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Determination of the key anthropometric and range of motion measurements for the ergonomic design of motorcycle

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ABSTRACT

In India, where 92% of motorcycle users are male, existing anthropometry and range of motion (ROM) databases of Indian male motorcyclists are either inadequate in terms of relevant information or not a representative of the whole Indian population. A data-set including 29 anthropometric and 20 ROM measurements were gathered from 120 male participants following Intra- and inter-observer reliability techniques. Using dimensional reduction technique, 14 and 6 most influential anthropometric and ROM variables were identified, which explain almost total variance. The percentage of difference ranged from −26% to 56% was noticed while comparing the variables of the current study with the database of the general population of India as well as other (inter)national databases of the motorcyclist/driver. Although the sample size is relatively less, the developed data-set can be used for the ergonomic design of motorcycles for Indian users till a larger database is generated considering insights from the current study.

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1. Introduction

Ergonomics plays a vital role in the motorcycle design process for effective user-centered design towards successful, marketable products. The ergonomics of the motorcycles are evaluated using Digital Human Modeling (DHM) tools, which are commercially available (like CATIA, Jack, SANTOS, etc.) [10,46]. These DHM tools facilitate a designer to rapidly simulate and visualizes the results for further improvements and design approvals. These tools aid the anthropometrics and range of motion (ROM) measurements in the human model (called manikin) for an ergonomics analysis like compatibility and comfort of a motorcyclist. Therefore, the database pertaining to anthropometry and ROM of the targeted user population is essential to develop manikins to be used in the design process of the motorcycle.

Presently, few anthropometrics databases of motorcyclists are available as published research articles. Whereas, to the best of our knowledge and literature survey, no ROM database of motorcyclists was documented so far (till writing this article). A few studies surveyed only anthropometric dimensions but not ROM of motorcycle riders in the UK [38] and Nigeria [17].

Though the car driver's population is higher than the motorcyclist worldwide, more motorcycle users are there in Southern Asian regions [30]. Amongst the South Asian countries, India has a higher number of motorcyclist population when compared with other automotive users [41]. The reason for the high motorcycle users in low-middle-income countries like India could be the cost of affordability. Despite the existence of a large number of motorcycle users in India, the comprehensive anthropometric and ROM databases of the motorcyclist population are rarely reported in any research article. However, in the Indian context, few of the anthropometric studies [23,4] reported a mixed survey of the motorcycle, car, and truck driver population. Amrutkar and Rajhans [2] conducted an anthropometric survey on 70 young-adult (aged: 18–25 years) motorcyclists from a particular geographical location (Pune city) of India. Since most of the potential anthropometric variables were missing, these surveys may not be applicable and useful for considering an anthropometry database for a motorcycle design process.

The aforesaid publications from India either have not mentioned the exact number of male and female participants or not given the due importance of male dominance (92% motorcycle license holders) [13] during the development of anthropometric databases of Indian drivers of two/four-wheelers. Although significant efforts were put forth by the researchers conducting field experiments, these studies missed presenting a comprehensive database (all required dimensions) of male motorcyclist's ROM and anthropometric measurements. Each of these studies measured different sets of variables, and therefore, hardly any consistency was maintained. Thus, many a time, it is not possible to compare these databases. These anthropometric surveys lack in justifying the relevance of variables considered, i.e., every survey considered their own set of variables according to their articulation of interest. Hence, the comprehensiveness of these databases is

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still questionable. For these reasons, motorcycle manufacturers are forced to use the general-population database of India [7] during the design of motorcycles for the Indian market.

Developing comprehensive general-population databases are important for any country to prepare estimates and analyze the social and economic development, quality of healthcare and daily living. Most national governments sponsor creating such databases for their own country by funding through research and education schemes. It is noteworthy that the development of these databases come at a cost proportional to population size and incurs huge financial burden, time, and manpower. Developing an anthropometric and biomechanical database for a specific area (motorcycle design) in highly populated countries like India involves potential risk of relevancy, population coverage, and accuracy. Motorcycle manufacturers may find it more suitable to use the general population database rather than investing in developing one.

Also, it would be a redundant database unless there is any substantial difference between a specific group (drivers/motorcyclists) and general population. Therefore, before moving forward to develop such detailed anthropometric and biomechanical database, the present study should be considered as preliminary research. It proposes the need for such a database.

A few recent studies also tried to compile the anthropometry database to design products/facilities that could fit the user's anthropometry, in turn, provide more comfort and less physical stress. Lee et al. [27] investigated the gender differences in Singaporean adult and elderly people anticipating mismatch in standard product/facilities used. They conducted cross-national comparisons of anthropometry considering further development of ergonomic product design. Adnan and Dawal [1] compiled a Malaysian anthropometry database consisting of 52 wheelchair users (41 males and 11 females) to test the anthropometric variation between wheelchair users and a healthy population.

Earlier studies [10,38] reflected that the anthropometry and ROM databases for motorcycle users are essential in motorcycle design and ergonomics evaluation. Application of general-population data in the design of specific target groups (male Indian motorcyclists) may arise several ergonomic issues like body-parts discomforts, musculoskeletal disorders, etc. [12,22]. Moreover, applying anthropometric and ROM data from other countries during the design of motorcycles for Indian riders might lead to dimensional (mis)match [7].

The reported anthropometry studies of Indian motorcyclists suggest that these may be inadequate/inappropriate in terms of design and ergonomics aspects. Besides, there may be a difference between general-population and the motorcyclist population. Since the reported literature on both anthropometry and ROM database is very rare in the Indian context, it is very difficult to identify the most potential anthropometric and/or ROM variables which could be used in developing CAD human models (manikins) during the process of design and development of a motorcycle. Hence, the present study aims at answering the following two research questions (RQ):

RQ1: What are the principal anthropometric and ROM variables that define the physical characteristics of Indian male motorcyclists?
RQ2: What is the percentage difference of anthropometry and ROM variables between the present study and other national/international databases (motorcyclist/driver and the general population of India)?

2. Methods and materials

2.1. Participants

The motorcyclist population of India (29 states and nine union territories) is estimated as four hundred seven million in 2016 [13]. Among them, 92% are male motorcyclists in the age group of 19–44 years. Therefore, the collection of physical data (anthropometry and ROM measurements) should be focused on dominating users (male, age 19–44 yrs.) for ergonomically effective motorcycle design.

The minimum sample size was estimated using the International Organization for Standardization [19], which establishes general requirements for sample size calculations while conducting anthropometry studies. While calculating a minimum number of samples based on the formula (Eq. (1)), the recommended sample size for the study was determined as ($n \geq$) 117.

$$n \geq \left(1.96 \times \frac{CV}{\alpha}\right)^2 \times (1.534)^2 \tag{1}$$

where n = number of samples and; CV (coefficient of variation) = (Standard Deviation/Mean) × 100; α is relative accuracy (1% relative accuracy was assumed for 95% confidence)

The minimum recommended sample size was determined by the characteristics of stature data collection based on the mean value $\left(\bar{x} = 167.5\text{cm}\right)$, SD (6.1 cm). To avoid biased estimation, the mean and SD values of male stature were referred from the reputed (SIZE India) database of automotive drivers [23].

The anthropometric and ROM measurements were collected using stratified random sampling, and 120 male participants were randomly selected. One hundred twenty participants with at least one-year riding experiences, a valid motorcycle license, and aged between 19 and 44 years were surveyed to pool the subsets of the strata in the experiment. The study covered the participants from 20 major states of India. The participants were split into six zonal categories in India viz. northeastern, northern, western, eastern, southern, and central India. Assuming that all the six zones have an equal percentage of male motorcyclists, therefore, we tried to segment the sample population into an equal proportion of each zonal category of interest (yielded 15% to 17% in each group). The motorcyclists (participants) who had previous health issues like bone fractures, hypermobility, musculoskeletal disorders/pains problems were excluded in the initial screening.

2.2. Selection of body dimensions

We have measured 29 anthropometrics (which include body mass index (BMI) and four skinfold measurements), and 20 ROM of measurements (see Figs. 1 and 2) recognized from the previously published research articles [3,22,26,33,38]. The measurement procedures of the anthropometrics and ROM measurements were followed as per the previously published ISO standards, books, and research articles [7,20,21,29,36,8,31,40]. The measurements like the position of the subject (sitting, standing, etc.), the orientation of particular segments (head, arm, leg, etc.) and the plane of measurement (Frankfurt, Dorsal, etc.) were measured undergoing the procedures as mentioned above research articles. The anatomical landmarks used for 29 anthropometrics and 20 ROM measurements are indicated in Appendices A and B, respectively.

2.3. Measuring instruments and apparatus

Anthropometric dimensions and ROM were manually measured using a different set of instruments (see Fig. 3). Fig. 3I-VI shows different instruments viz. anthropometer (GPM model 101 anthropological instruments, Switzerland), adjustable rods (expandable up to 2100 mm), base plate, plastic tape (2000 mm), portable weighing scale (136 kg maximum capacity, Model: GVC 9837, Make: GVC, India), and sliding caliper used for all the physical measurements. A 360° or Full circle goniometer (Fig. 3VII) (body has a 30 cm length of

