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Perceived comfortable posture and optimum riding position of Indian male motorcyclists for short-duration riding of standard motorcycles

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A R T I C L E I N F O

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A B S T R A C T

Dimensional incompatibility between rider and motorcycle is one of the most causative factors responsible for the prevalence of musculoskeletal discomfort among motorcyclists. The present study aims to identify the comfortable riding posture (CRP) and optimum riding position (ORP) for improving motorcycle design for better riding experience. The data (through image processing technique) was acquired from 120 Indian male motorcyclists (aged 19–40 years) using a static simulator test-rig. The CRP was achieved by adjusting three controls (handgrip, seat, and footrest of the test-rig), and perceived comfort and discomfort ratings. Weighed mean comfort joint angles of ten body-joints defining CRP were estimated and compared with the earlier studies. The best possible ORP among the nine test conditions (defined by the positions of the three controls) was estimated using Taguchi DOE. The study outcomes will help automobile designers to conceptualize the comfortable standard motorcycles.

1. Introduction

The automotive industry plays an essential role in economic growth and contributes substantially to the gross domestic product (GDP) for many developing economies like India. This sector contributed to 2.5% (US$ 67 billion) to the country's GDP (US$ 2652 billion) in 2016–17 (Miglani, 2019). Especially, two-wheelers (scooter/motorcycles) market influences the most to the growth in this sector (OICA, 2019). Admittedly, India's GDP growth was reduced in the first quarter of 2019 due to the slowdown in market demand and sales of two-wheelers (scooter/motorcycles) (SIAM members, 2018). In India, standard motorcycles are the most frequently used two-wheeler among the 4 different types of motorcycles. They could be classified based on the "rider triangle" method (Arunchalam and Karmakar, 2021).

Generally, the market success of any product can be derived from customer/user satisfaction. A good design of a motorcycle is supposed to fulfill the expectations of the customers/users from design perspectives (Pandya and Jani, 2011). While buying a motorcycle, besides its cost/-price, the riding comfort is considered to be one of the most crucial factors (Sai Praveen and Ray, 2015). Many researchers across the globe witnessed this factor (riding comfort) as a critical problem among motorcycle users (motorcyclists).

Researchers of various countries conducted different studies to understand the postural discomfort level among the motorcyclists. Robertson (1987) observed the discomfort experienced by 120 U.K motorcyclists (110 male and 10 female) using a self-reported questionnaire. He found that 78% of the motorcyclists felt discomfort associated with riding a motorcycle. Karmegam et al. (2013, 2009) conducted questionnaire-based longitudinal studies to assess the discomfort level among 957 adult Malaysian motorcyclists. The majority of respondents perceived discomfort; specifically, the male motorcyclists felt more discomfort compared to the females while riding motorcycles. Similarly, Khamis et al. (2014) observed high discomfort among Malaysian teenage motorcyclists (19 years old). A study by Berrones-Sanz (2018) described the health conditions of Mexican motorcycle taxi riders. Larger parts of them were suffering from musculoskeletal disorders (MSDs) in the neck, lower back, elbow, and shoulder regions.

Despite the large population of two-wheeler riders (SIAM members, 2018), fewer researches have been reported in the Indian context, in the perspective of both comfort and postural assessment. Sai Praveen and Ray (2015) conducted a study on 221 Indian male motorcyclists with an average monthly riding of 610 km. They observed 95% of the users perceived at least some degree of discomfort in the recent past, while 87% of them perceived predominant discomfort in the lower back

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region. Dutta et al. (2014) found that the riders exposed to prolonged static posture with significant angular deviations of certain body joints were prone to MSD symptoms. Although the transmitted body vibrations remained within the recommended limit of Occupational Safety and Health Administration (OSHA), the perceived vibrational discomfort and body-pain of a rider were observed to have strong correlations (Anoop G.A and Binoosh S A, 2019; Dutta et al., 2014; Mohan A and Raghuathan R, 2017) observed that most of the Keralite's (an ethnic group in India) suffered MSD problems due to prolonged motorcycle usage.

A British study on the postural assessment of the riding posture in different motorcycles (sports/standard) revealed that higher riding time (with static posture adopted) was associated with greater postural risks (Stedmon, 2007). In a similar study on Malaysian users, Ma'arof et al. (2014) assessed riding postures for different motorcycle types (sport/standard/cruiser) using postural assessment tools (RULA, REBA, and WERA). They observed that the riding postures of different motorcycle models were found to be highly uncomfortable. Patel (2017) used QEC (postural assessment tool) on daily motorcycle commuters to understand the postural stress faced by the Indian riders. The study suggested immediate design modification in Indian motorcycles since the QEC scores among 67.60% of subjects were very high in most of the body regions. During the literature review (from 1974 to 2016), Alias et al. (2016) witnessed that the riding posture was one of the major risk factors in commuter motorcycles used for everyday riding. Ospina-Mateus and Quintana Jiménez (2019) showed that 83% of reviewed literature (from 1970 to 2019) indicated the occurrence of postural discomfort among motorcyclists.

Few researchers have assessed muscle fatigue during motorcycle riding by conducting different experiments. Velagapudi et al. (2010) found that the muscular fatigue caused due to control of the motorcycle in high traffic and the bumpy road was similar for forward-leaning and erect/straight postures. Said et al. (2015) experimentally found that the muscle fatigue level in Malaysian motorcyclists was similar to the muscle fatigue in car drivers. Most of the studies used electromyography (EMG) to experimentally quantify the muscle activity as the motorcyclist undergo muscle fatigue during riding (Balasubramanian and Jagannath, 2014; Rashid et al, 2015, 2018). Similarly, Muhammad et al.(2015) used heart rate monitor to determine the riding posture distress in terms of cardiac muscular activity, which can also be influenced by psycho-social factors.

Since the above-mentioned instruments cannot directly measure the postural (based on joint angles) discomfort/comfort, some studies (De Looze et al., 2003; Mansfield et al., 2020; Vink and Hallbeck, 2012) suggested using subjective methods (perceived (Dis)comfort rating scale) for measuring the postural discomfort/comfort. Some researchers used postural evaluation tools (RULA, REBA, OWAS, etc.) and close-ended questionnaire for subjective evaluation of motorcycle riding posture. They included RGB pain scale, Borg's scale (Karuppiah et al., 2012; Mathurkar, 2016), Likert rating scale (Velagapudi and Ray, 2015; Karmegama et al., 2009; Karmegam et al., 2013; Karuppiah et al., 2012) in their questionnaire. Discomfort and comfort are two opposite "subjective perception" opinions based on personal experience. It can be measured using a Likert rating (of 10-point scale) for an effective judgment of an individual's personal belief (Fatollahzadeh, 2006). Since the subjective measurements of postural comfort/discomfort may possess issues related to reliability, many studies (De Looze et al., 2003; Helander and Zhang, 1997; Kee and Lee, 2012; Mansfield et al., 2020; Vink and Hallbeck, 2012) used both discomfort and comfort scales to check the reliability of subjective measure.

A few articles attempted designing interventions to resolve the problems associated with riding discomfort. Karmegam et al. (2008) and Karuppiah et al. (2012) developed lumbar support seat interventions to reduce the discomfort while riding a motorcycle for a longer duration. These interventions were focused on improving the comfort level of specific body regions like lower back and buttock. Similarly, Mathurkar (2016) also introduced a lumbar support seat design and compared it with the existing seats using CAD/CAE models. Moreover, these interventions claimed to improve the overall static seating comfort, mainly in the lower back region for the long duration of riding. Nevertheless, these studies did not focus on improving the overall or whole-body comfort of the motorcyclists. Hence, it is evident from the literature that the research lacks improvising the whole-body comfort of riding posture for motorcyclists.

Motorcycling duration is one of the critical factors which could influence the comfort/discomfort posture of the motorcyclist (Praveen and Ray, 2018). Diyana et al. (2020) found that daily riding duration influences the riding comfort among male traffic policeman in Malaysia. Apart from traveling long distances, motorcycles are frequently used in India for shorter duration (less than 10 min continuously) for diverse personal and occupational scenarios, which include delivery services (parcel, grocery, milk, fast food etc.), traffic-policing, personal commuting for nearby shopping, banking, and educational/social/financial institutions and so on. Praveen and Ray (2018) investigated the influence of driving duration on static factors of seating comfort in motorcycles. They found that riding comfort reduces 10 min onwards, and the comfort rating becomes saturated after 30 min. It is evident from their research that longer duration (10 min or more) affect the subjective comfort rating due to various static riding factors (posture and related loads, interface pressure, load distribution, etc.). The current researchers anticipated that the comfort evaluation for a "shorter duration" about 5 min might be helpful for studying optimal riding position according to subjective comfort/discomfort rating of body joint angles while many other static riding factors (e.g. tissue compression, muscular fatigue, interface pressure, load distribution, etc.) are not prominent. Thus, in the present study, the comfort evaluation was decided for a shorter duration (5 min), in line with earlier similar studies by Grainger et al. (2017) and Barone and Curcio (2004). They estimated subjective discomfort while riding a scooter/bicycle under laboratory conditions.

The existing and widely used Japanese Automobile Standards (JASO T003:2009, 2009; JASO T006:2007, 2007; JASO T102-84, 1975) recommends the dimensional adjustability range for the three components (handlebar, seat, and footrest) in the motorcycle frame. For example, the recommended handlebar width (end-to-end distance between handlebars) should be between 35 cm and 80 cm (JASO T003:2009, 2009). These adjustable dimensions could determine the riding position for a motorcycle rider. The experts established the standards by conducting a photography survey of 12 young (17-year-old) Japanese male (stature: 171 $\pm$ 2 cm) in 7 (different engine capacity) motorcycles. It is important to know the effect of the dimensional change (within the specific dimensional adjustability range offered by these standards) on postural joint angles and, thereby, comfort level. Unfortunately, the present standards do not cast any light on these issues. For example, it would be challenging for a designer to choose one optimum handlebar width value that shall be within the wide range from 35 cm to 80 cm (as per JASO T003:2009), achieving maximum riding comfort. Although there are dimensional variations across the standard motorcycles (Arunachalam et al., 2020), it is not feasible to design a motorcycle with adjustable features. It is assumed by the present researchers that the motorcycle design eventually will have a fixed vertical distance among footrest, seat and handlebar. It is found from the several existing literature that the major challenges lie in designing a motorcycle without an adjustable system to cover all kind of rider's physical characteristics and preferences. As the contribution of current research, these challenges would be possible to overcome by proposing a motorcycle design with fixed vertical/horizontal distance between the handlebar, seat, and footrest, which would likely to cover most of the rider's physical characteristics and preferences.

