pi}{2} & ; if\ \Delta y < 0,\ \Delta x = 0 \end{cases}$$

Appendix C

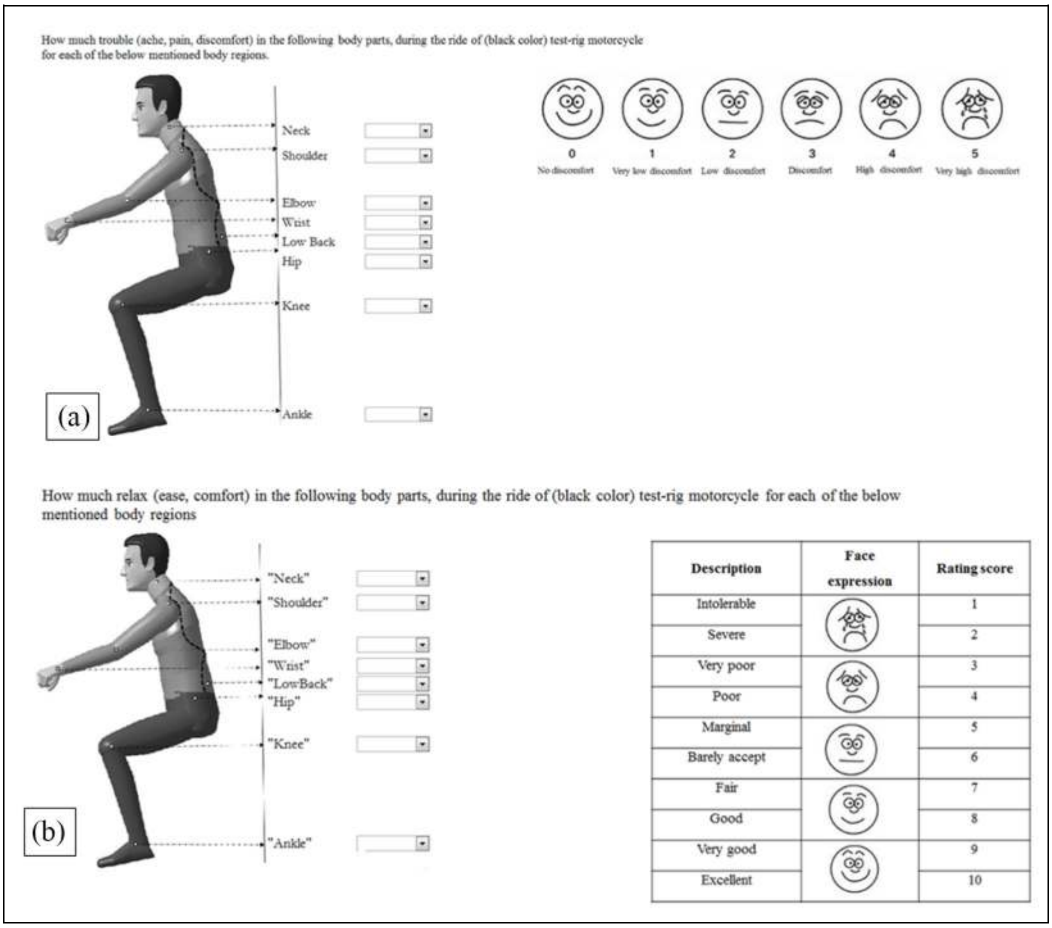

Figure C. (a) Discomfort and (b) comfort – subjective rating scales.

Appendix D

Intra-correlation among postural and position variables

Table D1. Intra-correlation among postural variables.

	θ_{neck}	$\theta_{shoulder}$	θ_{elbow}	$\theta_{lowerback}$	θ_{hip}	θ_{knee}	θ_{ankle}	θ_{wrist}	$\theta_{shoulder\ abd/add}$
θ_{neck}	–								
$\theta_{shoulder}$	0.446[b]	–							
θ_{elbow}	0.423[b]	0.639[b]	–						
$\theta_{lowerback}$	0.353[b]	0.357[b]	0.391[b]	–					
θ_{hip}	0.250[b]	0.268[b]	0.148	0.685[b]	–				
θ_{knee}	0.096	0.246[b]	0.406[b]	0.375[b]	0.304[b]	–			
θ_{ankle}	0.300[b]	0.225[a]	0.241[b]	0.400[b]	0.351[b]	0.426[b]	–		
θ_{wrist}	0.344[b]	0.209[a]	0.267[b]	0.398[b]	0.235[b]	0.225[a]	0.234[a]	–	
$\theta_{shoulder\ abd/add}$	0.092	0.267[b]	0.471[b]	0.315[b]	0.202[a]	0.324[b]	0.268[b]	0.241[b]	–
$\theta_{hip\ abd/add}$	0.124	0.05	–0.096	0.344[b]	0.481[b]	0.042	0.287[b]	0.203[a]	0.381[b]

Table D2. Intra-correlation among riding position variables.