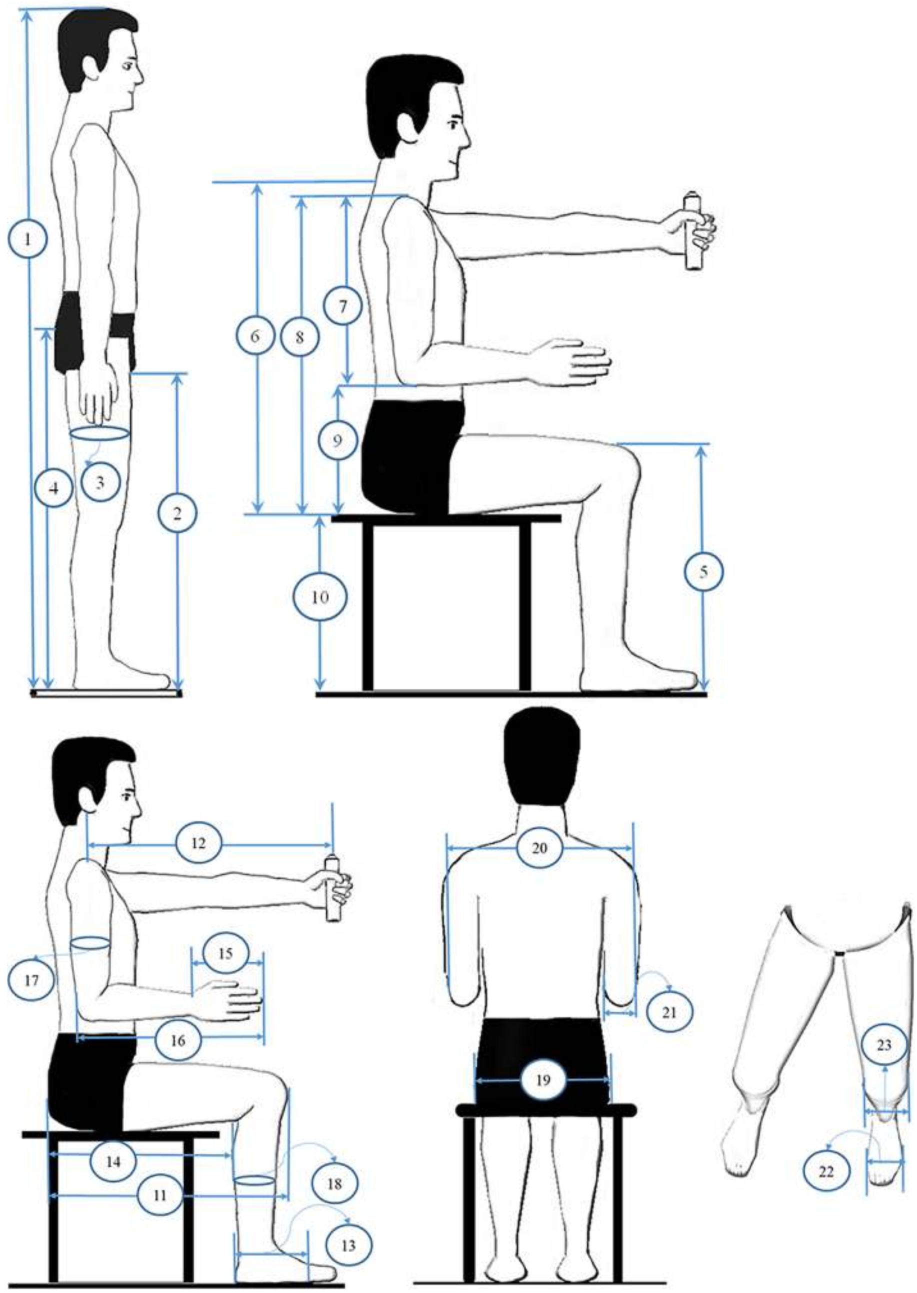

Fig. 1. Anthropometric dimensions measured in the study. Note: circled numerics represent the following anthropometric nomenclatures and acronyms: [3] Stature (S); [3] Crotch height (CH); [4] thigh circumference (TC); [5] Buttock extension (BE); [6] Knee height (KH); [7] Cervical height sitting (CHS); [8] Shoulder-elbow length (SEL); [9] Shoulder height sitting SHS); [10] Elbow height, Sitting (EHS); [11] Lower leg length (LLL) [11] Buttock-knee length (BKL); length (AL); [13] Ball of foot length (BFL); [14] Buttock-Popliteal length (PL); [15] Hand length (HL); [16] Elbow-Hand Length arm circumference (UC); [18] Calf circumference (CC); [19] Hip breadth, sitting (HBS); [20] Elbow to elbow breadth (EEB); (HB); [22] Foot breadth (FB); and [23] Femur breadth (FrB).

stationary-arm and moving-arm) was used for measuring the ROM measurements. Slim sliding skinfold caliper (Fig. 3VIII) (range: 0 – 80 mm) was used to measure the thickness of the skinfolds. An adjustable stole (Fig. 3IX) and the table was used throughout the sitting posture and supine position measurements, respectively.

2.4. Experimental procedure

Two researchers/observers were involved in the data collection procedure. Both of them (trained anthropometrist) were professionally familiar with human anatomical landmarks, equipment, and measurement techniques. Before the measurement, the participants were informed about the measurement procedures, and written consent was obtained from them. The study was approved by the ethics committee of the institute, and the data collection procedure was conducted according to Helsinki guidelines [47]. Before the measurement sessions, general information like age, motorcycle riding experiences, state of origin (in India) of the participant was also documented in the data collection sheet.

In this study, the measurement information was acquired after five subsequent sessions: (1) Anthropometric measurements - standing posture; (2) Anthropometric measurements - sitting posture; (3) ROM measurements - standing posture; (4) ROM measurements - sitting posture; (5) ROM measurements - supine

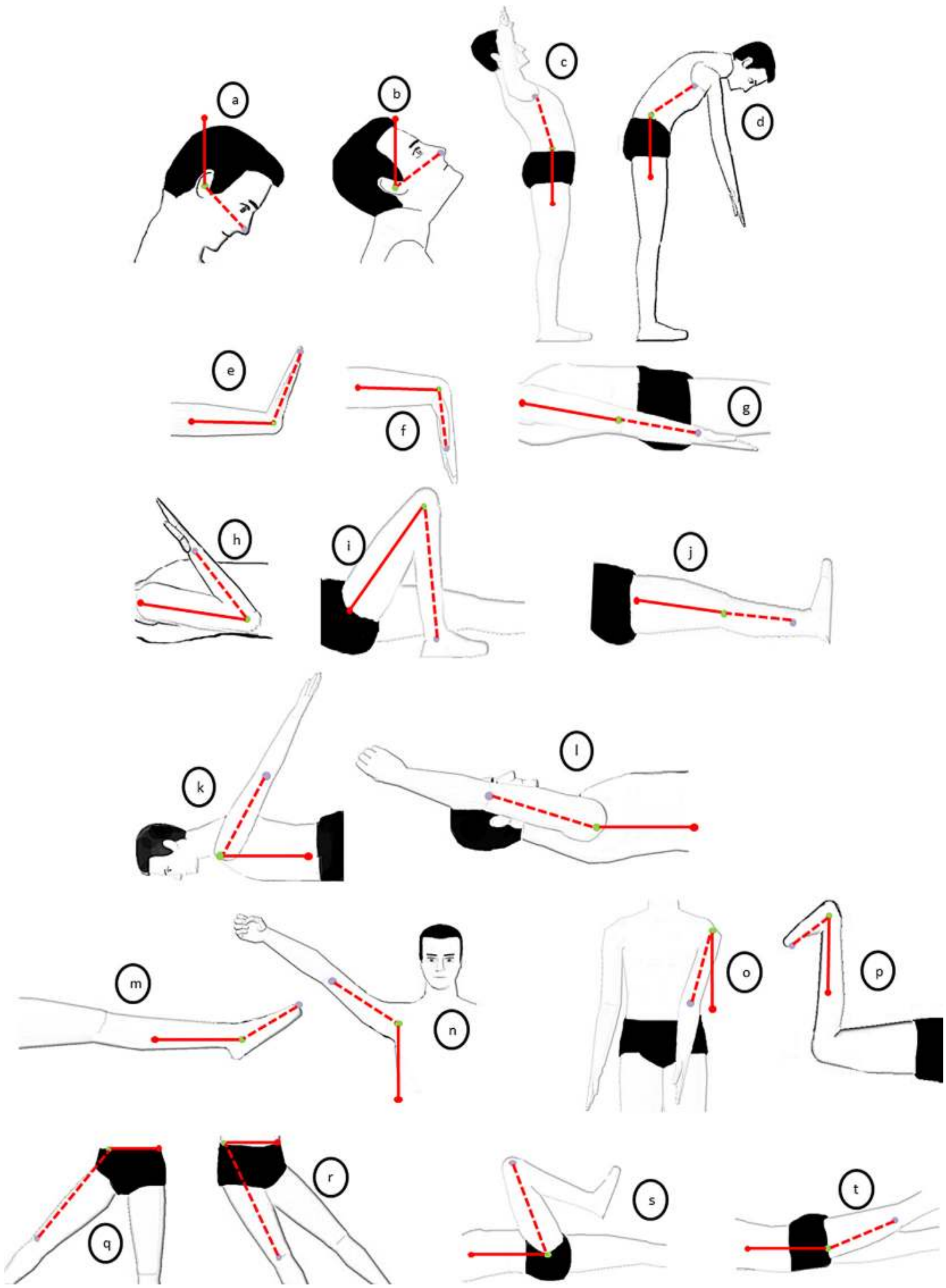

Fig. 2. Anatomical landmarks of Range of motion (ROM) measurements in the study. Note: Circled alphabets represent the following ROM nomenclatures and acronyms: [a] Neck Flexion (NF); [b] Neck Extension (NE); [c] Lumbar Extension (LE); [d] Lumbar Flexion (LF). Redline - the stationary-arm or distal arm of the goniometer, and the red dotted line - movable-arm or Proximal arm of the goniometer. Note: Circled alphabets represent the following ROM nomenclatures and acronyms: [e] Wrist Extension (WE); [f] Wrist Flexion (WF); [g] Elbow Extension (EE); [h] Elbow Flexion (EF); [i] Knee Flexion (KF); [j] Knee Extension (KE); [k] Shoulder Extension (SE); [w] Shoulder Flexion (SF). Red solid line - the stationary-arm or distal arm of the goniometer; and red dotted line - movable-arm or proximal arm of the goniometer. Note: Circled alphabets represent the following ROM nomenclatures and acronyms: [m] Ankle plantar flexion (AF); [p] Ankle dorsiflexion (AD); [n] Shoulder Abduction (SA); [o] Shoulder Adduction (SAd); [q] Hip Abduction (HA); [r] Hip Adduction (HAd); [s] Hip Flexion (HF); [t] Hip Extension (HE). Redline - the stationary-arm or distal arm of the goniometer, and the red dotted line - movable-arm or proximal arm of the goniometer. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

posture. Subjects were asked to wear only shorts during these measurement sessions (as shown in Appendix D). The duration of the entire data collection of anthropometry and ROM for each participant was about an hour.

2.4.1. Reliability of measurements

Before the anthropometric and ROM measurements on 120 participants, Intra-observer and Inter-observer reliability tests were performed on randomly chosen 10 participants to evaluate the accuracy of linear and angular measurements. To ensure the accuracy in measurement of both anthropometric and ROM data, reliability of the measurement technique was calculated in terms of intra-/inter-observer Technical Error of Measurement (%TEM) and intra-/inter- class correlation coefficient (ICC) or coefficient of reliability (R). These techniques were used to identify instrumental or manual errors [44].

During the Intra-observer reliability assessment, initially, observer-1 measured all ROM and anthropometric dimensions on ten participants during the first week. After a week, all the measurements were repeated on the same participants by observer-1 to find the intra-observer variability and error. Similarly, to determine Inter-observer consistency estimates, observer-1 and 2 measured the ROM and anthropometric dimensions among 10 participants during the same day.

These variability and errors were statistically estimated by Intra-/Inter- observer %TEM (see Eq. (2)), and ICC or R (see Eq. (3)) [21,43]. The Eqs. (2) and (3) were incorporated in the spreadsheet and used to calculated %TEM and R for an individual variable of anthropometric and ROM measurements.

$$\%TEM = \frac{\mathrm{TEM}}{\mathrm{M}};\ \text{Where},\ TEM = \sqrt{\left(\sum D^2\right)/2N} \tag{2}$$

$$R = 1 - \left\{\frac{(\mathrm{TEM})^2}{\mathrm{SD}^2}\right\} \tag{3}$$

where D is the difference between measurements, N is the number of participants, M is the mean of the measurement, SD is the standard deviation of the measure.

2.5. Data analysis

The anthropometric and ROM measurements of 120 participants were manually transferred from the datasheet to IBM SPSS version 25.0 software for data analysis. The statistical analyses were performed at a chosen confidence level set to 0.05 and 0.01. Primarily, the data were visually inspected with histograms, Q-Q plots, box plots, and checked for normality using the Shapiro-Wilk test ($p > 0.05$). The majority of anthropometry and ROM values were found to be normally distributed across the variables. The descriptive statistics were presented through the mean, standard deviation (SD), maximum, minimum, and percentiles (5th, 50th, and 95th) for each anthropometry and ROM variables.

Principal component analysis (PCA) is commonly known for dimensional reduction of a more extensive set of variables into a smaller subset [35,45]. This statistical method was applied on 29 anthropometric and 20 ROM variables to find the answers to our first research question. This analysis was performed under the following consideration (1) extraction method as varimax rotation, (2) eigenvalues greater than 1, and (3) factor loading greater than 0.4 (Eigenvectors below 0.4 suppressed for display in tables). Before performing the PCA on the anthropometrics and ROM variables, the data were checked for the following assumptions of the PCA. (1) The association between all the variables using Pearson's correlation coefficient; (2) The adequate sample size estimation using Kaiser-Meyer-Olkin and Bartlett's sphericity values and; (3) the number of significant outliers using the box plots for each of the variables.