Hence, the present research has been planned to clarify the aforementioned issues related to the comfortable riding posture (postural joint angles) and optimal riding position. The findings of the current

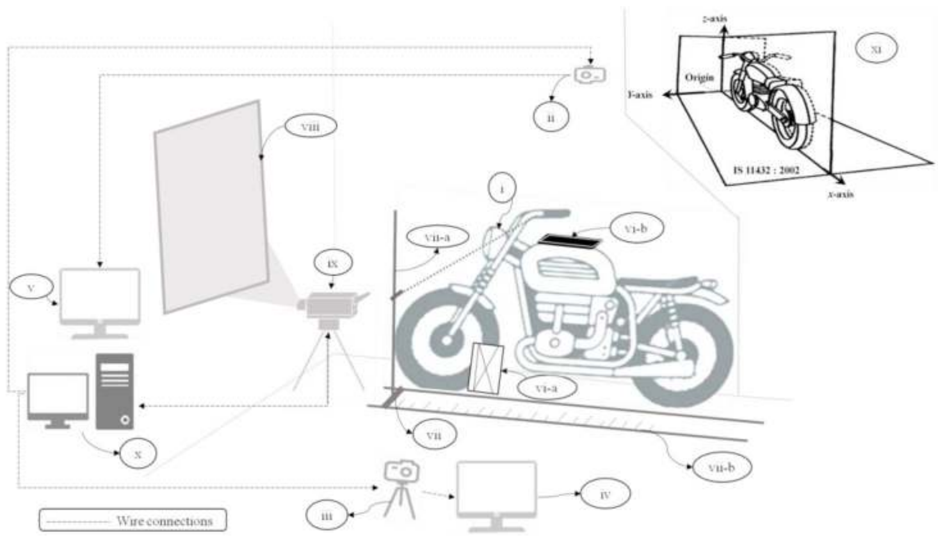

Fig. 1. Experimental mock-up -static simulator. Note: (i) Test-rig motorcycle; (ii) Camera – Top-view; (iii) Camera-side view; (iv) Extended camera monitors for side view; (v) Extended camera monitors for topview; (vi-a) Calibration system of side view; (vi-b) Calibration system of topview; (vii)Laser pointer – measuring setup, (vii-a) Z-axis ruler for seat/handle grip measurement, (vii-b) X-axis ruler for seat/handle grip measurement; (viii) White screen; (ix) Projector; (x) Master controller computer; (xi) coordinate system for defining the dimensional measurements.

research don't aim to question JASO standards (JASO T003:2009; JASO T005:2009; JASO T006:2007), nor the method suggested by JASO standards (JASO T003:2009). This research aims to define/identify the comfortable riding posture and optimal riding position for comfortable riding experience. The study aims to answer two research questions (RQ):

RQ1 What is the comfortable riding posture for male Indian motorcyclists for short-duration riding of standard motorcycles?

RQ2 What is the optimum riding position for Indian male motorcyclists for short-duration riding of standard motorcycles?

2. Methods and materials

2.1. Experimental setup

The study objectives were achieved through experimentations on a static simulator (in-house experimental set-up, see Fig. 1), which was developed to provide a naturalistic riding posture (in static condition) to the subjects. Velagapudi and Ray (2019), through their experimentation, verified that the overall seating comfort during static (in laboratory settings) and dynamic conditions (riding on a flat road) had no significant difference. Moreover, many of the postural studies of four-wheeler drivers were carried out in static conditions for unbiased subjective assessment and to avoid biases from other unnecessary environmental factors (Park et al., 2016; Peng et al., 2017).

The experimental data of riding position and posture of the subjects were collected from a motorcycle test-rig (see Fig. 1-i). This test-rig was

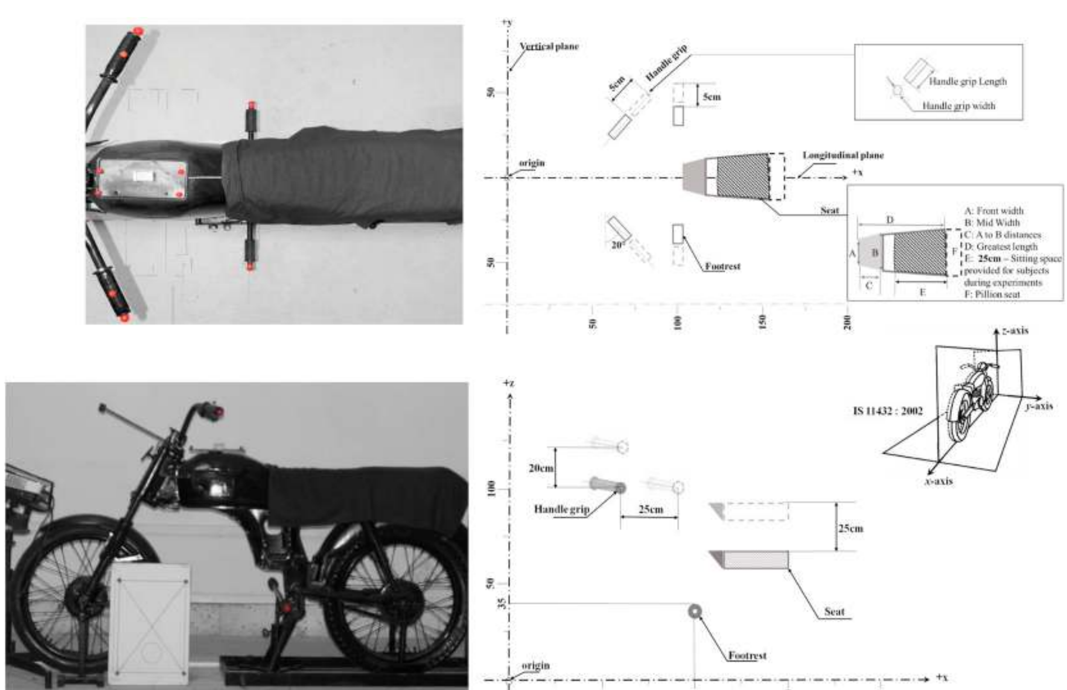

Fig. 2. Adjustable ranges of handle grip, footrest and seat. (a) Topview adjustability features and (b) Side view adjustability features.

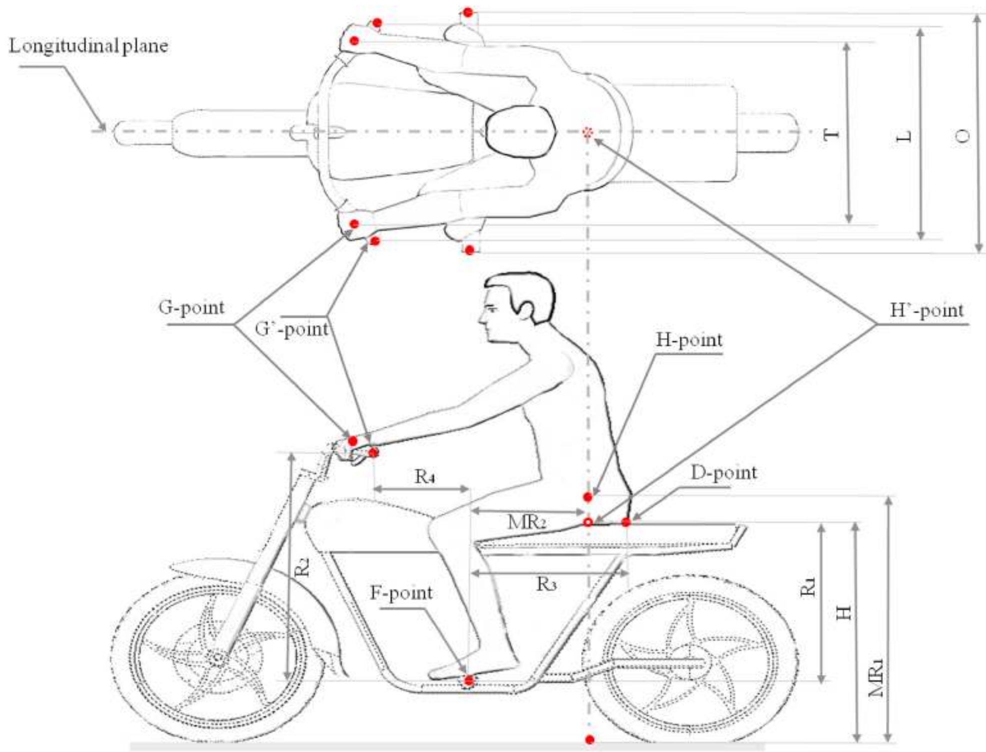

Fig. 3. Landmarks for measuring riding position.

constructed using parts (like mainframe, fork, wheels, stands) from a motorcycle (Make: Bajaj, Model: CT 100, year: 1999), which was further modified by providing a level of adjustability to the handle grip, seat, and footrest. The reference point (origin) for defining all the dimensional measurements during the experiment was fixed (as per Hale et al. (2007), Sabbah and Bubb (2008) on the ground/floor in front of the rig. The central and the farthest end of the useable portion (F-point) of the footrest (of test-rig) was set at the distance of 100 cm backward (along x-axis) and 35 cm upwards (along z-axis) and 0 cm sidewise (along y-axis) from the origin point (as shown in Fig. 1-xi).