	R_1	R_2	R_3	R_4	MR_1	MR_2	H	L	T
R_2	0.328[b]	–							
R_3	0.167	0.181[a]	–						
R_4	0.021	−0.168	−0.468[b]	–					
MR_1	0.904[b]	0.276[b]	0.222[a]	−0.072	–				
MR_2	0.182[a]	0.265[b]	0.810[b]	−0.371[b]	0.023	–			
H	0.95[b]	0.328[b]	0.167	0.021	0.850[b]	0.182[a]	–		
L	0.071	0.121	0.245[b]	−0.445[b]	0.217[a]	0.019	0.071	–	
T	0.071	0.121	0.245[b]	−0.445[b]	0.217[a]	0.019	0.071	0.950[b]	–
O	−0.083	−0.041	−0.024	0.1	0.018	−0.046	−0.083	0.009	0.009

[a]Correlation is significant at the 0.05 level (two-tailed).
[b]Correlation is significant at the 0.01 level (two-tailed).

Appendix E1

Description of ROM measurements

Neck flexion and neck extension were measured in standing position, as the axis of the goniometer, placed at the center of the external auditory meatus. The stationary-arm is parallel to the vertical line and the movable-arm aligned with nostrils.

Lumbar extension and lumbar flexion were measured in standing position, as the axis of the goniometer is center of the iliac crest, the stationary-arm parallel to the vertical line along the thigh and the movable-arm aligned with anterior axillary line.

Wrist extension and wrist flexion was measured in sitting position, as the axis of the goniometer is center of the lateral wrist (triquetrum), the stationary-arm aligned with the ulna and the movable-arm aligned with the fifth metacarpal.

Elbow extension and elbow flexion were measured in sitting position, as the axis of the goniometer is center of the lateral epicondyle of humerus, the stationary-arm parallel to the humerus (center of acromion process), and the movable-arm aligned with radius (styloid process).

Knee flexion and knee extension were measured in spine position, as the axis of the goniometer is the center of the femur's lateral epicondyle, the stationary-arm aligned with greater trochanter and the movable-arm aligned with the lateral malleolus.

Shoulder extension and shoulder flexion were measured in sitting position, as the axis of the goniometer is center of the humerus, the stationary-arm parallel to the midaxillary line and the movable-arm aligned with midline-humerus.

Ankle plantarflexion and ankle dorsiflexion were measured in spine position, as the axis of the goniometer is center of the lateral malleolus, the stationary-arm parallel to the fibular head and the movable-arm aligned with the fifth metatarsal.

Shoulder abduction and shoulder adduction were measured in spine position, as the axis of the goniometer is center of the acromion process, the stationary-arm parallel to the midline of the sternum and the movable-arm aligned with the midline of the humerus.

Hip abduction and hip adduction, were measured in spine position as the axis of the goniometer is center of the anterior superior iliac spine, the stationary-arm parallel to the opposite anterior superior iliac spine and the movable-arm aligned with the femur (center of patella).

Hip flexion and hip extension were measured in spine position, as the axis of the goniometer is center of the greater trochanter, the stationary-arm parallel to the midline of the pelvis and the movable-arm aligned with the femur (lateral epicondyle).

Appendix E2

Anthropometric and ROM measurements

Table E1. Descriptive statistics of anthropometric measurements ($n = 120$) (unit: mm unless specified).

Anthropometric dimension	Mean	SD	Min	Max	Percentile		
					Fifth	50th	95th
Weight (W) in kg	68	11	38	96	51	68	84
Stature (S)	1690	70	1540	1880	1580	1680	1830
Body mass index(BMI) (kg/m^2)	24	4	14	32	18	24	29
Crotch height (CH)	780	50	670	950	690	770	860
Buttock extension (BE)	840	60	580	980	720	860	940
Cervical height sitting (CHS)	640	30	580	710	590	640	690
Shoulder height sitting (SHS)	580	30	510	650	520	570	630
Elbow height sitting (EHS)	220	30	160	280	180	220	270
Knee height (KH)	550	40	46	84	490	550	600
Lower leg length (LLL)	450	40	370	710	390	440	500
Shoulder-elbow length (SEL)	350	20	300	410	310	350	400
Elbow-hand length (EHL)	470	30	420	540	430	480	520
Buttock-knee length (BKL)	590	40	500	680	530	590	660
Buttock-popliteal length (PL)	490	40	400	570	420	490	560
Acromion grip length (AL)	630	40	530	750	550	630	700
Ball of foot length (BFL)	180	20	100	210	160	180	200
Hand length (HL)	180	10	150	210	150	180	200
Foot-breadth (FB)	100	10	80	120	90	100	110
Elbow-Elbow breadth (EEB)	430	40	330	530	370	440	490
Hip breadth, sitting (HBS)	340	30	270	430	290	340	380
Thigh circumference (TC)	450	50	340	570	380	450	540
Triceps skinfold (T) (mm)	8	2	4	14	5	8	12
Subscapular skinfold (SS) (mm)	10	2	5	15	6	10	13
Supraspinal skinfold (SR) (mm)	11	2	5	16	7	10	15
Medial calf skinfold (MC) (mm)	10	2	5	14	7	10	13
Calf circumference (CC)	330	50	210	520	270	330	410
Upper arm circumference (UC)	290	30	190	340	230	290	330
Femur breadth (FrB)	90	10	60	110	80	90	100
Humerus breadth (HB)	70	10	60	90	60	70	80

Table E2. Descriptive statistics of the range of motion measurements ($n = 120$) (unit: °).