The comparative analysis was done by estimating the percentage difference between the present study and the previous studies from (inter)national database. Notably, the national database from general [7] and automotive driver population of India [4,23,2] the international motorcyclist population database from U.K [38],

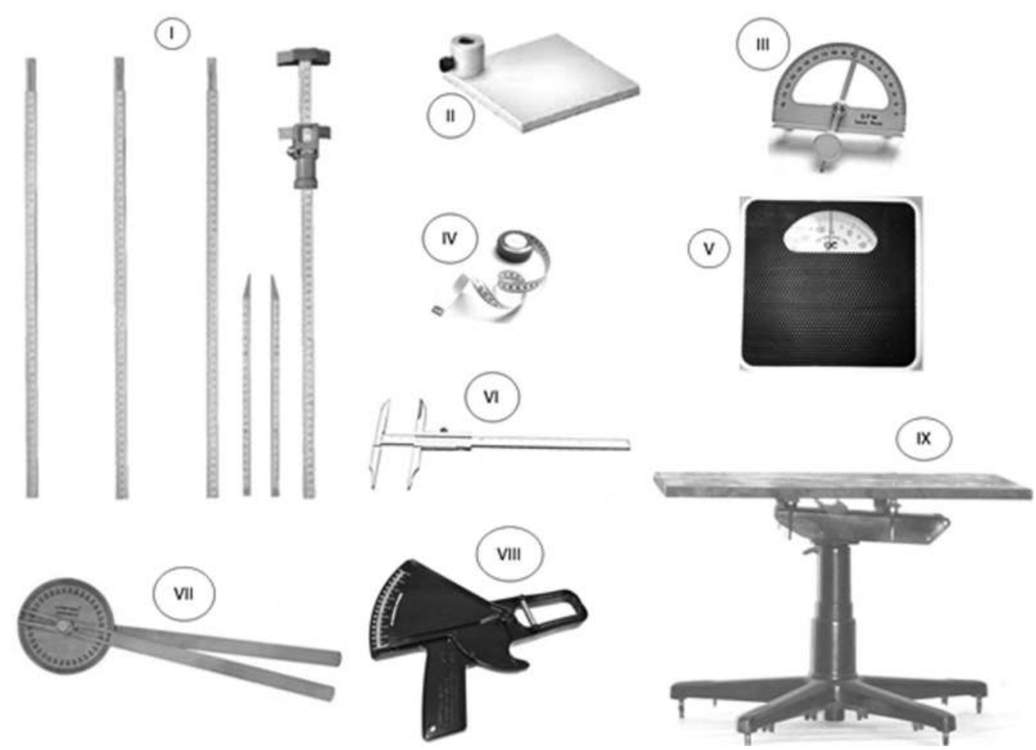

Fig. 3. Anthropometrics and Range of motion (ROM) – Apparatus. Note. (I) Anthropometer; (II) Base Plate; (III) Detachable goniometer; (IV) Tapes; (V) Weighing scale (VI) Sliding caliper; (VII) Full-scale goniometer; (VIII) skinfold caliper; (IX) Adjustable stole.

and Nigeria [17] were used for the comparison. The percentage of differences was calculated using Eq. (4), which was inspired and formulated from earlier studies [18,32].

$$\%D = ((PM_j - PRM_j)/PM_j) \times 100 \quad (4)$$

where %D is Percentage differences,
PM_j is the mean of jth variable of anthropometric or ROM from the present study,
PRM_j is the mean of a jth variable of anthropometric or ROM from the previous study.

Since the standard deviation of the ROM and anthropometry dimensions were not presented in some studies [7,23], we have used percentage differences estimation instead of other statistical tests (e.g., independent *t*-test used in [3,27] for the comparative analysis.

3. Results and discussion

3.1. Descriptive of the study

The 120 male participants holding a valid license with a mean age of 29 years (SD 8.8 years) were included for physical measure-

Table 1
Descriptive statistics of anthropometric measurements among the subjects (n = 120) (Unit: cm unless specified).

Anthropometric dimension	Mean	SD	Min	Max	Percentile 5th	50th	95th
Weight (W) in kg	68	11	38	96	51	68	84
Stature (S)	169	7	154	188	158	168	183
Body mass index (BMI) (Kg/m^2)	24	4	14	32	18	24	29
Crotch height (CH)	78	5	67	95	69	77	86
Buttock extension (BE)	84	6	58	98	72	86	94
Cervical height sitting (CHS)	64	3	58	71	59	64	69
Shoulder height sitting (SHS)	58	3	51	65	52	57	63
Elbow height, Sitting (EHS)	22	3	16	28	18	22	27
Knee height (KH)	55	4	46	84	49	55	60
Lower leg length (LLL)	45	4	37	71	39	44	50
Shoulder-elbow length (SEL)	35	2	30	41	31	35	40
Elbow-hand length (EHL)	47	3	42	54	43	48	52
Buttock-knee length (BKL)	59	4	50	68	53	59	66
Buttock-popliteal length (PL)	49	4	40	57	42	49	56
Acromion grip length (AL)	63	4	53	75	55	63	70
Ball of foot length (BFL)	18	2	10	21	16	18	20
Hand length (HL)	18	1	15	21	15	18	20
Foot-breadth (FB)	10	1	8	12	9	10	11
Elbow-Elbow breadth (EEB)	43	4	33	53	37	44	49
Hip breadth, sitting (HBS)	34	3	27	43	29	34	38
Thigh circumference (TC)	45	5	34	57	38	45	54
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)	33	5	21	52	27	33	41
Upper arm circumference (UC)	29	3	19	34	23	29	33
Femur breadth (FrB)	9	1	6	11	8	9	10
Humerus breadth (HB)	7	1	6	9	6	7	8

Table 2
Descriptive statistics of the range of motion measurements among the subjects (n = 120) (Unit: ○).

Range of motion	Mean	SD	Min	Max	Percentile 5th	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 Abbuction (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 Abbuction (SAb)	41	11	1	70	30	40	60
Shoulder Extension (SE)	44	11	20	80	27	45	60
Ankle Plantarflexion (AP)	36	7	20	50	25	35	47
Ankle Doris flexion (AD)	30	10	0	70	10	20	30

Table 3
Anthropometric dimensions -Intra and Inter-observer technical errors.

Anthropometric dimension	Intra-observer technical error		Inter-observer technical error	
	%TEM	ICC	%TEM	ICC
Weight (W)	0.05	0.999	0.34	0.999
Stature (S)	0.51	0.999	0.24	0.991
Crotch height (CH)	0.43	0.994	0.56	0.995
Buttock extension (BE)	0.34	0.992	0.48	0.981
Cervical height sitting (CHS)	0.90	0.989	0.63	0.978
Shoulder height sitting (SHS)	0.93	0.988	1.09	0.977
Elbow height, Sitting (EHS)	1.68	0.984	1.54	0.985
Knee height (KH)	0.54	0.994	0.78	0.988
Lower leg length (LLL)	1.23	0.982	0.97	0.997
Shoulder-elbow length (SEL)	1.24	0.981	1.09	0.992
Elbow-hand length (EHL)	0.93	0.968	0.88	0.975
Buttock-knee length (BKL)	0.66	0.987	0.73	0.975
Buttock-popliteal length (PL)	1.39	0.971	0.87	0.989
Acromion grip length (AL)	0.79	0.986	0.63	0.986
Ball of foot length (BFL)	0.72	0.983	1.55	0.971
Hand length (HL)	1.35	0.974	1.51	0.981
Foot-breadth (FB)	0.78	0.972	0.98	0.978
Elbow-Elbow breadth (EEB)	0.80	0.987	0.89	0.987
Hip breadth, sitting (HBS)	0.96	0.987	1.18	0.975
Thigh circumference (TC)	0.78	0.986	0.88	0.987
Triceps skinfold (T)	2.69	0.987	3.26	0.972
Subscapular skinfold (SS)	2.07	0.983	3.03	0.982
Supraspinal skinfold (SR)	3.14	0.986	3.89	0.979
Medial calf skinfold (MC)	4.56	0.981	4.76	0.978
Calf circumference (CC)	1.62	0.973	1.78	0.96
Upper arm circumference (UC)	0.26	0.998	0.56	0.989
Femur breadth (FrB)	1.02	0.971	1.45	0.978
Humerus breadth (HB)	0.89	0.981	1.05	0.971

ments. These participants had a mean riding experience of 10 years (SD 4 years). Tables 1 and 2 presents the descriptive statistics of 29 anthropometric measurements and 20 ROM measurements among all the participants.

3.2. Reliability of the study

Intra and inter-observer technical errors of anthropometric measurements are presented in Table 3. The %TEM and ICC of these measurements were ranged from 0.05 to 1.8% and 0.97 to 0.99, respectively. Similarly, %TEM and ICC of skinfold ranged from 2.06 to 4.56% and 0.98 to 0.99 for both of observer technical errors, respectively. Researchers [9,21,43] in previous studies agreed that the measurements could be considered reliable and error-free for higher than 0.95 reliability values.

Intra and inter-observer technical errors of ROM measurements are presented in Table 4. The %TEM and ICC of these measurements ranged from 0.9 to 1.7% and 0.96 to 0.99 for both observer technical errors. Previous literature [42] showed that the ROM measurements are expected error-free when the reliability coefficient exceeds 0.96, respectively. Since the ICC measurements in the pilot study (10 participants) were higher than the suggested values in the past literature, the overall result implies that the anthropometric and ROM measurements would be trustworthy for the further survey, including more subjects.

Table 4
Range of motion measurements – Intra and Inter-observer technical errors.

ROM measurements	Intra-observer technical error		Inter-observer technical error	
	TEM%	ICC	TEM%	ICC
Neck Flexion (NF)	1.05	0.987	1.71	0.997
Neck Extension (NE)	0.87	0.989	0.96	0.978
Lumbar Flexion (LF)	0.15	0.998	0.23	0.998
Lumbar Extension (LE)	1.02	0.986	1.58	0.978
Wrist Flexion (WF)	1.07	0.987	1.69	0.968
Wrist Extension (WE)	1.32	0.975	1.56	0.982
Knee Flexion (KF)	1.02	0.971	0.88	0.979
Knee Extension (KE)	0.9	0.972	1.26	0.967
Hip Flexion (HF)	0.75	0.987	1.10	0.968
Hip Extension (HE)	0.92	0.984	1.26	0.967
Hip Abbuction (HAb)	0.45	0.992	0.78	0.978
Hip Abduction (HA)	0.35	0.995	0.69	0.977
Elbow Extension (EE)	1.02	0.974	1.35	0.967
Elbow Flexion (EF)	0.48	0.997	0.78	0.977
Shoulder Flexion (SF)	0.26	0.994	0.67	0.978
Shoulder Abduction (SA)	0.57	0.998	0.78	0.977
Shoulder Abbuction (SAb)	1.04	0.98	1.62	0.976
Shoulder Extension (SE)	0.56	0.992	0.96	0.975
Ankle Plantarflexion (AP)	0.35	0.991	0.64	0.987
Ankle Doris flexion (AD)	1.12	0.976	1.32	0.968

3.3. Dimensional reduction analysis using principal component analysis (PCA)

3.3.1. Principal components (PC) of anthropometry measurements

This statistical method yields five PCs (PC1-PC5) from the 29 anthropometrics variables. The potential PCs were identified graphically using the scree plot (see Fig. 4). This plot implied that the potent PCs were having an eigenvalue greater than 1. The Kaiser-Meyer-Olkin measure of sampling adequacy was obtained as 0.79 (ranged between 0.70 and 0.79). It can be interpreted as a "middling" sample size for the study [6]. Bartlett's test of sphericity was also found to be significant ($p < 0.001$), which indicates that the sample size was acceptable [24].The correlation coefficient between all the anthropometric variables was ranged from −0.7 to 0.7 (see Appendix C, Tables C1 and C2 for matrix correlation tables) implies a strong linear relationship between anthropometric variables.