The riding position and posture angles were acquired through a set of two digital cameras (Make: Sony, Model: A58 DSLR, Camera Megapixel (MP): 20 MP, Maximum resolution: 5456 X 3632 pixels) with extended camera monitors (HP 21.5-inch full HD) and calibration systems. One camera was used to capture the top view (xy plane) of the subject. It was kept at the coordinates of (120 cm, 0 cm, 366 cm) from the origin to decrease the parallel axis error (Hung et al., 2004) (as shown in Fig. 1-ii). Similarly, another camera was used to capture the side view (xz plane) of the subject. It was kept at the coordinates of (80 cm, 457 cm, 60 cm) from the origin (see Fig. 1-iii) to reduce the parallel axis error (Gavan et al., 1952). The extended camera monitor for both side and top view (see Fig. 1-iv and 1-v) provided enlarged projections of the captured images and helped to ensure the precise focus on the subject. The calibration system of side view kept along the xz plane of the motorcycle test-rig (as shown in Fig. 1-vi-a). Similarly, the calibration system of top view kept on the fuel tank along the xy plane of the motorcycle test-rig (as shown in Fig. 1-vi-b). The role of calibration system was to extrapolate the real measurement from the images with known size.

A laser pointer based measuring setup was constructed (following Chou and Hsiao, 2005) to measure the riding position of the motorcyclist. This setup had a horizontal ruler for measuring the distance of seat and handgrip from the origin point (as shown in Fig. 1-vii). The setup had vertical rulers with laser pointers for measuring the height of handle grip (as shown in Fig. 1-vii-a) and seat from the floor (as shown in Fig. 1-vii-b). The setup was installed parallel to the xz plane of the motorcycle test-rig at 91 cm (3 ft) distant from the frame (as shown in Fig. 1-vii). This setup facilitated an understanding of the alternative form of reliability between the ruler and the image-based measurement of the subject's riding position during the experiment.

Unlike most of the previous research (Chou and Hsiao, 2005; Lawrence, 2013), a driving simulation was created to provide a realistic riding experience to the subjects. Few short-duration road riding simulation videos were played through the projector on the screen with the same procedure mentioned by Barone and Curcio (2004); Barone and Lo Iacono (2015); Hsiao et al. (2015); Porter and Gyi (1998). The projector and screen were kept at a distance of 6 ft and 4 ft from the motorcycle test-rig and the floor (as shown in Fig. 1-viii and 1-ix). A master computer (HP ProDesk Intel i5-processor, windows 8.1) (as shown in Fig. 1-x) was used to control the projector as well as both the digital cameras through wires (HDMI and USB).

2.1.1. *Dimensional adjustability in the test rig*

The detailed dimensions (e.g., length, width, height, etc.) and range of adjustment of handle grip, footrest, and seat used in the standard motorcycle test-tig (shown in Fig. 2a and b) were determined based on a field survey Arunachalam et al. (2020a) and JASO T003:2009 (2009) standards.

Despite the fact that handlebar inclination affects the two-wheeler riding posture, it was decided to be 20° based on the finding of the previous studies.Arunachalam et al. (2020) observed that most of the standard motorcycle handlebar inclination were found at 20° which explains the recommended practice of the motorcycle industry. Doria et al. (2020) stated that handlebar inclination is a critical factor which could directly affect the safety, stability and control of the two-wheelers. The handlebar inclination was kept as 20° to maintain the industry recommended practice (JASO T102-84, 1975) and avoiding trade-offs in the safety for comfortable posture. As per JASO T102-84 (1975), 20° handlebar inclination was recommended along with handle grip length of 11 cm, and handle grip width of 35 cm (see Fig. 2-a, right side corner). A commercially available smaller fuel tank (SAE J 1241, 2012; SAE J30,

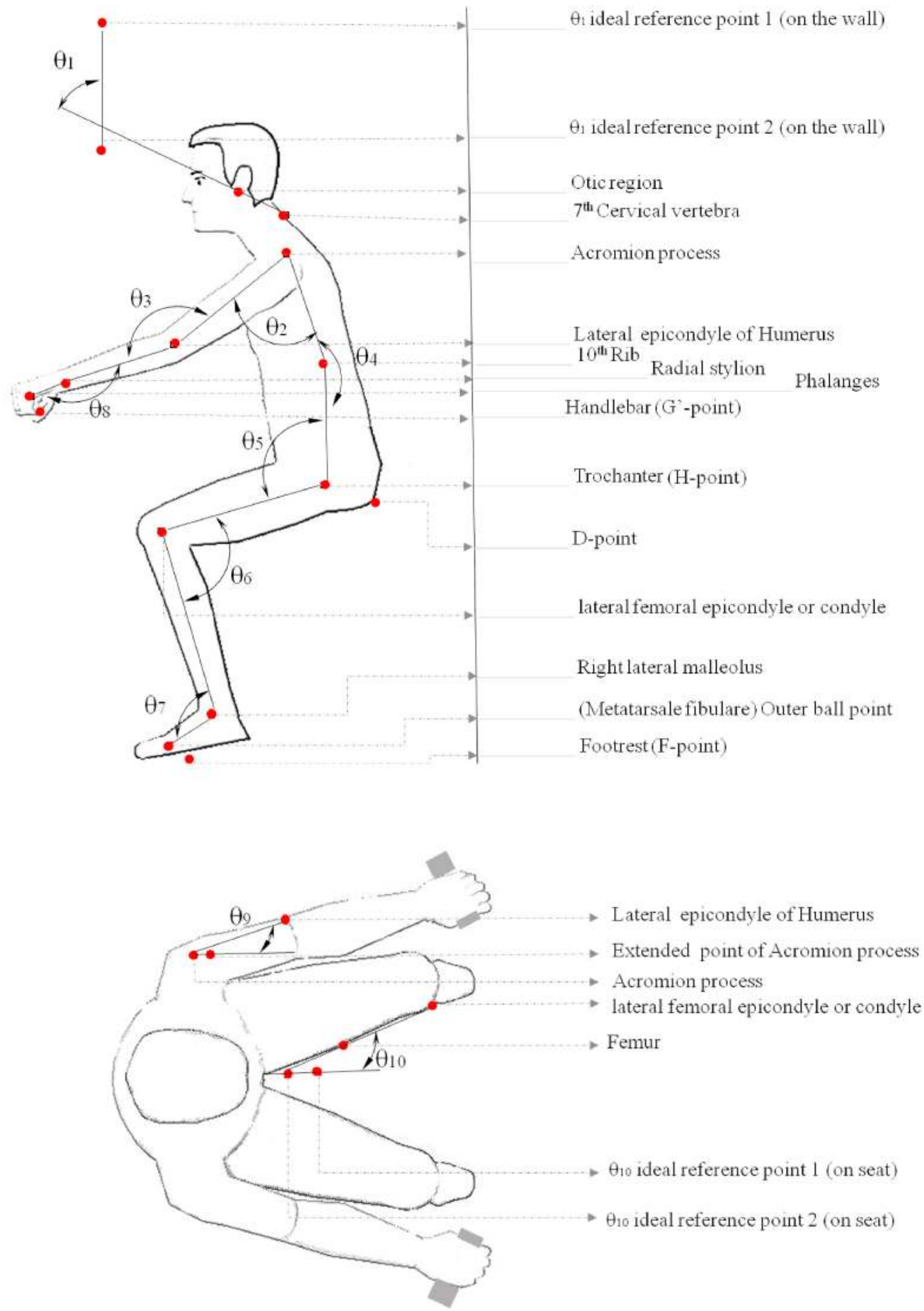

Fig. 4. Landmarks for measuring postural joint angles
Note: Two red markers were affixed on the background wall of the subject (show in Fig. 5-a)to locate the θ_1 ideal reference point 1 and 2. Two red markers were affixed on the seat (show in Fig. 5-b) to locate the θ_{10} ideal reference point 1 and 2. . (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

1998) was deployed in the test-rig for maximum and flexible lateral thigh moments (adduction/abduction) of the subject. A normal footrest having a length of 8.5 cm (standard, commercially available) was installed in the motorcycle test-rig.

The handlebar and footrest were provided with some adjustability features to allow the rider/subject to set these according to their requirement of perceived comfort. Since the handlebar inclination was fixed at 20° (with no rotational adjustment), the only adjustability provided was mechanical translation (up/down and forward/backward movement) of handlebar/grips at xz plane. The range of adjustment was given to both handle grip and footrest by 5 cm at their longitudinal center-line along the xy plane (Fig. 2-a). Moreover, a range of 20 cm in vertical (in xz plane) and 25 cm in horizontal direction for the handle grip were provided (Fig. 2-b). The seat in the test-rig could be maneuvered 25 cm vertically in the xz plane as per the comfort of the rider.

The range of seat dimensions (see Fig. 2-a, right side corner) was decided based on the measurement of 23 standard motorcycle models (Arunachalam et al., 2020a). The survey revealed that the motorcycles

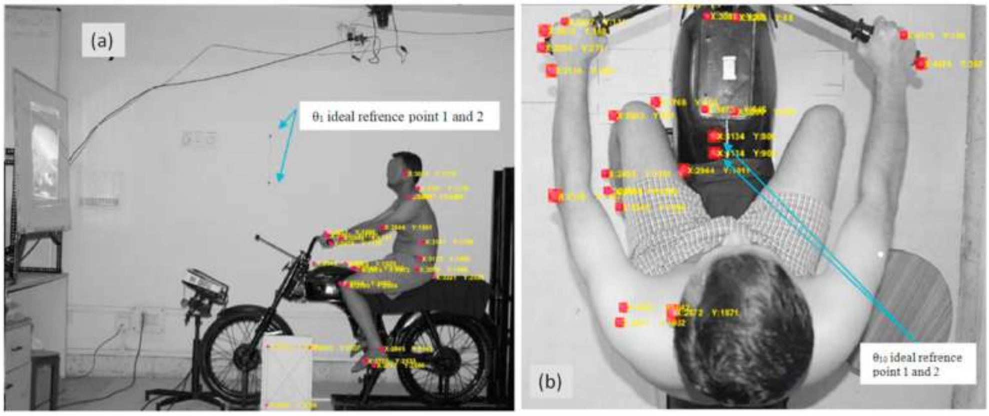

Fig. 5. A typical output of DIP with coordinates of landmarks (a) sideview image (b) topview image.

had the following seat dimensions: front-width (mean: 16 cm; SD: ± 2 cm), mid-width (mean: 21 cm; SD: ± 2 cm) at the distance of 15 cm from front-width, the widest width (mean: 26 cm; SD: ± 2 cm) and seat length (mean: 36; SD ± 2). Mean values of the seat dimensions, except the length (45 cm) were used for the seat of the test-rig used in present experiment. The greatest length of the seat was decided as 45 cm for providing a maximum sitting surface for a subject.