Range of motion	Mean	SD	Min	Max	Percentile		
					Fifth	50th	95th
Neck flexion (NF)	37	8	20	60	20	35	50
Neck extension (NE)	40	7	25	56	30	40	53
Lumbar flexion (LF)	104	7	80	124	90	104	115
Lumbar extension (LE)	21	6	10	40	10	20	35
Wrist flexion (WF)	75	8	50	90	60	80	90
Wrist extension (WE)	69	9	50	90	58	70	80
Knee flexion (KF)	128	7	110	145	120	130	140
Knee extension (KE)	2	2	0	10	0	1	5
Hip flexion (HF)	107	11	70	140	90	105	130
Hip extension (HE)	17	6	5	30	10	20	26
Hip abduction (HAb)	17	9	10	90	10	15	25
Hip abduction (HA)	46	9	25	70	30	47	60
Elbow extension (EE)	2	3	0	15	0	0	8
Elbow flexion (EF)	140	7	120	150	130	140	150
Shoulder flexion (SF)	164	10	120	180	150	166	180
Shoulder abduction (SA)	137	15	110	175	120	130	170
Shoulder abduction (SAb)	41	11	1	70	30	40	60
Shoulder extension (SE)	44	11	20	80	27	45	60
Ankle plantar flexion (AP)	36	7	20	50	25	35	47
Ankle dorsiflexion (AD)	30	10	0	70	10	20	30

Appendix F

Zero-degree correlation

Table F1. Correlation of riding posture joint angles variables with ROM, anthropometry dimensions, and riding position variables.

	Comfort hip joint angles	Comfort angles of upper limbs	Comfort angles of lower limbs
Body length indicator	0.081	−0.063	−0.362[b]
Volume indicator	−0.281[b]	−0.014	0.075
Body fat indicators	−0.092	−0.055	−0.077
Sitting height indicator	−0.099	0.193[a]	−0.174
Body bilateral length indicators	−0.094	0.277[b]	−0.115
Motion at Sagittal plane	0.335[b]	0.089	−0.07
Motion at Transverse plane	−0.213[a]	0.15	−0.096
Upperlimb motions at Sagittal plane	0.182[a]	−0.227[a]	0.058
Lower limb motions at the Sagittal plane	0.027	−0.068	−0.015
Lower limb motion at Transverse plane	−0.193[a]	0.095	−0.042
Spine motion at Sagittal plane	−0.139	0.004	0.317[b]
Knee-elbow motion at Sagittal plane	−0.142	−0.151	−0.165
Vertical dimensions at Sagittal plane	−0.183[a]	0.11	0.165
Dimensions at Transverse plane	0.159	−0.297[b]	0.037
Horizontal dimensions at Sagittal plane	0.014	−0.254[b]	0.014
Footrest dimensions at Transverse plane	−0.139	0.076	0.01

[a]Correlation is significant at the 0.05 level (two-tailed).
[b]Correlation is significant at the 0.01 level (two-tailed).

Table F2. Correlation of riding position variables with ROM, anthropometry dimensions, and comfort joint angles.

	Vertical dimensions at Sagittal plane	Dimensions at Transverse plane	Horizontal dimensions at Sagittal plane	Footrest dimensions at Transverse plane
Body length indicator	−0.042	−0.014	0.248[b]	0.115
Volume indicator	0.15	0.007	0.082	0.036
Body fat indicators	−0.233[a]	0.009	0.064	−0.049
Sitting height indicator	0.114	0.101	0.022	0.056
Body bilateral length indicators	0.047	−0.594[b]	−0.067	0.002
Motion at Sagittal plane	−0.279[b]	0.204[a]	0.076	−0.074
Motion at Transverse plane	−0.141	−0.297[b]	−0.089	0.214[a]
Upper limb motions at Sagittal plane	0.102	0.407[b]	−0.29[b]	0.016
Lower limb motions at the Sagittal plane	0.083	0.017	−0.062	−0.091
Lower limb motion at Transverse plane	0.086	−0.144	−0.039	0.208[a]
Spine motion at Sagittal plane	0.102	0.017	−0.093	0.05
Knee-elbow motion at Sagittal plane	−0.095	−0.02	0.074	0.135
Comfort hip joint angles	−0.183[a]	0.159	0.014	−0.139
Comfort angles of upper limbs	0.11	−0.297[b]	−0.254[b]	0.076
Comfort angles of lower limbs	0.165	0.037	0.014	0.01

[a]Correlation is significant at the 0.05 level (two-tailed).
[b]Correlation is significant at the 0.01 level (two-tailed).