Following varimax orthogonal rotation, five PCs of the anthropometric measurements accounted for 71.95% of the total variance

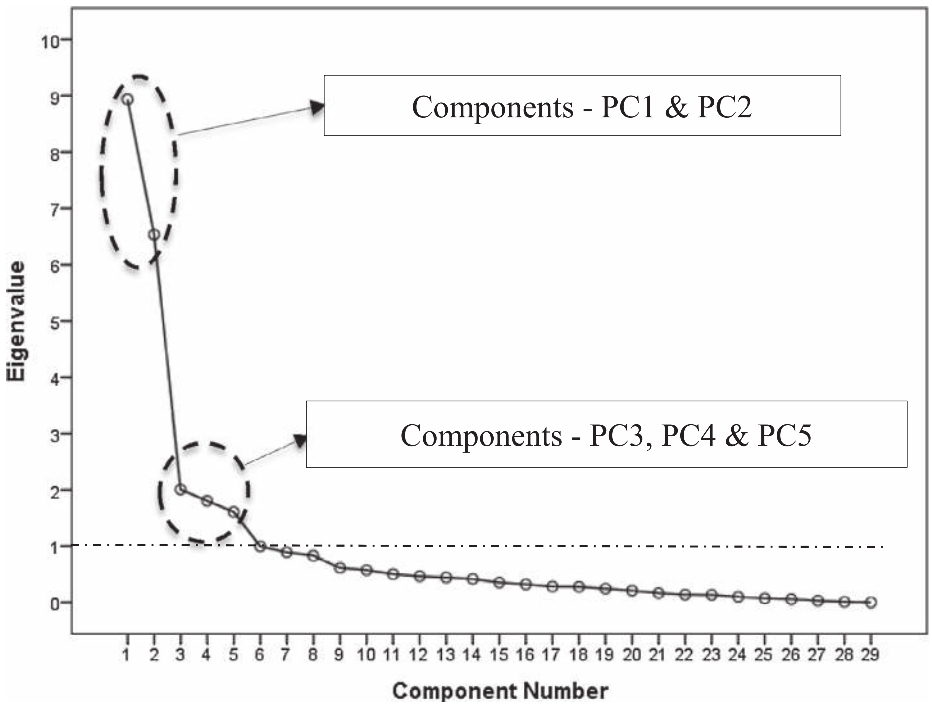

Fig. 4. Scree plot of anthropometric measurements.

Table 5
Total variance explained for anthropometric measurements.

Component	Initial Eigenvalues			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	8.934	30.807	30.807	8.180	28.207	28.207
2	6.529	22.514	53.321	5.757	19.852	48.058
3	2.002	6.903	60.224	2.543	8.771	56.829
4	1.799	6.204	66.428	2.286	7.883	64.712
5	**1.602**	**5.524**	**71.952**	2.100	7.240	71.952
6	0.991	3.418	75.370			
7	0.885	3.053	78.423			
8	0.828	2.857	81.279			
9	0.614	2.117	83.396			
10	0.574	1.980	85.376			
11	0.503	1.736	87.112			
12	0.466	1.606	88.717			
13	0.443	1.529	90.246			
14	0.417	1.439	91.686			
15	0.354	1.222	92.908			
16	0.323	1.113	94.020			
17	0.284	0.980	95.000			
18	0.280	0.964	95.964			
19	0.245	0.846	96.810			
20	0.211	0.729	97.539			
21	0.167	0.576	98.116			
22	0.138	0.476	98.592			
23	0.135	0.465	99.058			
24	0.099	0.341	99.399			
25	0.073	0.252	99.651			
26	0.057	0.198	99.849			
27	0.032	0.109	99.958			
28	0.011	0.037	99.995			
29	0.001	0.005	100.000			

Table 6
Results of factor analysis (eigenvectors values) for anthropometric measurements.

	Component				
	1	2	3	4	5
Weight (W) in kg		0.877			
Stature (S)	0.910				
Body mass index(BMI) (Kg/m^2)		0.847			
Crotch height (CH)	0.652				
Buttock extension (BE)	0.779				
Cervical height sitting (CHS)	0.569			0.708	
Shoulder height sitting (SHS)	0.541			0.797	
Elbow height, Sitting (EHS)				0.936	
Knee height (KH)	0.622				−0.448
Lower leg length (LLL)	0.647				
Shoulder-elbow length (SEL)	0.881				
Elbow-hand length (EHL)	0.872				
Buttock-knee length (BKL)	0.849				
Buttock-popliteal length (PL)	0.796				
Acromion grip length (AL)	0.721				
Ball of foot length (BFL)	0.671				
Hand length (HL)	0.777				
Foot-breadth (FB)					-0.768
Elbow-Elbow breadth (EEB)		0.676	0.411		
Hip breadth, sitting (HBS)		0.811			
Thigh circumference (TC)		0.802			
Triceps skinfold (T) (mm)			0.847		
Subscapular skinfold (SS) (mm)		0.572	0.470		
Supraspinal skinfold (SR) (mm)		0.590	0.561		
Medial calf skinfold (MC) (mm)			0.786		
Calf circumference (CC)		0.792			
Upper arm circumference (UC)		0.696			
Femur breadth (FrB)		0.657			
Humerus breadth (HB)					0.762

Note. Eigenvectors values < 0.4 suppressed for display in the table.

in the original variables (see Table 5). PC 1 includes 14 variables (see Table 6), and accounts 30.8% of the total variance (eigenvalue = 8.9). These factors were labeled as "*Body length indicator*". PC 2 was comprised of ten variables and labeled as the "*Volume indicator*". It accounted for 22.5% of the variance (eigenvalue = 6.5). PC 3 consisted of five variables (6.9% of the variance; eigenvalue = 2) and labeled as "*Body fat indicators*". PC 4 consisted of three variables (6.2% of the variance; eigenvalue = 1.7) and labeled as "*Sitting height indicator*". PC 5 consisted of three variables (5.5%

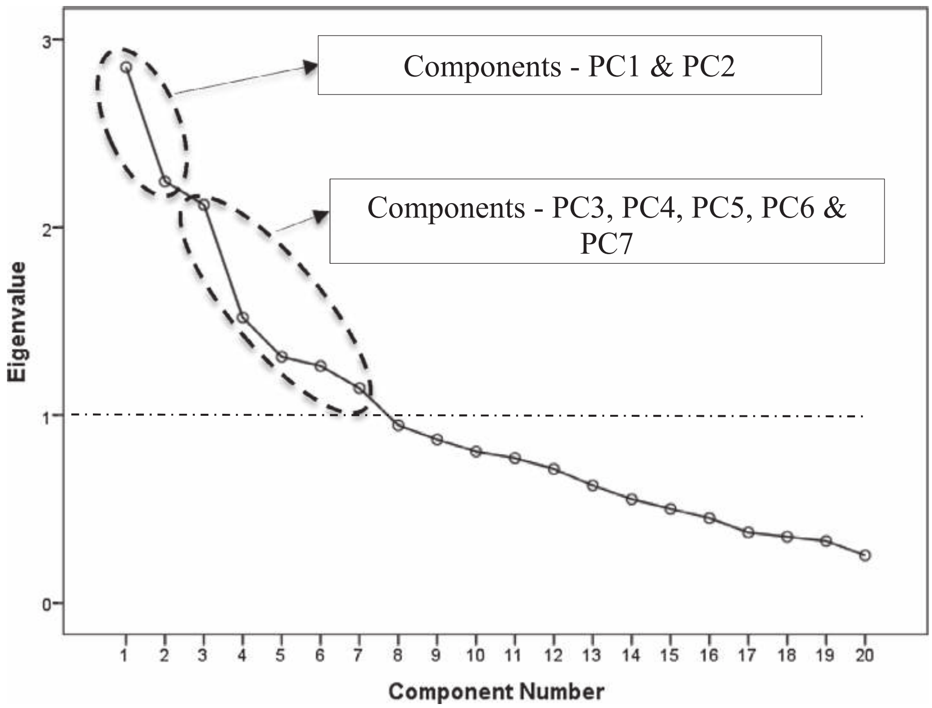

Fig. 5. Scree plot of ROM measurements.

Table 7
Total Variance Explained for Range of motion measurements.

Component	Initial Eigenvalues			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	2.853	14.267	14.267	2.341	11.704	11.704
2	2.244	11.218	25.485	1.998	9.990	21.693
3	2.120	10.598	36.083	1.930	9.651	31.345
4	1.518	7.592	43.674	1.741	8.705	40.050
5	1.310	6.549	50.223	1.557	7.785	47.835
6	1.260	6.301	56.524	1.546	7.730	55.565
7	1.142	5.710	62.234	1.334	6.670	62.234
8	0.946	4.731	66.965			
9	0.871	4.353	71.318			
10	0.806	4.031	75.349			
11	0.771	3.856	79.205			
12	0.714	3.568	82.773			
13	0.626	3.131	85.904			
14	0.553	2.764	88.669			
15	0.501	2.506	91.175			
16	0.452	2.262	93.436			
17	0.376	1.878	95.315			
18	0.353	1.765	97.080			
19	0.330	1.651	98.731			
20	0.254	1.269	100.000			

of the variance; eigenvalue = 1.6) and labeled as "*Body bilateral length indicators*".

The PCA result interprets that the "*Body length indicator*" (PC-1) was the major component, which defines the physical characteristics of Indian male motorcyclist. This PC includes 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. Whereas, in comparison, the "*Body bilateral length indicators*" and "*Body fat indicators*" PCs express weaker variables in terms of physical characteristics of Indian male motorcyclist.

In line with our results, the study by Dasgupta et al. [11] on Indian automotive male drivers (car/truck/motorcycle) revealed that the length related dimensions (precisely stature and elbow-hand height) were expressing higher physical characteristics than other anthropometric dimensions. On the contrary, Majumder [28] recognized that "*Volume Indicator*" and "*Body fat indicator*" were the governing PCA estimates for the general Indian male population when compared with the "*Body length indicator*." Previous research has also shown that the physical characteristics of the driver population differ from the general population. Guan et al. [14] performed a PCA on anthropometry measurements of the U.S drivers (cab and truck) and compared them with U.S general population. Haslegrave [16] used the factor extraction method (PCA) on anthropometry measurements of the female and male cab drivers of the UK and compared their results with U.K general population. Both of these studies found substantial differences between drivers and the general population.

3.3.2. Principal components (PC) of ROM measurements

The PC analysis yielded seven PCs from 20 ROM measurements. The PC considered was having more than one as eigenvalues (see scree plot Fig. 5). The Kaiser-Meyer-Olkin measure of sampling adequacy was estimated as 0.61. This value falls in the range between 0.60 and 0.69 and called a "mediocre" sample size [6]. The Bartlett's test of sphericity was also found to be significant ($p < 0.001$), which indicates that the sample size was acceptable [24]. The correlation coefficient between all variables of ROM was found within a range from −0.5 to 0.5 (see Appendix C for matrix correlation tables), which implies a moderate linear relationship between ROM measurements.