The seat used for the experiment had flat seat contour (no curvature/flat seat surface i.e., zero depth when no one sitting on the seat), the same as mounted on most of the standard motorcycle models in India (Velagapudi and Ray, 2019). The effect of different seat contours on sitting comfort yet to be studied for the economy/executive motorcycle models in India (Praveen and Ray, 2018). Notwithstanding that the prolonged riding cause discomfort, Velagapudi and Ray (2017) argued that seat design did not affect the riding comfort of motorcyclists for a short duration of motorcycling (below 10 min). Hence, the effect of seat design and contour was not taken into consideration in the present experiment.

2.2. Riding posture and position acquisition approach

2.2.1. Definition of riding position

The landmarks used to measure the riding position were shown in Fig. 3. To locate landmarks on the test-rig, red spherical markers (Ø 19 mm) were placed on the respective test rig locations. The landmark position defined in JASO T003:2009 standards are as follows:

- F-point is located at the central and the farthest end of the useable portion of the footrest from the longitudinal median plane of the motorcycle.
- G-point is located at the center of the upper part of the effective portion of the handle grips, while G′-point is located at the central and the farthest end of the useable portion of the handle grip.
- H-point is the pivot center of the torso and thigh of the subject. H′-point is the cross point of the vertical line that passes through the H-point and the upper surface of the seat.
- D-point is located at the seat surface, where the lowest point of the subject's buttock touches the seat surface in the xz plane of the motorcycle.

As evident from Fig. 3, these landmarks for riding position depends on the three key factors, i.e., seat, handle grip, and footrest on the motorcycle's frame. The riding position was measured in the present experiment following the procedure adopted by JASO T003:2009 and B. B. V. Shamasundara and M. S. Ogale (1999). The F-point was fixed at a height 35 cm from the ground and 100 cm from the origin (see Fig. 2-b). The following nomenclature was preferred to present the inter distance between the landmarks:

- T represents the distance between the G-points on the right and left handle grips
- L represents the distance between the G′-points on the right and left handle grips
- O represents the distance between the F-points on the right and left footrest
- R_1 is the vertical distance between the F-point and D-point
- R_2 is the vertical distance between the F-point and G′-point
- R_3 is the horizontal distance between the F-point and D-point
- R_4 is the horizontal distance between the F-point and G′-point
- MR_1 is the vertical distance between the H-point and the ground
- MR_2 is the horizontal distance between the H-point and the F-point

According to JASO T003:2009, H (shown in Fig. 3) should be measured from the H′-point under the unladen condition to the ground. Practically, it was challenging to identify the H′-point when the subject was sitting on the seat. Therefore, for the sake of convenience, the D-point was assumed to be H′-point under the unladen condition (Robertson, 1987).

2.2.2. Definition of riding postural joint angles

The 10 body-joint angles (θ_1 to θ_{10}) in riding posture were defined through the subject's body landmark (as shown in Fig. 4), which were also predominantly used in the similar type of previous studies (Grainger et al., 2017; Hsiao et al., 2015; Young et al., 2012). Red spherical markers (Ø 19 mm) were affixed on the respective body locations to highlight the coordinate of the landmarks. The 2D coordinate (x, y) of these spherical markers of the body landmarks were substituted in equations (1) and (2) to obtain the joint angles. These equations (1) and (2) were referenced from the previous studies (Hsiao et al., 2015; Chou and Hsiao, 2005) and tangent rules (for estimating intersection angle between 2 lines). θ_2 to θ_9 can be determined by using equation (1). θ_1 and θ_{10} can be determined by equation (2). The rigorous procedure adopted in joint angles estimation was explained in Supplementary S.1.

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

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

Where,

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

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

2.2.3. Digital image processing (DIP)

In this study, the DIP technique was used to obtain the *x*-, *y*-

coordinates of the landmarks (shown in Fig. 5). Later, these coordinates acted as inputs in equations (1) and (2) for computing the posture joint angles. Using the subtraction operation, the horizontal/vertical distance between two coordinates were estimated. A couple of images were captured from each subject with (Ø 19 mm) red spherical markers placed on the body landmarks. These images were captured using side/top-view cameras with color filtration mode to locate the landmarks (as shown in Fig. 5-a and 5-b) using MATLAB programmed.

2.2.3.1. Image calibration. These images were calibrated using two rectangular boards (Fig. 1-vi-a and 1-vi-b) of known size were used to calibrate the captured images. The detailed procedure adopted while calibrating the images was elaborated in supplementary S.2 and S.3. Overall, the calibration results revealed that the percentage of error deviation in angular and dimensional of both the side and top-view images were 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).

2.3. Experimental procedure

The study objectives were achieved through a series of two experiments. The experiments were stated as the (1) Experiment for estimating comfortable riding posture (Dis)comfort)/main experiment and (2) Experiment for estimating optimal riding position (using Taguchi DOE). Each experiment had a different experimental procedure and sampling technique. However, the inclusive and exclusive criteria for the two experiments were the same. The main experiment was conducted to evaluate the most comfortable (perceived) riding posture achieved by the rider through the adjustment of the handlebar/grip, footrest, and seat of the test-rig. Since the study involved a high number (ten) of variables (body-joint angles) for defining riding posture (which was explained in subsection 2.2.2), the second experiment used the Taguchi design of experiments (DOE) to identify the optimal riding position.

Those subjects who had musculoskeletal discomfort, hypermobility, bone fractures, or other health problems were excluded. Male subjects (age group of 19–44 years) at least one-year riding experience with a valid motorcycle license was included from the experiments. Before each experiment, the subjects were informed about the experimental procedures, and duly signed consent was obtained from them. The ethical board of the institute agreed to the study, and the method of data collection conducted rendering to Helsinki guidelines (World Medical Association, 2001).

2.3.1. Experiment for estimating comfortable riding posture/main experiment

As the present experiment is the subsequent part of a longitudinal study (Arunachalam et al., 2020), the same 120 randomly selected male subjects aged between 19 and 44 years were invited to participate. These subjects holding a valid license with an average age of 30 years (SD: 9 years) were included in the main experiment. These subjects had an average riding experience of 11 years (SD: 5 years). Before starting the experiment, subjects were informed about the experimental protocol. It consisted of four subsequent steps: (1) Iterative process, (2) Anthropometric measurements, (3) Subjective/perceived (Dis)comfort evaluation, (4) Computing weighted comfort joint angle.

2.3.1.1. Iterative process. Also called "method of fitting trials" (Jones, 1969), the iterative process helped the subjects to achieve a comfortable posture through adjustment of the handgrip, seat, and footrest. Initially, the subjects were asked to sit on the motorcycle test-rig and attain a comfortable posture as well as safe riding condition/position. Subsequently, a (commercial motorcycle simulator) video was played on the white screen for their continuous attention towards the experiment. This simulator video was played to provide a realistic road environment to the subjects while maintaining the static posture. After every 2 min, the subject was verbally asked for any perceived discomfort or pain in their body joints. If any discomfort was reported, the respective component (handgrip/seat/footrest) was adjusted (back/forth/up/down) manually by the experimenter at discrete increment/decrement, in accordance with the procedure mentioned in Porter and Gyi (1998). The process was repeated until the subject perceived no discomfort or attained comfortable sitting. Following adjustment of all other controls, the position was fine adjusted until the subject perceived completely comfortable at all the joints. Finally, the components were temporarily fixed for the corresponding subject. It is an iterative process, and hence there was no time limit to complete this task.

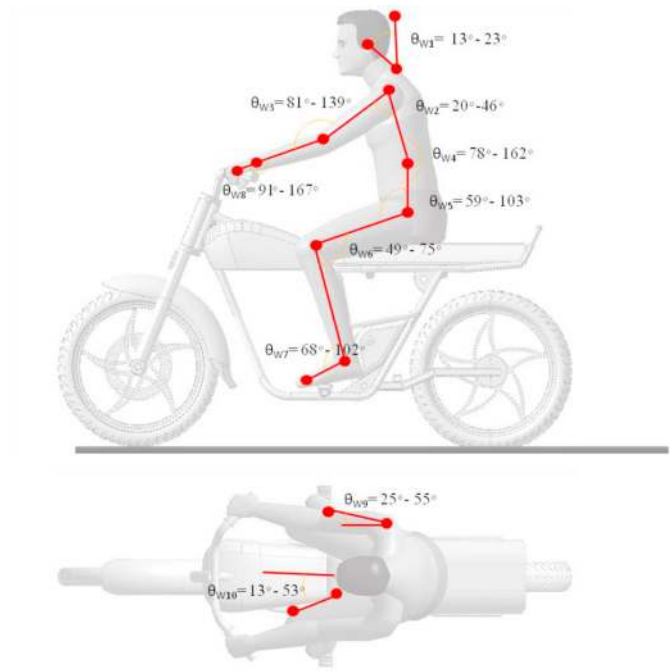

Fig. 6. Comfort joint angles in degree (°) in a motorcycle design.

The number of iteration and duration of each iteration process by all 120 subjects were noted in MS Access Form (in-house made) for further analysis. At least, 3 to 4 iteration or fitting trial has been taken by the subjects to obtain a completely comfortable posture.

2.3.1.2. Anthropometric measurements. Following the iterative process, an interval break of 10 min was introduced to prevent the subjective biases between the consecutive experiments (Manasnayakorn et al., 2009). Before the upcoming trial (perceived (Dis)comfort evaluation), during this interval time, anthropometric measurement (stature and weight) were recorded. Since stature and weight of motorcyclist were considered to be crucial anthropometric measurement for designing a motorcycle (Arunachalam et al., 2020b; Dasgupta et al., 2012), as well as for other vehicles (Wibneh et al., 2020, 2021), these two measurements were measured using the anthropometric kit and weighing machine. The mean (SD) of weight and stature of the 120 subjects were found as 68 (11) kg and 169 (7) cm, respectively.

2.3.1.3. Subjective/perceived discomfort and comfort evaluation. This test was conducted to confirm whether the comfortable posture was optimum or not. Once the subject seated on the test-rig, approved as comfortable in the "iterative process", the red markers were fixed at the landmarks (as mentioned in subsection 2.2.1 and 2.2.2) by the experimenter. A 5 min road riding simulation video was played in front of the rider through the projector on the white screen. During the 5 min time, subjects were informed to identify/perceive (dis)comfort at their body

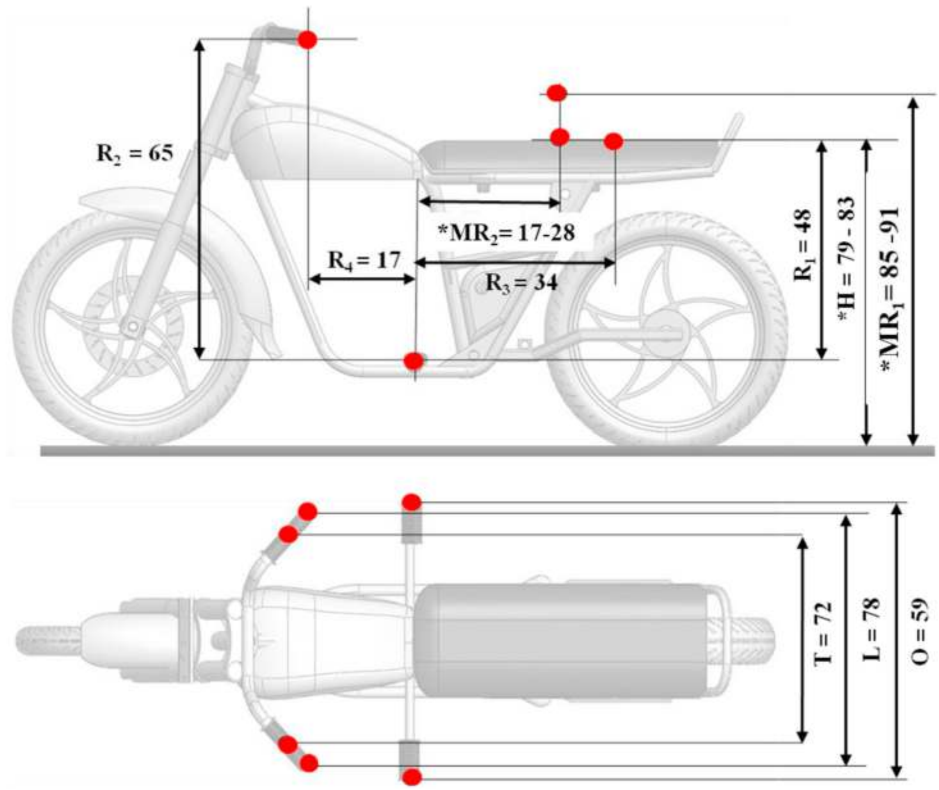

Fig. 7. Suggested optimum riding position in a motorcycle design (unit: cm).
Note: The recommendations for H, MR_1, and MR_2 shall be represented as mean ± SD ((B. V. Shamasundara and M. S. Ogale, 1999)). H ~81 ± 2 cm, MR_1 ~ 88 ± 3 cm and MR_2 ~ 23 ± 5 cm).

joints. During this time, the experimenter captured images (shown in Fig. 5) from the top and side-view. Later, these images were processed using MATLAB and coordinates of the red markers on body-landmarks were noted in the MS Access Form (shown in Annexure, Figure S4 and S5).

After riding for 5 min, the subjects were asked to leave the test-rig and fill the questionnaire, which was aided in the MS access form (shown in Annexure, Figure S6 and S7). The subject were asked to fill the questionnaire for reporting the (dis)comfort on their left side, since the riding/driving posture remain symmetrical while driving on a straight path (Chou and Hsiao, 2005; Kyung and Nussbaum, 2009; Peng et al., 2017). This questionnaire had three subsections including (1) General information; (2)Discomfort rating scale; and (3) Comfort rating scale.

The first section of the questionnaire documented general information like age, state of origin/native, and riding experience (How long you are using motorcycle?). In the second section of the questionnaire, perceived rating on discomfort was measured in the body parts (shown in Annexure, Figure S6) associated with eight body joints viz. Neck, shoulder, elbow, wrist, low back, hip, knee, and ankle (Sai Praveen and Ray, 2015). The subjects rated the perceived discomfort using a scale of 0-no discomfort, 1-very low discomfort, 2-low discomfort, 3-discomfort, 4-high discomfort, and 5- very high discomfort. In the third section of the questionnaire, the rating on comfort in the body's local regions (shown in Annexure, Figure S7) was measured based on the (SAE 2000), which was included to establish validity and reliability of the responses. The subjects were asked to rate the comfort of the body parts using a scale of 1-Intolerable, 2-severe, 3-very poor, 4-poor, 5-marginal, 6-barely accept, 7-fair, 8-good, 9-very good, and 10-excellent. The discomfort ratings were used only for reliability evaluation. Since the aim of the research is to estimate the comfort posture and position, the comfort ratings were used to achieve the study objectives.

2.3.1.4. Computing weighted comfort joint angle. The weighted comfort joint angle can express the combined impact of the joint angles obtained for the comfortable riding posture adopted by the subjects and their ratings for perceived comfort. According to Chou and Hsiao (2005) and Deng et al. (2015), the computation of comfort joint angles should be weighted with the perceived comfort rating of the subjects. Since the comfort rating for each of the body-joint can not be the same among subjects, the weighted mean joint angle can be used to normalize the joint angle between the subjects. Hence, the mean and standard deviations (or tolerance) of weighted comfort joint angles were estimated using equations (3) and (4), respectively. These equations were adopted from previous studies (Chou and Hsiao, 2005; Deng et al., 2015).

$$\theta_{wj} = \frac{\sum_{n=1}^{120} \theta_{jn} w_{jn}}{\sum_{n=1}^{120} w_{jn}} \tag{3}$$

Where, $w_{jn} = C_n$ %; n = 1,2, 3, …..120 and j = 1,2,3 …. 10. θ_{wj} 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 converted from the comfort rating of individual joint of the subjects.

$$\Delta\theta_{wj} = \frac{\left|\theta_{wj} - (\theta_{nwj})_{max}\right| + \left|\theta_{wj} - (\theta_{nwj})_{min}\right|}{2} \tag{4}$$

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

2.3.2. Experiment for estimating optimal riding position (using taguchi DOE)

2.3.2.1. Sample size. In this experiment, the two-stage cluster sampling

Table 1
Descriptiveof riding position variable of the subjects (n = 120) (Unit: cm).

Riding position variables	Mean	SD	Range	Min	Max	Percentiles		
						5th	50th	95th
R_1	48	3	20	34	54	46	47	49
R_2	68	3	16	61	77	63	67	72
R_3	39	5	25	29	54	30	38	49
R_4	22	5	23	7	31	11	22	28
MR_1	88	3	21	75	96	84	89	93
MR_2	23	5	24	11	35	14	22	33
T	72	1	10	67	76	70	73	73
L	78	1	10	72	82	76	78	78
H	81	2	20	69	89	78	81	84
O	59	1	8	52	60	58	60	60

Note: R_1 is the vertical distance between the F-point and D-point; R_2 is the vertical distance between the F-point and G′-point; R_3 is the horizontal distance between the F-point and D-point; R_4 is the horizontal distance between the F-point and G′-point; MR_1 is the vertical distance between the H-point and the ground; MR_2 is the horizontal distance between the H-point and the F-point; T represents the distance between the G-points on the right and left handle grips; L represents the distance between the G′-points on the right and left handle grips; H is the vertical distance between the D-point and the ground; O represents the distance between the F-points on the right and left footrest.

technique was followed. This sampling technique requires lesser experimenting trials with few subjects to cover the appropriate representative of the population and reduce the subject's overhead cost (errors, time, and energy) (Collins et al., 2009). During the first stage (from the main experiment), 120 subjects who could be a representatives of Indian population were selected. They were randomly clustered into three percentile bandwidth groups. Since the stature (anthropometric) measurement is considered to be critical in the motorcycle design, its percentile values were used in the cluster sampling technique. The percentile bandwidths for the shorter, medium, and taller group were chosen as below $P_{30\%}$, $P_{30\%}$ to $P_{70\%}$, and above $P_{70\%}$ (Kong et al., 2005). Among them, a smaller cluster of 3 subjects (for each group) was formed by randomly choosing during the second stage of cluster random sampling. Therefore, the experimental group of nine subjects were categorized into three cluster groups: shorter group, medium group, and taller group, in accordance with the stature categorization mentioned in the previous research (Hashim et al., 2014).

2.3.2.2. Taguchi DOE. This experiment was conducted to achieve an optimal riding position using the Taguchi DOE method. Unlike full factorial design, the Taguchi DOE method was used to optimize four variables namely R_1, R_2, R_3, and R_4 at three levels (3^4) associated with riding position, reducing the set of well-balanced experimental trials to a practical level. The results obtained one optimal combination of variables of riding position to improve the perceived comfort among the subjects. Over the past few years, Taguchi DOE method has been applied in various scientific and industrial applications, including the workplace design of automotive drivers (Park et al., 2016; Spasojević Brkić et al., 2016).

In contrast to Taguchi DOE, while using traditional full factorial DOE, it would have been required $3^4 = 81$ experimental conditions. Since the present experiment deal with human subjects and manual arrangements (in the test rig), higher number of test runs would make the study arduous (Hsiang et al., 1997). Moreover, if the subject needs to run through the experiment more often, the effects of monotony lead to incur, which in turn might cause biased results. Therefore, Taguchi L9 orthogonal array that allowed reducing the experimental runs in a systematic and efficient manner to come up with an optimum solution was adopted. Taguchi DOE has fundamentally two parts: (1) Design array and (2) S/N –a signal to the noise ratio. The descriptive information of the ten riding position variables was shown in Table 1.

Among the ten variables of riding position, the variability was minimal among the three variable viz. L, T, and O. Hence, the mean

Table 2
Test Conditions for Taguchi DOE (control variables and levels) (Unit: cm).