Following varimax orthogonal rotation for ROM measurements, seven PCs accounted for 62.23% of the total variance in the original variables (see Table 7). PC 1 included 6 variables, (see Table 8), accounting for 14.2% of the total variance (eigenvalue = 2.8). This factor was labeled "*Motion at Sagittal plane*". PC 2 was comprised of four variables related to the "*Motion at Transverse plane*." This factor accounted for 11.2% of the total variance (eigenvalue = 2.2).

Table 8
Results of factor analysis (eigenvectors values) for Range of motion measurements.

	Component						
	1	2	3	4	5	6	7
Neck Flexion (NF)		−0.713					
Neck Extension (NE)		−0.782					
Lumbar Flexion (LF)						0.758	
Lumbar Extension (LE)						0.788	
Wrist Flexion (WF)	0.679						
Wrist Extension (WE)	0.571						
Knee Flexion (KF)							0.621
Knee Extension (KE)	−0.423						
Hip Flexion (HF)				0.757			
Hip Extension (HE)				0.608			
Hip Abbuction (HAb)					0.486		
Hip Abduction (HA)		0.649					
Elbow Extension (EE)							0.648
Elbow Flexion (EF)	0.495						
Shoulder Flexion (SF)			−0.772				
Shoulder Abduction (SA)	−0.528		0.462				
Shoulder Abbuction (SAb)		0.472					
Shoulder Extension (SE)	0.748						
Ankle Plantarflexion (AP)					0.824		
Ankle Doris flexion (AD)			0.632				

Note. Eigenvectors values < 0.4 suppressed for display in the table.

PC 3 included 3 variables, accounting for 10.5% of the total variance (eigenvalue = 2.1). This factor was labeled as "*Upperlimb Motions at Sagittal plane*". PC 4 included two variables, accounting for 7.5% of the variance (eigenvalue = 1.5). This factor was labeled as "*lower limb Motions at the Sagittal plane*." PC 5 included 2 variables, accounting for 6.5% of the variance (eigenvalue = 1.3). This factor was labeled as "*lower limb Motion at Transverse plane*". PC 6 included two variables, accounting for 6.3% of the total variance (eigenvalue = 1.26). This factor was labeled as "*Spine Motion at Sagittal plane*". PC 7 included 2 variables, accounting for 5.7% of the total variance (eigenvalue = 1.14). This factor was labeled as "*Knee-elbow Motion at Sagittal plane*".

It was evident in the ROM PC analysis that the "*Motion at Sagittal plane*" was the dominant PC, which defines the general joint flexibility characteristic of Indian male motorcyclist. It includes variables like wrist flexion, wrist extension, knee extension, elbow flexion, shoulder abduction, and shoulder extension. Whereas, "*Spine Motion at Sagittal plane*" and "*Knee-elbow Motion at Sagittal plane*" were nondominant PCs for representing the joint flexibility characteristic of Indian male motorcyclists. These PCs include the joint flexibility/motion of knee and lumbar.

PC 1 and PC 2 were found to more accountable in all PCs. The annexure (Table C2) presents the correlations between ROM measurements among all the variables associated with PCs (PC1 – PC5). The results demonstrated that there was a significant correlation between the variables associated with the most dominant PCs (PC1 and PC2) and all other PCs. In Laubach and McConville's [25] correlations study, they stated similar results and showed that the ROM movement at the sagittal plane (flexion/extension) was significantly associated with other ROMs of the body. Moreover, this infers that the two dominant PCs (PC1 and PC 2) were able to strongly contribute to the joint flexibility of motorcyclists. Whereas, on the contrary, Harris [15] study on the U.S student population was unable to acquire any single general characteristic (dominant PC) for joint flexibility.

3.4. Comparative assessment of the present study with other (inter)national databases of the motorcyclist/driver and the general population of India

Table 9 shows the anthropometric measurements from the present study were compared with (a) general Indian population data [7]; (b) Indian drivers [23]; (c) Indian drivers [4]; (d) Indian motorcyclists from Pune city, India[2]; (e) British motorcyclists [38]; (f) Nigerian motorcyclists [17]. While comparison, only 17 anthropometric and 14 ROM variables were considered due to the lack of similar data in the reported literature.

The comparative analysis of the present study with general Indian population data [7] reveals high dimensional differences of 16%. As we can see from Table 9, most of the variables clustered between 4% and 16% dimensional variations. The stature and weight of motorcyclists, which are among the crucial anthropometric dimensions [11], were 2% and 16% higher than the general population. Overall, it was evident that the anthropometric dimensions of the motorcyclist population (present study) was higher than the general population of India. These inferences from our research were also in line with previous literature [14] and [38], showing similar kinds of differences between the general and motorcycle/car driver population.

The comparative analysis with the driver population of India [23,4] illustrates that the dimensional differences were ranged from −1% to 6%. The dimensional variations of motorcyclist's statures were found marginally higher (1%) than four-wheeler drivers. Except for knee height, crotch height, and weight, the anthropometric dimension of a motorcyclist (present study) and driver population of India were almost similar to each other. However, many of the anthropometric variables were missing in those studies/databases.

When comparing our study with the anthropometric data of 70 motorcyclists from Pune city, India extracted from Amrutkar and Rajhans [2], we found that the percentage differences were ranging from −11% to 11%. Specifically, knee height, shoulder-elbow length, buttock-popliteal length, and lower leg length reflects more than 6% of dimensional differences. The same level of percentage differences was found when we compared our anthropometry results from India's general population [7]. Moreover, it shows that the anthropometric dimensions of the Indian motorcyclist population (considering six zones) were higher than the dimensions of both generals [7] and specific city (Pune) [2] population of India.

The Indian (present study) and British motorcyclist [38] comparisons showed a general trend of larger dimensions in the U.K population. The dimensional differences varied from −20% to 2%. The percentage difference in stature and weight was very high at

Table 9
Comparative analysis of anthropometric dimensions.

		National database/other studies								International database/other studies			
	Present study	Chakrabarti and NID [6]		Kulkarni et al. [21]		Shamasundara and Ogale [3]		Amrutkar and Rajhans (2011)		Robertson and Minter [35]		Lawrence [15]	
Gender, origin and type of population	Motorcyclist male of India	A general male of India		drivers male of India		drivers male of India		Motorcyclist of Pune city, India		Motorcyclist male of UK		Motorcyclist male of Nigeria	
Sample size (male)	120	710		N/M		1091		N/M		108		160	
Anthropometric Dimension		M	%D	M	%D	M	%D	M	%D	M	%D	M	%D
Weight (W) in kg	68	57	16	64	6	N/A		N/A		82	−20	N/A	
Stature (S)	169	165	2	167	1	167	1	N/A		177	−5	166	2
Crotch height (CH)	78	77	2	73	6	N/A		76	2	82	−4	N/A	
Buttock extension (BE)	84	84	0	N/A		N/A		83	1	N/A		N/A	
Elbow height, Sitting (EHS)	22	22	2	N/A		N/A		21	4	N/A		N/A	
Knee height (KH)	55	52	6	N/A		*49*	−11	51	7	54	2	52	6
Lower leg length (LLL)	45	43	5	N/A		N/A		42	7	N/A		42	7
Shoulder-elbow length (SEL)	35	32	10	N/A		*35*	−1	31	11	N/A		N/A	
Elbow-hand length (EHL)	47	N/A		N/A		*46*	−2	N/A		N/A		N/A	
Buttock-knee length (BKL)	59	56	6	N/A		N/A		N/A		63	−7	55	7
Buttock-popliteal length (PL)	49	46	7	N/A		N/A		45	8	N/A		45	8
Acromion grip length (AL)	63	N/A		N/A		N/A		N/A		66	−5	69	−9
Ball of foot length (BFL)	18	N/A		N/A		N/A		20	−11	N/A		N/A	
Hand length (HL)	18	18	−1	N/A		*19*	−3	18	1	N/A		N/A	
Foot-breadth (FB)	10	N/A		N/A		*10*	−1	9	7	N/A		N/A	
Elbow-Elbow breadth (EEB)	43	41	4	N/A		N/A		40	7	N/A		N/A	
Hip breadth, sitting (HBS)	34	33	2	N/A		*35*	−2	N/A		38	−11	N/A	

Note: M - mean values (Unit: cm) of anthropometric dimensions; %D is Percentage differences; N/A – Mean values not available; *Italic* style numbers are 50th percentile values of anthropometric dimensions; N/M - Not mentioned.

−20% and −5%, respectively. Perhaps the reason for this high difference could be the geographical diversity among the motorcyclists. Except for knee height, these results showed that the anthropometric dimensions of Indian motorcyclists were smaller than the U.K.

Table 10
Comparative analysis of ROM measurements.

Gender, origin, and type of population	Present study - Motorcyclist male of India	Chakrabarti and NID [7] - General male of India	
Sample size	120	961	
ROM	M	M	%D
Neck Flexion (NF)	37	45	−21
Neck Extension (NE)	40	30	24
Lumbar Flexion (LF)	104	90	14
Lumbar Extension (LE)	21	10	53
Wrist Flexion (WF)	75	80	−7
Wrist Extension (WE)	69	65	5
Elbow Extension (EE)	2	N/A	
Elbow Flexion (EF)	140	145	−3
Shoulder Flexion (SF)	164	180	−10
Shoulder Extension (SE)	44	45	−3
Hip Extension (HE)	17	20	−17
Hip Flexion (HF)	107	110	−3
Knee Flexion (KF)	128	135	−6
Knee Extension (KE)	2	N/A	
Ankle Plantarflexion (AP)	36	45	−26
Ankle Doris flexion (AD)	19	40	−33

Note: M - mean values (Unit: °) of ROM; %D is Percentage differences; N/A – Mean values are not available.

The dimensional differences between Nigerian [17] and Indian motorcyclists ranged from −9% to 8%. Except for acromion grip length, the percentage differences of the anthropometric dimensions of the Indian motorcyclist were higher than the Nigerian. The dimensions viz. acromion grip length, buttock-popliteal length, and lower leg length explicitly found larger (more than 7%) in Indian motorcyclists. Unlike the comparison of Indians with British anthropometry, the results point out that most of the anthropometric characteristics of Nigerian motorcycle riders were smaller than Indians.

Overall, the results showed that there was profound difference in most of the anthropometric dimensions between the non-Indian and Indian motorcyclist populations. Moreover, region-specific anthropometry studies would not be a reliable representation and accurate estimate of Indian motorcyclists. Although higher dimensional differences were evident while comparing general Indian population data, the anthropometry of Indian drivers was more or less similar to Indian motorcyclists (present study).

Since, along with anthropometry, ROM measurements are essential for the effective design of motorcycles, the ROM data from the present study were compared with general Indian population data [7]. Table 10 shows the variation in mean ROM difference between Indian motorcyclists with the general population [7]. The average angular difference was −29.4% ranged from −33.3% to 53.4%. The angular difference of lower limbs among Indian motorcyclists was smaller than the general population, whereas it was higher in the case of upper limbs. Hence, the ROM of the Indian motorcyclist was notably different from the general population.