Test Condition	R_1	R_2	R_3	R_4	L[a]	T[a]	O[a]
1	45	65	34	17	78	72	59
2		68	39	22			
3		71	44	27			
4	48	65	34	17			
5		68	39	22			
6		71	44	27			
7	51	65	34	17			
8		68	39	22			
9		71	44	27			

[a] L, T, O were fixed parameters for all test conditions.

dimension of these variables considered to be optimum and fixed parameter in the Taguchi DOE. Since MR_1 and H dimensions were strongly correlated (r = 0.90) with the R_1 dimension (shown in Annexure, Table S1), only R_1 was considered instead of MR_1 and H. Similarly, MR_2 was strongly correlated (r = 0.92) with R_3, only R_3 was considered instead of MR_2. Thus, four control variables R_1, R_2, R_3, and R_4 were considered in the design array part of the Taguchi DOE. Generally, level selection in Taguchi DOE is based on the early literature or intra association between the variables. Our literature search implies lack of early studies on motorcycle design using Taguchi DOE, therefore, the area needs to be explored. In this experiment, we have chosen three levels for the four control parameters. According to Hsiao et al. (2015), an optimal riding position of two-wheeler lies between within one standard deviation (i.emean ± SD) of the riding position dimensions. Therefore, this study considered the mean and SD of riding position variables as three different levels. The levels were selected, as follows: First level: Mean−SD, second level: Mean, and third level: Mean + SD. Later, it was validated with new group of subjects in the confirmation test. Based on the explanation above, the L9 (partial)orthogonal array of Taguchi DOE considered for the current experiment. Thus, the L9 orthogonal array (nine test conditions) was generated using Minitab 17 (as shown in Table 2).

2.3.2.3. Experimental procedure. The experiments were conducted in nine subsequent days. Each day, one test condition was used to collect data from the nine subjects. Heart Rate (HR) could also be considered as an indicator to assess physical/cognitive state of a person (Rowe et al., 1998; Camillo et al., 2011). Hence, to monitor the psychophysiological consistency among the subjects throughout the nine subsequent days, HR (bpm) was monitored before every experiment. It was measured using automatic blood pressure monitor (Model: OMR223, Make: Omron). The mean HR of the subjects measured in the nine subsequent days was shown in the Annexuretable S.2. These HR were in-line with the inter heart rate recommendations by Tan et al. (2011) for healthy subjects.

Following HR measurement, the subjects were asked to sit on the test-rig for 5-min, which was adjusted to the test conditions, respectively. During this period, subjects were asked to feel (dis)comfort (if any) in body joints/parts. After 5 min, subjects were asked to rate the overall body (dis)comfort using the same questionnaire mentioned in section 2.3.1 (perceived (dis)comfort evaluation. The mean rating scores of the 3 groups from the nine test conditions were analyzed. The observations have been presented in the results and discussion section.

2.3.2.4. S/N ratio estimation. The S/N equations (Taguchi and Wu, 1980) were used for conducting Taguchi DOE to estimate the optimal riding position among the nine test conditions. Minitab (Minitab Inc., PA; version 17) software was used to design and analyze Taguchi L9 orthogonal array. The "smaller is better" equation (5) was used to determine the S/N ratio of overall discomfort ratings from nine test conditions. Similarly, "Lager is better" equation (6) was used to estimate the S/N of overall comfort ratings.

Table 3
Descriptive statistics of basic anthropometric variables and body joint angles defining riding posture (n = 120 and unit is in degree (∘), unless specified).

Anthropometric and Posture variables	Mean	SD	Min	Max	Percentile		
					5th	50th	95th
Stature (cm)	168	6	150	188	158	169	182
Weight (kg)	68	11	38	90	51	67	83
θ_1	24	2	19	30	20	24	27
θ_2	45	12	16	67	21	44	65
θ_3	137	19	91	172	94	139	164
θ_4	179	10	150	199	156	179	192
θ_5	105	9	68	131	94	105	120
θ_6	74	8	58	88	63	74	87
θ_7	102	8	91	132	92	100	120
θ_8	166	20	119	269	127	168	192
θ_9	50	16	9	77	18	53	73
θ_{10}	42	22	5	116	9	42	82

$$\frac{S}{N}ratio = -10log\left(\frac{\sum_{i=1}^{n} y^2}{n}\right) \tag{5}$$

$$\frac{S}{N}ratio = -10log\left(\frac{\sum_{i=1}^{n}\frac{1}{y^2}}{n}\right) \tag{6}$$

2.3.3. Reliability evaluation of joint angles and riding position measurements

Manual (using goniometer and laser pointer) and image (using digital image processing) based measurements were checked for reliability. To ensure the accuracy, alternative-form of reliability was evaluated using Spearman's rank correlation coefficient in IBM SPSS version 23.0 involving data from these two different methods of measurements of joint angles and riding position (Heale and Twycross, 2015).

Before the main experimentation on 120 subjects, the reliability was tested on randomly selected ten subjects to assess the precision of the measurements (linear and angular). These subjects were different from the 120 subjects and the data have not been included in the main experiment. During the assessment, the subject was asked to sit in the test-rig, adjusted to match the comfort of the subject. The observer manually measured the joint angles and riding position using a goniometer (Make:Kristel; Model:3278) and larger sliding caliper/laser pointer – measuring setup, respectively. Following this measurement, images of the rider and test-rig were captured with red makers, which was affixed by an observer on the landmarks mentioned in section 2.2.1 and 2.2.2 Later, these images were processed in the DIP to ensure the image-based measurements.

The summary of physical and DIP measurements showed that the correlation coefficients for (joint) angular measurement and linear (riding position) dimensions were ranged between 0.92 to 0.98 and 0.94 to 0.99, significant at the 0.05 level (2-tailed). Several past investigations (Heale and Twycross, 2015; Mohajan, 2017; Mukaka, 2012) approved that the measurements could be considered consistent and reliable for alternate-form reliability values higher than 0.90.

2.3.4. Reliability evaluation of perceived comfort/discomfort

Like early studies (Kee and Lee, 2012; Helander and Zhang, 1997), we used the correlation method to estimate the reliability (alternate form) on subject's perceived discomfort and comfort rating scores. The reliability results showed that the spearman's rank correlation coefficient between discomfort and comfort in neck/shoulder/elbow/-wrist/low back/hip/knee/ankle was −0.83, −0.79, −0.85, −0.81, −0.84, −0.79, −0.85, −0.79, significant at the 0.01 level (2-tailed) respectively. The correlation coefficient between overall discomfort and comfort of the whole body was found as −0.85, during the experiment for the optimal riding position (in section 2.3.2).

Early research by Mukaka (2012) and De Looze et al. (2003) stated that the correlation coefficient between −0.7 and −0.9 could be interpreted as high negative-correlation. Since the discomfort is derived from and opposite of comfort, a negative correlation was anticipated during the reliability analysis. Altogether, the subjective (dis)comfort rating showed strong negative correlation, Hence, the perceived responses on comfort could be considered reliable for further analysis.

3. Results

3.1. Experiment for estimating comfortable riding posture/main experiment

The postural variables were measured/estimated, as stated in the earlier subsection (2.2.2). Table 3 presents descriptive information about the basic anthropometry and comfort joint angle among the subjects in terms of mean, standard deviation (SD), maximum (Max), minimum (Min), and percentiles (5th, 50th, and 95th) values.

Table 4 summarizes the frequency distribution of the comfort rating among 120 subjects during the main experiment (refer 2.2.2), whereas the frequency distribution of discomfort rating was presented in Annexure Table S3. It could be observed that most of the subjects rated beyond a comfort score of 5 (marginal comfort) after their main experiment.

Table 5 presents the descriptive statistics in terms of mean, standard deviation (SD), maximum (Max), minimum (Min), and percentiles (5th, 50th, and 95th) for the weighted comfort joint angles corresponding to each joint. The results presented in Table 5 are critical for evaluating the riding posture as one of the research questions was related to exploring the comfortable riding posture (joint angle) for the motorcyclists.

To visualize the weighted comfort joint angles ($\theta_{wj} \pm \Delta\theta_{wj}$) presented in Table 5, the digital manikin/human model (DHM) was created (using CATIA V5 software) (Karmakar et al., 2012) with comfortable riding posture by incorporating these angles (Fig. 6). This presentation of weighted comfort joint angles in manikin would help the readers to

Table 4
Comfort ratings for various body parts/joints by the subjects (n = 120) - Frequency distribution.

Comfort ratings[a]	Joints							
	Neck	Shoulder	Elbow	Wrist	Low Back	Hip	Knee	Ankle
Intolerable (1)	0	0	0	0	2	2	0	0
Severe (2)	3	2	1	3	4	1	0	0
Very poor (3)	4	3	1	3	6	1	0	2
Poor (4)	5	8	4	8	9	3	5	3
Marginal (5)	9	8	7	0	9	6	2	4
Barely accept (6)	17	11	5	11	14	11	4	5
Fair (7)	14	29	13	20	25	23	9	15
Good (8)	26	23	46	24	20	30	41	26
Very good (9)	28	19	22	21	20	24	28	36
Excellent (10)	14	17	21	30	11	19	31	29

[a] Ratings collected on the 10-point scale.

Table 5
Descriptive statistics of the weighted comfort joint angles in degree (∘) (n = 120).

Weighted comfort joint angles	Mean (θ_{wj})	SD ($\Delta\theta_{wj}$)	Min ($(\theta_{nwj})_{min}$)		Max ($(\theta_{nwj})_{max}$)	Percentile 5th	50th	95th
Neck - θ_{W1}	18	5	4	28		8	18	26
Shoulder - θ_{W2}	33	13	10	59		12	31	54
Elbow - θ_{W3}	110	29	52	168		58	110	154
Lower back - θ_{W4}	120	42	36	193		38	125	177
Hip - θ_{W5}	81	22	37	125		42	83	110
Knee - θ_{W6}	62	13	36	88		34	62	84
Ankle - θ_{W7}	85	17	51	119		48	86	107
Wrist - θ_{W8}	129	38	53	185		63	128	179
Sh-abd/add - θ_{W9}	40	15	10	70		12	43	62
Hip abd/add - θ_{W10}	33	20	2	73		4	30	65

Note: Sh-abd/add - Shoulder abduction/adduction; Hip abd/add -abduction/adduction.

Table 6
Tabular comparison of comfort joint angles (Unit: ˚) of the riding posture for the current study with previous studies.

	Population/Sample Size/Type of two-wheeler	Shoulder	Elbow	Lower back	Hip	Knee	Ankle	Wrist
Current study	120 Indian Standard Motorcycle	M:33° SD: 13° Min-Max 10° - 59°	M:110° SD: 29° Min-Max 52° - 168°	M:120° SD: 42° Min-Max 53° - 193°	M:81° SD: 22° Min-Max 37° - 125°	M: 62° SD: 13° Min-Max 36° - 88°	M:85° SD: 17° Min-Max 51° - 119°	M:129° SD: 38° Min-Max 53° - 185°
Jeyakumar and Gandhinathan (2014)	30 Indian Sport Motorcycle	M:40° Min-Max 54° - 75°	M:139° Min-Max 148° - 163°	M:170° Min-Max 92° - 79°	M:104° Min-Max 79° - 92°	M:79° Min-Max 74° - 85°	n/a	n/a
Imaekhai Lawrence (2013)	120 Nigerian Scooter	M:40° SD: 3° Min-Max 38° - 43°	M:139° SD: 7° Min-Max 133° - 146°	M:170° SD: 3° Min-Max 167° - 173°	M:104° SD: 4° Min-Max 100° - 108°	M:79° SD: 4° Min-Max 75° - 83°	n/a	n/a
Barone and Lo Iacono (2015)	(n/a) Italian Scooter	M:50°	M:128°	n/a	M:101°	M:121°	M:93°	n/a
Chou and Hsiao (2005)	60 Taiwan Scooter	M:40° SD: 3° Min-Max 37° - 42°	M:140° SD: 7° Min-Max 134° - 147°	M:170° SD: 3° Min-Max 167° - 173°	M:103° SD: 4° Min-Max 100° - 107°	M:78° SD: 4° Min-Max 74° - 82°	n/a	n/a
Barone and Curcio (2004)	4 Italian Scooter	Min-Max 37° - 61°	Min-Max 130° - 160°	Min-Max 150° - 169°	Min-Max 96° - 122°	Min-Max 99° - 136°	n/a	Min-Max 146° - 171°

Note: n/a – Not mentioned; M-mean; SD- Standard deviations; Min – minimum; Max-maximum.

Table 7
Summary of the S/N ration response for mean discomfort/comforts rating scores (N = 9).

Ratings		Discomfort[a]				Comfort[b]			
Groups		Tall (n = 3)	Medium (n = 3)	Short (n = 3)	S/N ratio	Tall (n = 3)	Medium (n = 3)	Short (n = 3)	S/N ratio
Test Conditions	1	2.2	1.3	2.8	−5.2	7.2	8.7	7.2	17.5
	2	1.3	1.1	1.9	−2.4	8.7	8.9	8.1	18.1
	3	2.1	0.2	0.8	−1.4	7.8	10.0	9.0	18.8
	4	**0.9**	**0.1**	**0.0**	***−1.3***	**9.1**	**10.0**	**10.0**	***19.1***
	5	0.9	2.4	0.7	−2.4	8.9	8.9	8.7	17.2
	6	2.3	0.6	1.1	−1.4	8.7	9.4	8.9	18.8
	7	2.2	0.8	1.0	−2.4	7.8	9.1	9.1	17.5
	8	1.9	1.1	1.0	−2.4	8.1	8.8	9.0	17.7
	9	0.7	2.2	1.9	−4.4	9.2	7.8	8.1	16.9

Note: Taller group– stature above 175 cm; Medium group - stature from 174 cm to 165 cm; Short group - stature below 165 cm [a]Rating consisted of a 5-point scale. [b]Rating consisted of 10-point scale.

apprehend the primary objective of the current study, i.e., the suggested angles for comfortable motorcycle riding. Moreover, these joint angle values can be directly applied in the DHM module (CATIA V5), without any modifications or manipulations as the joint angles used/defined in the present research are same as defined in the CATIA V5 Human manikin. Here, it is worthy to note that the angle $\theta 4$ is the representative of thoracic joint in the CATIA V5 manikin.

3.2. *Experiment for estimating optimal riding position (using Taguchi methods)*

The estimated S/N has been presented in Table 7 with mean

Table8a
Discomfort rating of the subjects (n = 30) – Distribution of frequency count and its percentage.

	Joints																	
Discomfort ratings[a]	Neck		Shoulder		Elbow		Wrist		Low Back		Hip		Knee		Ankle		Overall	
No discomfort (0)	7	23%	10	33%	12	40%	13	43%	6	37%	13	43%	18	60%	14	47%	11	37%
Very low discomfort (1)	10	33%	7	23%	7	23%	8	27%	8	20%	9	30%	7	23%	9	30%	8	27%
Low discomfort (2)	*7*	*23%*	*7*	*23%*	*8*	*27%*	*5*	*17%*	*6*	*20%*	*5*	*17%*	*3*	*10%*	*4*	*13%*	*5*	*17%*
Discomfort (3)	3	10%	5	17%	2	7%	4	13%	6	10%	2	7%	2	7%	2	7%	5	17%
High discomfort (4)	3	10%	1	3%	1	3%	0	0%	3	10%	1	3%	0	0%	1	3%	1	3%
Very High discomfort (5)	0	0%	0	0%	0	0%	0	0%	1	3%	0	0%	0	0%	0	0%	0	0%

[a] Rating consisted of 5-point scale.

discomfort/comforts rating scores of the 3 groups (<$P_{30\%}$- short, $P_{30\%}$ to $P_{70\%}$ - medium, < $P_{70\%}$ - taller).

All groups reported a maximum level of comfort rating and the minimum level of discomfort rating for the 4th test condition (R1 → 48 cm, R2 → 65 cm, R3 → 34 cm, R4 → 17 cm) when compared with other test conditions. Based on these ratings, the calculated S/N ratio of 4th test condition was found to be optimal. Perhaps, the reason for higher compatibility with 4th test condition could be the higher match in anthropometry with the riding positions. For example, R_1 (vertical distance between the F-point and D-point) closely matches with lower leg length of 50th percentile of Indian motorcyclists (is 44 cm) (Arunachalam et al., 2020). Similarly, the sum of R_3 and R_4 (horizontal distance between the F-point and G-point) 51 cm is closely matched with 5th percentile of Indian motorcyclist's acromion grip length (is 55 cm). On the other hand, the S/N ratio of 9th test condition (R_1→51 cm, R_2→71 cm, R_3→44 cm, R_4→27 cm) yielded the most unsatisfactory response from subjects. All groups reported a minimum level of mean comfort rating and maximum level of discomfort rating for the 9th test condition. Perhaps the reason could be the body dimensional mismatch between the motorcycle user and motorcycle dimensions, which in turn caused higher level of discomfort. For example, of R_3 and R_4 (horizontal distance between the F-point and G-point) 71 cm was even more than 95th percentile value of acromion grip length (is 70 cm) of Indian motorcyclist (Arunachalam et al., 2020).

3.2.1. *Confirmation test and results*

The last part in Taguchi DOE is performing the confirmation experiment to validate the optimal test condition. This test was conducted in the test-rig, which followed the optimum comfortable riding position: R_1 → 48 cm, R_2 → 65 cm, R_3 → 34 cm, R_4 → 17 cm, L → 78 cm, T → 72 cm, and O → 59 cm.

In this confirmatory experiment, 30 subjects were randomly selected. These 30 subjects were different from the previous experiment to avoid bias toward task repetitions. The inclusion and exclusion criteria of this experiment were the same as the early experiments. All 30 subjects were male and holding a valid license with an average age of 28 years (SD: 6 years). These subjects had an average riding experience of 7 years (SD: 6 years). The mean and SD of 30 subject's weight and stature were measured as 68 (11) kg and 170 (6) cm, respectively.

The confirmation experiment had the following experimental protocol. Before starting the confirmatory test in the test-rig, subjects were asked for 30 min rest at a supine position (on the bed) to avoid the prior bias of physical/cognitive exhaustion in their day-to-day tasks. Subsequently, the subject's weight and stature were recorded by the experimenter in the MS Access form. Later during the measurements (confirmatory test), the subject was asked to sit on the test-rig for 5 min. During these 5 min, a road riding simulation video was played on the white screen using a projector. Afterward, the subjects were asked to rate their (dis)comfort in their body parts on the discomfort rating scale of 0 (no discomfort) to 5 (Very high discomfort) and comfort rating scale of 0 (Intolerable) to 10 (excellent).

During the confirmatory test, the alternative form of reliability of the subjective ratings was found to be in the range from −0.7 to −0.9 (calculated using Spearman's rank correlation coefficient), which can be considered reliable enough for further analysis. Tables 8a and 8b shows the distribution of frequency count and percentage of discomfort/comfort rating among the 30 subjects.

The majority of perceived discomfort ratings were between 0 (no discomfort)to 2 (low discomfort). A rating of 3 (discomfort) to 5 (very high discomfort) in the neck, shoulder, elbow, wrist, low back, hip, knee ankle were reported by only 20%, 20%, 10%, 13%, 23%, 10%, 7% and 10% of the subjects, respectively. Whereas, in case of comfort rating, most subjects rated between 5 (marginal) to 10 (excellent comfort). A rating of 1–4 (intolerable complaints to poor comfort) in the neck, shoulder, elbow, wrist, low back, hip, knee ankle were mentioned by 7%, 12%, 5%, 13%, 18%, 7%, 4% and 5% of the subjects, respectively. Although a few subjects were involved in the confirmatory test, it might be concluded from these overall results that most of the subjects were rated below the low discomfort level (rating 2) and above the marginal comfort level (rating 5) during the confirmatory test.

4. Discussion

The study evaluated the CRP and ORP for improving Indian standard motorcycle design. This study is first of its kind to cover 10 important body joint angles to define riding posture for Indian male standard-

Table8b
Comfort rating of the subjects (n = 30) – Distribution of frequency count and its percentage.