To date, to the best of our literature search, the motorcyclist ROM measurements and its comparison with the general popula-

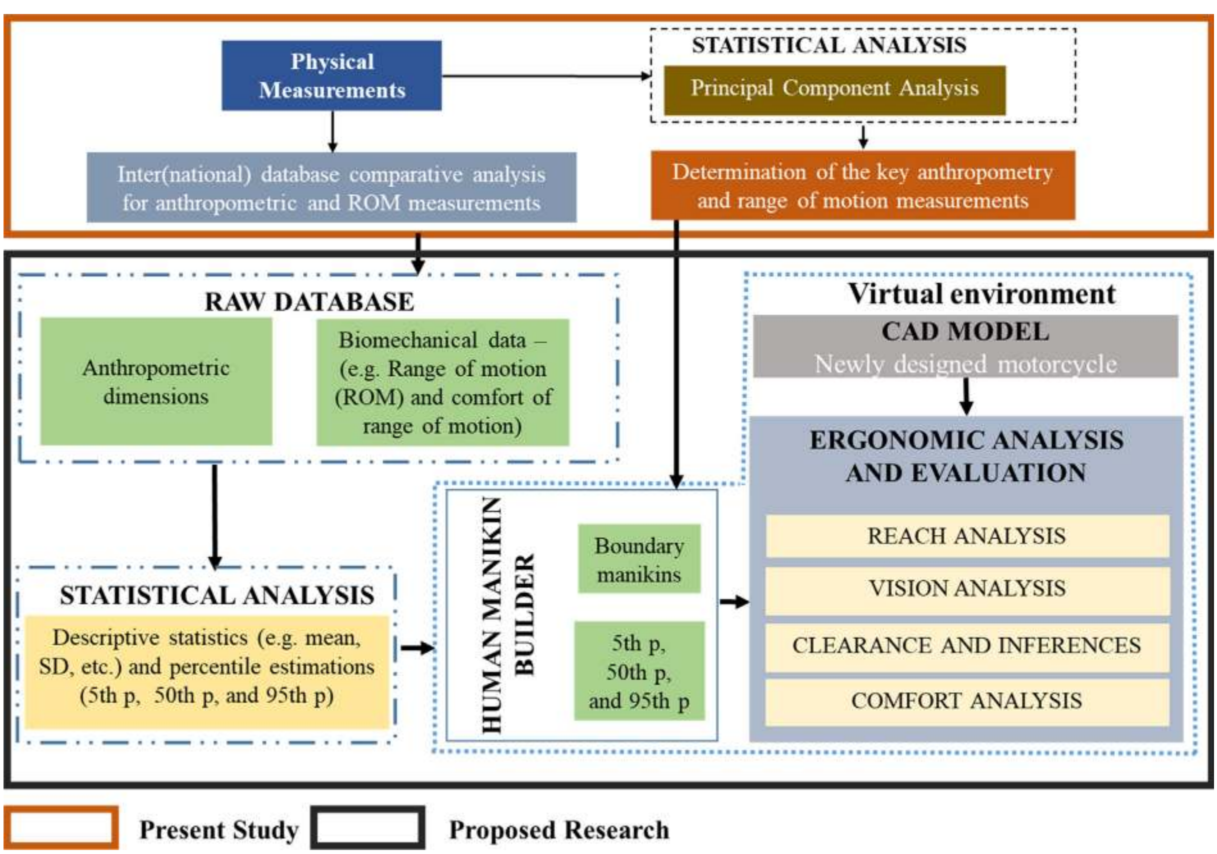

Fig. 6. Block diagram of proposed research for ergonomics measurement implementation in a motorcycle design process.

tion have never previously been studied. The present study is first of its kind to undertake this approach. Collectively, the empirical evidence from the quantitative analyses can lead to gain attention to the researchers and ergonomists for conducting large-scale surveys to develop anthropometry and ROM database required for the ergonomics design of Indian motorcycles.

3.5. Implementation of measurements in the motorcycle design process – Future scope

A generic project workflow usually starts from project exploration stage → Project validation stage → Design freeze → Final Data → Production. In this workflow, the manikin (CAD model

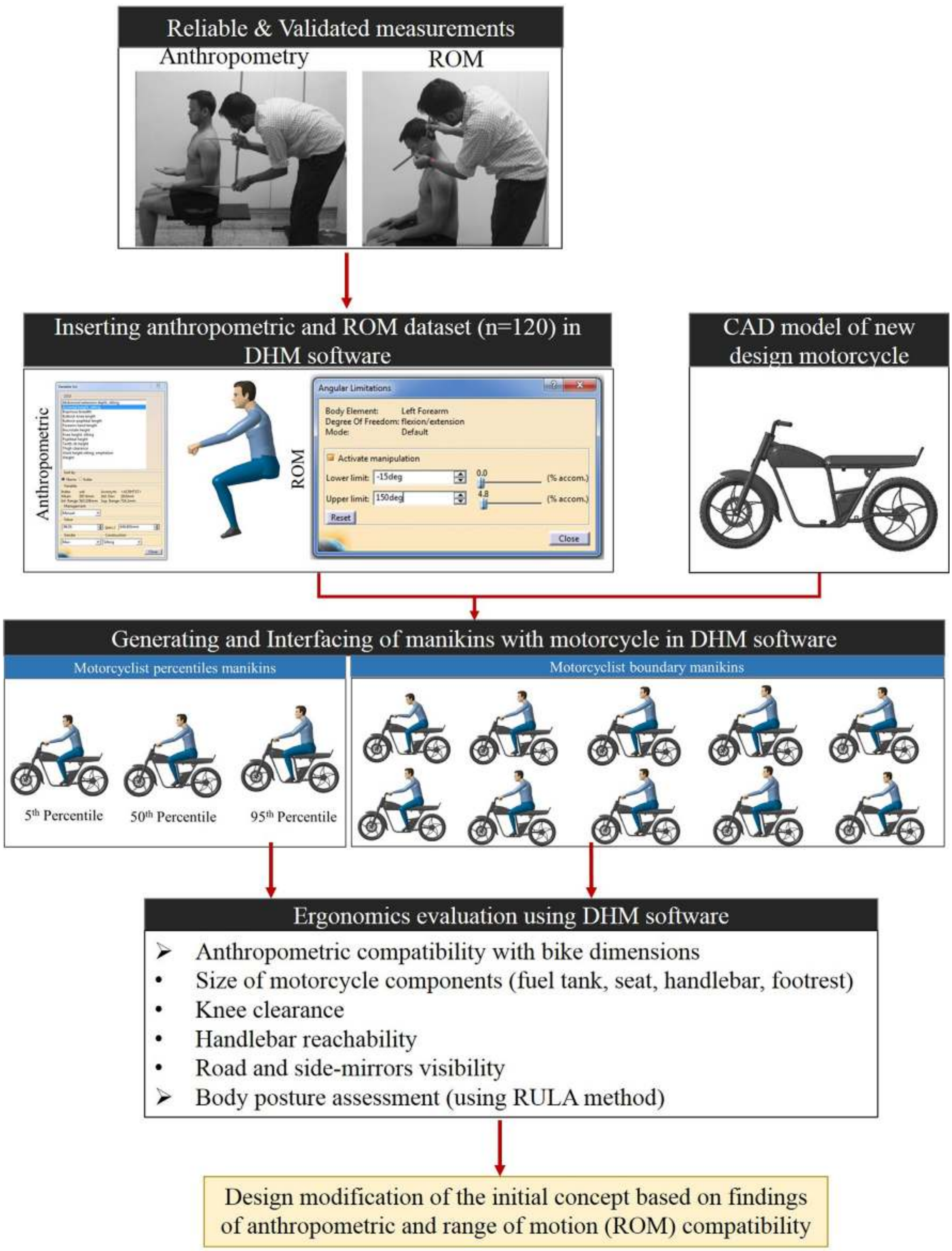

Fig. 7. Application of the present research in virtual ergonomics evaluation of newly design motorcycle.

represents human) is used in the project exploration and validation stage. More specifically, the percentile manikins (5th p, 50th p, and 95th p) are used in the project exploration stage and boundary manikin (a multiple percentiles approach) in the project validation stage [5,39].

As there is no other anthropometric and ROM database for the Indian motorcyclist population, the physical measurements acquired in current research could be used for the ergonomic design of motorcycles for Indian users unless a larger database is generated. The future directions of the present study include two directions (as shown in Fig. 6).

Firstly, boundary manikin (CAD model represents human) can be easily generated from the PC analysis of anthropometric dimensions and ROM measurements [37]. The methodology of creating boundary manikins can be referenced from many studies [11,34,48]. Further, it could be useful in the virtual environmental analysis, where, reach, vision, clearance, and inferences, and the comfort of the newly designed motorcycle could be performed in the stage of project validation.

Secondly, the insights from the comparative and PC analysis of the present study could be considered while creating a large-scale database for Indian motorcyclists. Further, the statistical descriptive from the larger measurements can be used in the virtual environment for ergonomics evaluation of newly designed motorcycle (as shown in Fig. 7). The present research could be considered as a baseline study to establish ergonomics progress in the motorcycle design process.

The present study limited the age group ranged between 19 and 44 years, but it was assumed to be the representative of the entire state/zone of the Indian male motorcyclists. However, authors recommend expanding the range of age width beyond 44 years to achieve higher accuracy in the representation of the Indian population. Due to resource and time constraints, the study sample size was relatively small while considering the larger population of Indian motorcycle riders. Unavailability of zonal or state wise motorcyclists' data on regional transport office (RTO) website leads the current researchers to assume an equal percentage of male motorcyclists in six zones, in turn, an equal proportion of the strata. Due to limited access to the data descriptive in earlier published research papers/databases, a comparative study of mean difference instead of statistical tests was conducted. Further studies with a larger sample size may lead to a much reliable anthropometric and ROM database of Indian motorcyclists. Larger database generation in the future may also consider the nutrition, ethnicity, etc. which may affect the body dimensions and ROM.

4. Conclusion

It can be established from the results of PCA that out of 29 anthropometric variables, only 14 variables (stature, crotch height, buttock extension, cervical height sitting, shoulder height sitting, 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) and out of 20 ROM variables only six variables (wrist flexion, wrist extension, knee extension, elbow flexion, shoulder abduction, and shoulder extension) were identified as the most influential to elucidate almost total variance. The 14 "*Body length indicator*" variables and six "*motion at sagittal plane*" variables explain the physical and joints flexibility characteristics of the male Indian motorcyclist.

This is the first attempt to evaluate the percentage difference between motorcyclists and other (inter)national driver/motorcyclists/general population databases. It can be concluded that most of the anthropometrics and ROM measurements resulted in the percentage difference ranging from −29% to 54%. Particularly, it should be noted that the dimensional variations for ROM measurements were higher than the anthropometrics.

It is evident from the current study that the existing anthropometry and ROM databases of Indian male motorcyclists are either inadequate in terms of relevant information or not representative of the whole Indian motorcycle rider population. Therefore, it is suggested to conduct extensive anthropometric and ROM surveys to establish the true representative database. While the sample size is relatively smaller, the data-set developed in current research could be used for the ergonomic design of motorcycles for Indian users unless a larger database is generated considering insights of the current study.

CRediT authorship contribution statement

Muthiah Arunachalam: Data curation, Formal analysis, Finding acquisition, Methodology, and Writing- original draft. **Ashish Kumar Singh:** Validation and Writing-reviewing & editing. **Sougata Karmakar:** Conceptualization, Project admiistration, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Anatomical landmarks of anthropometric measurements

[1] Stature (S) was measured as the vertical distance between the floor and the highest point of the head
[2] Crotch height (CH) was measured as the vertical distance between the floor and the distal part of the inferior ramus pubic bone.
[3] Thigh circumference (TC) was measured as the maximal circumference of the thigh
[4] Buttock extension (BE) was measured as the maximal extended point of the buttocks
[5] Knee height (KH) was measured as the vertical distance between the floor and the highest point of the superior border of the patella
[6] Cervical height sitting (CHS) was measured as the vertical distance between the horizontal sitting surface and cervical.
[7] Shoulder-elbow length (SEL) was measured as the vertical distance between the acromion and the bottom of the elbow fold at 90^0 angles with the horizontal forearm
[8] Shoulder height sitting (SHS) was measured as the vertical distance between the acromion process and the horizontal sitting surface
[9] Elbow height, Sitting (EHS) was measured as the vertical distance between the parallel sitting surface and the bottom of the elbow fold at 90^0 angles with the horizontal forearm

[10] Poplitieal height or Lower leg length (LLL) was measured as the vertical distance between the horizontal sitting surface and footrest surface
[11] Buttock-knee length (BKL) was measured as the horizontal distance between the knee-cap (foremost point) and the buttock (rearmost point)
[12] Acromion grip length (AL) was measured as the distance between the center of an object gripped in the hand and acromion process.
[13] Ball of foot length (BFL) was measured as the distance between the inner ballpoint and the posterior heel point
[14] Buttock-Popliteal length (PL) was measured as the horizontal distance between the knee hollow and the buttock (rearmost point)
[15] Hand length (HL) was measured as the vertical distance between the styloid processes and the middle fingertip
[16] Elbow-Hand Length (EHL) was measured as the horizontal distance between the elbow (rearmost point) and the middle fingertip
[17] Upper arm circumference (UC) was measured as the maximal circumference of the upper arm
[18] Calf circumference (CC) was measured as the maximal circumference of calf
[19] Hip breadth, sitting (HBS) was measured as the maximal portion of the hip
[20] Elbow to elbow breadth (EEB) was measured as the maximal horizontal distance between the bilateral surfaces of the elbow area
[21] Humerus breadth (HB) was measured as the horizontal distance of the medial and lateral epicondyles of the humerus
[22] Foot breadth (FB) was measured as the maximal distance between the inner ballpoint and outer ballpoint
[23] Femur breadth (FrB) was measured as the horizontal distance of the medial and lateral epicondyles of the femur
[24] Medial calf skinfold (MC) was measured (in mm) as the vertical skin fold on the largest circumference of the calf
[25] Supraspinal skinfold (SR) was measured (in mm) as the diagonal skin fold on the superior-iliac crest (topmost of hip bone)

Table C1
Correlation coefficients between anthropometric measurements.

	S	BMI	CH	BE	CHS	SHS	EHS	KH	LLL	SEL	EHL	BKL	PL	AL
W	0.323**	0.840**	0.064	0.182*	0.318**	0.311**	0.136	0.122	−0.065	0.229*	0.320**	0.405**	0.273**	0.151
S	–	-0.238**	0.639**	0.690**	0.715**	0.661**	0.048	0.593**	0.616**	0.806**	0.801**	0.787**	0.707**	0.628**
BMI		–	-0.295**	-0.212*	−0.08	−0.059	0.116	-0.220*	-0.416**	-0.232*	−0.129	−0.035	−0.125	-0.207*
CH			–	0.451**	0.498**	0.447**	0.033	0.385**	0.454**	0.543**	0.517**	0.577**	0.606**	0.276**
BE				–	0.437**	0.415**	−0.101	0.484**	0.516**	0.663**	0.656**	0.650**	0.576**	0.609**
CHS					–	0.845**	0.515**	0.399**	0.377**	0.561**	0.554**	0.559**	0.533**	0.355**
SHS						–	0.663**	0.443**	0.425**	0.596**	0.537**	0.488**	0.512**	0.407**
EHS							–	0.023	0.012	-0.183*	−0.037	−0.132	−0.069	−0.078
KH								–	0.856**	0.552**	0.485**	0.543**	0.515**	0.423**
LLL									–	0.530**	0.469**	0.492**	0.505**	0.457**
SEL										–	0.736**	0.769**	0.742**	0.598**
EHL											–	0.810**	0.753**	0.643**
BKL												–	0.919**	483**
PL													–	0.450**
AL														–

BFL	HL	FB	EEB	HBS	TC	T	SS	SR	MC	CC	UC	FrB	HB	
0.244**	0.255**	−0.121	0.807**	0.721**	0.617**	0.354**	0.549**	0.590**	0.431**	0.718**	0.759**	0.518**	0.340**	W
0.575**	0.661**	0.131	0.178	0.241**	0.006	0.236**	0.095	−0.011	0.092	0.053	0.035	0.359**	0.172	S
−0.081	−0.114	-0.205*	0.722**	0.606**	0.638**	0.219*	0.502**	0.606**	0.383**	0.702**	0.761**	0.328**	0.251**	BMI
0.403**	0.483**	0.132	0.056	−0.018	−0.087	0.113	0.11	−0.031	−0.019	−0.123	−0.111	0.193*	−0.024	CH
0.427**	0.495**	0.126	0.075	0.157	−0.048	0.155	−0.034	−0.003	0.147	−0.027	−0.123	0.16	0.113	BE
0.339**	0.395**	−0.008	0.221*	0.218*	−0.02	0.247**	0.087	0.021	0.119	0.034	0.078	0.247**	0.015	CHS
0.262**	0.405**	−0.018	0.251**	0.206*	−0.069	0.268**	0.053	0.011	0.17	0.068	0.04	0.230*	0.116	SHS
−0.155	−0.101	−0.172	0.167	0.13	−0.012	0.086	0.036	0.04	0.074	0.128	0.064	0.047	0.045	EHS
0.356**	0.340**	0.357**	−0.015	0.086	−0.145	0.222*	0.022	−0.032	0.019	−0.009	-0.210*	0.234**	−0.118	KH
0.366**	0.375**	0.322**	−0.085	−0.057	-0.253**	0.194*	−0.045	−0.157	−0.024	-0.191*	-0.303**	0.134	−0.092	LLL
0.500**	0.630**	0.149	0.121	0.106	−0.096	0.250**	0.017	−0.049	0.13	−0.077	−0.047	0.244**	0.085	SEL
0.532**	0.741**	0.122	0.187*	0.256**	−0.004	0.344**	0.147	0.128	0.250**	0.023	0.064	0.290**	0.124	EHL
0.531**	0.591**	0.251**	0.200*	0.380**	0.065	0.347**	0.17	0.139	0.255**	0.102	0.062	0.329**	−0.016	BKL
0.481**	0.525**	0.325**	0.102	0.203*	−0.088	0.310**	0.106	0.005	0.200*	−0.027	−0.07	0.258**	−0.13	PL
0.376**	0.544**	0.002	0.066	0.111	−0.07	0.171	−0.018	−0.053	0.11	−0.062	−0.048	0.204*	0.164	AL
–	0.500**	0.17	0.209*	0.158	0.098	0.166	0.071	0.033	0.01	0.016	0.007	0.261**	0.178	BFL
	–	−0.089	0.183*	0.092	0.065	0.309**	0.116	0.086	0.152	−0.029	0.05	0.327**	0.274**	HL
		–	−0.154	0.076	−0.145	−0.02	−0.095	-0.247**	−0.07	−0.122	-0.281**	0.057	-0.403**	FB
			–	0.536**	0.448**	0.435**	0.510**	0.533**	0.506**	0.529**	0.754**	0.293**	0.365**	EEB
				–	0.606**	0.242**	0.481**	0.512**	0.353**	0.557**	0.553**	0.538**	0.171	HBS
					–	−0.051	0.392**	0.439**	0.166	0.491**	0.554**	0.441**	0.241**	TC
						–	0.367**	0.460**	0.631**	0.108	0.411**	0.013	0.218*	T
							–	0.680**	0.439**	0.432**	0.508**	0.305**	0.128	SS
								–	0.567**	0.531**	0.519**	0.254**	0.205*	SR
									–	0.291**	0.458**	0.116	0.214*	MC
										–	0.555**	0.454**	0.211*	CC
											–	0.214*	0.425**	UC
												–	−0.049	FrB
													–	HB

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).

[26] Subscapula skinfold (SS) was measured (in mm) as the diagonal skin fold on the scapula (lower end of the shoulder blade)
[27] Triceps skinfold (T) was measured (in mm) as the vertical skinfold middle from the acromion to olecranon processes
[28] Weight (W) was measured (in kg) as the mass was disrupted evenly on both feet at the head up and eye looking straight
[29] Body mass index (BMI), a measure of fat content in the body was calculated by the metric formula Weight (in Kg)/height (in m^2)

Appendix B. Anatomical landmarks of ROM measurements

[a] Neck Flexion (NF) and [b] Neck Extension (NE) were measured as the axis of the goniometer is center of the external auditory meatus, the stationary-arm parallel to the vertical line and the movable-arm aligned with nostrils
[c] Lumbar Extension (LE) and [d] Lumbar Flexion (LF) were measured as the axis of the goniometer is center of the iliac crest, the stationary-arm parallel to the vertical line along with thigh and the movable-arm aligned with Anterior axillary line
[e] Wrist Extension (WE) and [f] Wrist Flexion (WF) was measured 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
[g] Elbow Extension (EE) and [h] Elbow Flexion (EF) were measured 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)
[i] Knee Flexion (KF) and [j] Knee Extension (KE) were measured 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
[k] Shoulder Extension (SE) and [l] Shoulder Flexion (SF) were measured 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
[m] Ankle plantarflexion (AF) and [p] Ankle dorsiflexion (AD) were measured 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
[n] Shoulder Abduction (SA) and [o] Shoulder Adduction (SAd) were measured 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
[q] Hip Abduction (HA) and [r] Hip Adduction (HAd) were measured 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)
[s] Hip Flexion (HF) and [t] Hip Extension (HE) were measured 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 C

See Tables C1 and C2.

Appendix D. Sample photograph while measuring one of the (a) anthropometric dimensions and (b) ROM measurement in a participant

Table C2
Correlation coefficients between ROM measurements.

	NF	NE	LF	LE	WF	WE	KF	KE	HF	HE	HAb	HA	EE	EF	SF	SA	SAb	SE	AP	AD
NF	–																			
NE	0.452**	–																		
LF	0.222*	−0.095	–																	
LE	0.035	-0.246**	0.336**	–																
WF	−0.092	−0.051	0.074	−0.103	–															
WE	−0.121	−0.018	-0.180*	−0.064	0.262**	–														
KF	-0.191*	−0.135	−0.034	-0.211*	0.121	−0.006	–													
KE	0.16	0.002	0.062	0.193*	-0.211*	-0.245**	−0.048	–												
HF	-0.329**	−0.143	−0.031	−0.098	0.068	0.270**	0.245**	-0.413**	–											
HE	−0.029	0.079	0.011	0.102	−0.174	0.032	0.200*	−0.021	0.142	–										
HAb	0.003	−0.043	−0.091	0.01	0.045	−0.015	0.236**	0.049	0.064	0.230*	–									
HA	-0.239**	-0.338**	−0.103	0.002	−0.109	−0.042	0.036	0.09	−0.12	−0.142	−0.093	–								
EE	−0.096	-0.180*	0.076	−0.052	−0.006	−0.138	0.128	0.114	−0.152	−0.11	−0.045	0.219*	–							
EF	0.012	0.021	−0.067	−0.09	0.012	0.263**	−0.03	−0.052	−0.058	−0.013	−0.038	−0.129	−0.13	–						
SF	−0.027	−0.075	0.124	0.158	0.105	0.045	−0.15	−0.162	0.024	-0.218*	−0.028	−0.048	0.099	−0.135	–					
SA	0.017	0	0.058	0.220*	-0.234*	-0.319**	0.180*	0.320**	-0.210*	0.236**	0.175	0.108	0.086	-0.239**	-0.338**	–				
SAb	-0.272**	-0.231*	−0.018	0.002	0.058	−0.018	0.049	−0.081	0.006	0.017	−0.056	0.187*	0.079	-0.202*	0.203*	−0.03	–			
SE	-0.198*	0.03	−0.121	-0.247**	0.386**	0.354**	0.131	-0.371**	0.243**	0.033	0.056	−0.105	−0.108	0.240**	−0.016	-0.264**	-0.216*	–		
AP	−0.007	−0.161	0.022	0.11	0.024	-0.246**	0.136	−0.023	-0.230*	0.112	0.195*	0.038	0.057	−0.1	0.012	0.174	0.205*	−0.085	–	
AD	−0.024	−0.145	−0.072	−0.107	−0.002	0.011	0.091	0.105	0.036	0.195*	0.197*	0.106	−0.1	0.115	-0.406**	0.232*	0.037	0.044	0.206*	–

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).

(a) Shoulder-elbow length

(b) Neck Flexion

References

[1] N. Adnan, S.Z.M. Dawal, Applied anthropometric for wheelchair user in Malaysia, Measurement 136 (2019) 786–794, https://doi.org/10.1016/j.measurement.2018.11.002.
[2] A.S. Amrutkar, N.R. Rajhans, Ergonomic posture for motorcycle riding, in: Proceedings of international conference 'Humanizing Work and Work Environment (HWWE)-2011', IIT-Madras, Chennai, India, 2011, pp. 6–12.
[3] N. Adnan, S.Z.M. Dawal, Applied anthropometric for wheelchair user in Malaysia, Measurement 136 (2019) 786–794, https://doi.org/10.1016/j.measurement.2018.11.002.
[4] B.V. Shamasundara, M.S. Ogale, Ergonomic study on indian driving population, in: SAE Technical Paper, Technical Paper. Presented at the Symposium on International Automotive Technology (SIAT99), Society of Automotive Engineers, Pune, India, 1999, p. 13, https://doi.org/10.4271/990021.
[5] F. Caputo, A. Greco, M. Fera, R. Macchiaroli, Digital twins to enhance the integration of ergonomics in the workplace design, Int. J. Ind. Ergon. 71 (2019) 20–31, https://doi.org/10.1016/j.ergon.2019.02.001.
[6] B.A. Cerny, H.F. Kaiser, A study of a measure of sampling adequacy for factor-analytic correlation matrices, Multivar. Behav. Res. 12 (1977) 43–47.
[7] D. Chakrabarti, N.I. of D. NID, Indian anthropometric dimensions for ergonomic design practice, National Institute of Design, 1997.
[8] C. Chertman, H.M.C. dos Santos, L. Pires, M. Wajchenberg, D.E. Martins, E.B. Puertas, A comparative study of lumbar range of movement in healthy athletes and non-athletes, Rev. Bras. Ortop. 45 (2010) 389–394.
[9] F. Crenna, G.B. Rossi, L. Bovio, Perceived similarity in face measurement, Measurement 50 (2014) 397–406.
[10] F. Cucinotta, E. Guglielmino, F. Sfravara, A CAE method for ergonomic assessment of motorcycles' driver and passenger, Int. J. Interact. Des. Manuf. IJIDeM 2 (2019) 699–712, https://doi.org/10.1007/s12008-019-00555-w.
[11] A. Dasgupta, B. Vijayaraghavan, N. Rajhans, D. Kulkarni, A. Mannikar, Digital Human Modeling for Indian Anthropometry, in: Asian Workshop on 3D Body Scanning Technologies, in: Presented at the Asian Workshop on 3D Body Scanning Technologies, Tokyo, Japan, 2012, pp. 165–172.
[12] S.Z.M. Dawal, Z. Ismail, K. Yusuf, S.H. Abdul-Rashid, N.S.M. Shalahim, N.S. Abdullah, N.S.M. Kamil, Determination of the significant anthropometry dimensions for user-friendly designs of domestic furniture and appliances – experience from a study in Malaysia, Measurement 59 (2015) 205–215, https://doi.org/10.1016/j.measurement.2014.09.030.
[13] Government of India, Ministry of Road Transport & Highways, Government of India, 2018 [WWW Document]. URL http://morth.nic.in/ (accessed 7.18.19).
[14] J. Guan, H. Hsiao, B. Bradtmiller, T.-Y. Kau, M.R. Reed, S.K. Jahns, J. Loczi, H.L. Hardee, D.P.T. Piamonte, US truck driver anthropometric study and multivariate anthropometric models for cab designs, Hum. Factors 54 (2012) 849–871.
[15] M.L. Harris, A factor analytic study of flexibility, Res. Q. Am. Assoc. Health Phys. Educ. Recreat. 40 (1969) 62–70.
[16] C.M. Haslegrave, Anthropometric profile of the British car driver, Ergonomics 23 (1980) 437–467.
[17] Imaekhai Lawrence, Ergonomic design of Motor Bikes in Nigeria, Stand. Sci. Res. Essays 1 (2013) 313–339.
[18] S.N. Imrhan, M.D. Sarder, N. Mandahawi, Hand anthropometry in Bangladeshis living in America and comparisons with other populations, Ergonomics 52 (2009) 987–998.
[19] ISO, ISO (International Organization for Standardization) 15535:2012, General requirements for establishing anthropometric databases, 2012 [WWW Document].
[20] ISO, ISO (International Organization for Standardization) 7250-1:2008(E), Basic human body measurements for technological design — Part 1: Body measurement definitions and landmarks, 2008 [WWW Document].
[21] H. Jamaiyah, Reliability, Technical Error of Measurements and Validity of Length and Weight Measurements for Children Under Two Years Old in Malaysia, vol. 65, 2010, pp. 7.
[22] Snehal Kolekar, N.R. Rajhans, Design inputs for motorbike riding posture: An anthropometric approch, in: Innovative Engineering Technologies, in: Presented at the 709th International Conference on Innovative Engineering Technologies (ICIET), V.V.P COLLEGE OF ENGINEERING, India, 2011, pp. 6–12.
[23] D. Kulkarni, R. S, V. Chitodkar, V. Gurjar, C.V. Ghaisas, A.V. Mannikar, SIZE INDIA- Anthropometric Size Measurement of Indian Driving Population, 2011. https://doi.org/10.4271/2011-26-0108.
[24] C.-C. Kuo, M.-J. Wang, J.-M. Lu, Developing sizing systems using 3D scanning head anthropometric data, Measurement (2019) 107264, https://doi.org/10.1016/j.measurement.2019.107264.
[25] L.L. Laubach, J.T. McConville, Relationships between flexibility, anthropometry, and the somatotype of college men, Res. Q. Am. Assoc. Health Phys. Educ. Recreat. 37 (1966) 241–251.
[26] B. Lecoublet, D. Boisclair, M. Evin, E. Wagnac, Y. Petit, C.-E. Aubin, P.-J. Arnoux, Assessing the global range of motion of the helmeted head through rotational and translational measurements, Int. J. Crashworth., n.d. https://doi.org/10.1080/13588265.2019.1593288.
[27] Y.-C. Lee, C.-H. Chen, C.-H. Lee, Body anthropometric measurements of Singaporean adult and elderly population, Measurement 148 (2019) 106949, https://doi.org/10.1016/j.measurement.2019.106949.
[28] J. Majumder, Anthropometric dimensions among Indian males—A principal component analysis, Eurasian J. Anthropol. 5 (2014) 54–62.
[29] M.J. Marfell-Jones, A.D. Stewart, J.H. De Ridder, International standards for anthropometric assessment, 2012.
[30] Michael Gastner, Tim Levell, Mike Ellis, Mopeds and Motorcycles, 2018 [WWW Document]. Worldmapper. URL http://archive.worldmapper.org/display.php?selected=32.
[31] C.C. Norkin, D.J. White, Measurement of Joint Motion: A Guide to Goniometry, FA Davis, 2016.
[32] O. Oviedo-Trespalacios, L. Martínez Buelvas, J. Hernández, J. Escobar, Hand anthropometric study in northern Colombia, Int. J. Occup. Saf. Ergon. 23 (2017) 472–480.
[33] N.F. Paiman, A. Shabadin, A.H. Ariffin, S.M. Syazwan, H. Azhar, Child motorcycle pillion rider anthropometric measurement, Appl. Mech. Mater. 663 (2014) 557–561, https://doi.org/10.4028/www.scientific.net/AMM.663.557.
[34] M.B. Parkinson, M.P. Reed, Creating virtual user populations by analysis of anthropometric data, Int. J. Ind. Ergon. 40 (2010) 106–111.
[35] K. Pearson, LIII. On lines and planes of closest fit to systems of points in space, Lond. Edinb. Dublin Philos. Mag. J. Sci. 2 (1901) 559–572.
[36] S. Pheasant, Bodyspace: Anthropometry, Ergonomics and the Design of Work, CRC Press, 2016.
[37] V.R. Preedy, Handbook of Anthropometry: Physical Measures of Human Form in Health and Disease, Springer Science & Business Media, 2012.
[38] S.A. Robertson, A. Minter, A study of some anthropometric characteristics of motorcycle riders, Appl. Ergon. 27 (1996) 223–229, https://doi.org/10.1016/0003-6870(96)00007-5.
[39] S. Scataglini, G. Paul, DHM and Posturography, Academic Press, 2019.
[40] S.M. Shariff, A.F. Merican, A.A. Shariff, Development of new shoe-sizing system for Malaysian women using 3D foot scanning technology, Measurement 140 (2019) 182–184.

[41] SIAM members, Society of Indian Automobile Manufacturers, 2018 [WWW Document]. SIAM. URL http://www.siamindia.com/ (accessed 7.18.19).
[42] J.M. Soucie, C. Wang, A. Forsyth, S. Funk, M. Denny, K.E. Roach, D. Boone, H.T.C. Network, Range of motion measurements: reference values and a database for comparison studies, Haemophilia 17 (2011) 500–507.
[43] S. Stomfai, W. Ahrens, K. Bammann, E. Kovacs, S. Mårild, N. Michels, L.A. Moreno, H. Pohlabeln, A. Siani, M. Tornaritis, Intra-and inter-observer reliability in anthropometric measurements in children, Int. J. Obes. 35 (2011) S45.
[44] I.Z. Sutalaksana, A. Widyanti, Anthropometry approach in workplace redesign in Indonesian Sundanese roof tile industries, Int. J. Ind. Ergon. 53 (2016) 299–305, https://doi.org/10.1016/j.ergon.2016.03.002.
[45] M. Tavana, M.R. Kazemi, A. Vafadarnikjoo, M. Mobin, An artificial immune algorithm for ergonomic product classification using anthropometric measurements, Measurement 94 (2016) 621–629, https://doi.org/10.1016/j.measurement.2016.09.007.
[46] B.J.A.R. Tony, M.S. Alphin, G.S. Krishnan, Analysis of upper body ergonomic parameters on commuter motorbike users, J. Transp. Health 16 (2020) 100828, https://doi.org/10.1016/j.jth.2020.100828.
[47] World Medical Association, World Medical Association Declaration of Helsinki, Ethical principles for medical research involving human subjects, 2001.
[48] K.S. Young, S. Margerum, A. Barr, M.A. Ferrer, S. Rajulu, Generation of Boundary Manikin Anthropometry, SAE Technical Paper, 2008.