Comfort ratings[b]	Joints																	
	Neck		Shoulder		Elbow		Wrist		Low Back		Hip		Knee		Ankle		Overall	
10 – Excellent	4	12%	4	14%	5	18%	8	25%	3	9%	5	16%	8	26%	7	24%	5	18%
9 - Very good	7	23%	5	16%	6	18%	5	18%	5	17%	6	20%	7	23%	9	30%	6	21%
8 – Good	7	22%	6	19%	12	38%	6	20%	5	17%	8	25%	10	34%	7	22%	7	25%
7 – Fair	4	12%	7	24%	3	11%	5	17%	6	21%	6	19%	2	8%	4	13%	5	15%
6 - Barely accept	4	14%	3	9%	1	4%	3	9%	4	12%	3	9%	1	3%	1	4%	2	8%
5 – Marginal	*2*	*8%*	*2*	*7%*	*2*	*6%*	*0*	*0%*	*2*	*8%*	*2*	*5%*	*1*	*2%*	*1*	*3%*	*1*	*5%*
4 – Poor	1	4%	2	7%	1	3%	2	7%	2	8%	1	3%	1	4%	1	3%	1	5%
3 - Very poor	1	3%	1	3%	0	1%	1	3%	2	5%	0	1%	0	0%	1	2%	1	2%
2 – Severe	1	3%	1	2%	0	1%	1	3%	1	3%	0	1%	0	0%	0	0%	0	1%
1 – Intolerable	0	0%	0	0%	0	0%	0	0%	1	2%	1	2%	0	0%	0	0%	0	0%

[b] Rating consisted of the 10-point scale.

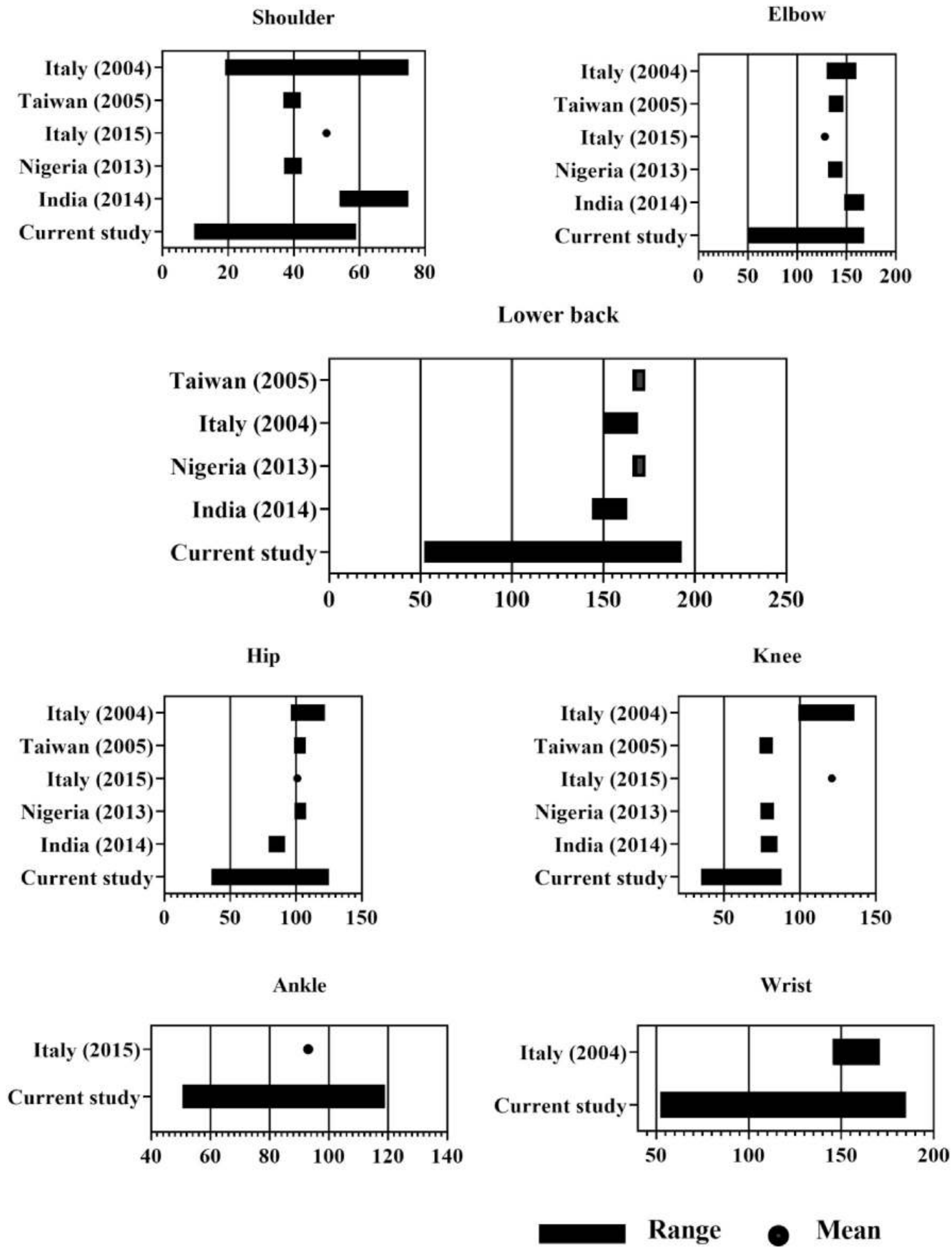

Fig. 8. Demonstration of graphical comparative analysis of the weighted comfort joint angles across different countries. Note: *x*-axis unit: ∘. Bar graph represents the minimum and maximum of comfort joint angles ranges. Dot plot represents the mean of comfort joint angles.

motorcycle riders. Few joint angles (shoulder and thigh adduction/abduction angles) used in current study have not been reported by any of the earlier researchers during the study of motorcycle rider's posture. It summarize and synthesize the comfortable posture (joint angles) of two-wheeler (sport-motorcycle, motorbikes and scooters) riders and depicted comparison with the findings of previous literature. The values of weighted comfort joint angles from the current study were further compared (in tabular format) with the data obtained in other earlier studies which followed similar joint angle measurement procedures (Table 6). Other studies considered for this purpose included a) Indian sport motorcycle riders (Jeyakumar and Gandhinathan, 2014); b) Nigerian motorbike riders (Lawrence, 2013); c) Italian scooter riders (Barone and Lo Iacono, 2015); d) Taiwan scooter riders (Chou and Hsiao, 2005); and d) Italian scooter riders (Barone and Curcio, 2004).

As evident from Table 6 and Fig. 8, seven angular variables (θ_{W2}-θ_{W8}) were taken into consideration. Neck angle (θ_{W1}) was excluded for the comparison since the neck angle measurement adopted in the current study was different from the earlier studies. In most of the previous studies, at the static conditions, only riding postures in the Sagittal plane (θ_{W1} - θ_{W8}) were studied. However, in the present research, the authors have considered the transverse plane to record the abduction/adduction angles for the hip and shoulder joint (θ_{W9} and θ_{W10}) measurements. A recent review on motorcycle riding posture (Arunachalam et al., 2019) also expressed the difficulty in the comparison of comfort joint angles among different studies, due to different approaches adopted for measuring joint angles (e.g., type of two-wheeler, measurement technique, and the number of trials for adjustments in test-rig, etc.). Perhaps body diversity among the riders (subjects from different zones of India) in current study could be a reason for a wider range-bar in Fig. 8. Whereas, other studies does not considered the body diversity during the sample estimation. Being aware of these constraints of comparing comfort joint angles reported from different studies, graphical comparison of the ranges (from minimum to maximum) of weighted comfort joint angles of the current study with the comfortable/preferred angles (shoulder, elbow, lower back, hip, knee, ankle, and wrist joint) suggested by few earlier studies have been depicted in Fig. 8.

The observed range of comfortable shoulder angle (from 10° to 59°) in the current study corroborates with range obtained by an Italian study (Barone and Curcio, 2004). Nigerian (Lawrence, 2013) and Taiwanese (Chou and Hsiao, 2005) studies got a narrow range from 37° to 42°and 38°–43° with the mean values (40°) much higher than the current study (33°). Moreover, the observation from the present study was different from the suggestion by Barone and Lo Iacono (2015) and one previous Indian (Jeyakumar and Gandhinathan, 2014) study. Both the studies collected measurements from the sports motorcycles. The motorcycle manufacturers optimize the sports motorcycle for maximum acceleration and minimum aerodynamic drag. Henceforth, the posture is the sports motorcycle rider is always different from the standard motorcycle. Comfortable range of elbow angle obtained in the current study was 50°–168° with a mean value much lower than the suggested angle by previous Italian (Barone and Lo Iacono, 2015) and Indian (Jeyakumar and Gandhinathan, 2014) studies. However, this comfort range coincided with the observations made by another Italian investigation (Barone and Curcio, 2004), Nigerian (Lawrence, 2013) and Taiwanese (Chou and Hsiao, 2005) studies. Concerning the lower back angle, the current study obtained range (53°–193°) cover the suggested range of Indian (Jeyakumar and Gandhinathan, 2014) study. Barone and Lo Iacono (2004) found a lower-back angle ranging from 150° to 169° with a mean value slightly higher than the current study. It was somewhat different from the suggestions by Lawrence (2013) and Chou and Hsiao (2005). For the hip angle, the current study range (37°–125°) was in agreement with the range observed by other Indian (Jeyakumar and Gandhinathan, 2014) study. Italian (Barone and Lo Iacono, 2015), Nigerian (Lawrence, 2013), Taiwanese (Chou and Hsiao, 2005) and Italian (Barone and Curcio, 2004) studies observed a narrow range of hip angle with a mean value much higher than the current study. Regarding the comfortable knee angle, ranges suggested by Indian (Jeyakumar and Gandhinathan, 2014), Nigerian (Lawrence, 2013), and Taiwanese (Chou and Hsiao, 2005) studies were found slightly narrower with its mean value relatively higher than the current study. Barone and Lo Iacono (2004) recommend the range (99°–136°) which does not comply with the current study. In addition, it's observed that most of the subjects in the current study perceived better comfort in the inclined backward sitting position (see Annexure Figure S8 for measurement method of inclined forward/backward sitting position).

The empirical evidence from the comparison (Table 6) depicts that the majority of the early studies ignored considering minor segments (body parts) like ankle and wrist joint angles. However, in both Italian conducted by Barone and Curcio (2004) and Barone and Lo Iacono (2015), they only considered ankle and wrist joint angle measurements, respectively. The range of comfortable ankle angle in the current study was slightly lower than the suggestions by Barone and Curcio (2015) whereas the range of the comfortable wrist angle the current study is covered the range reported by Barone and Lo Iacono (2004).

Fig. 7 demonstrates the motorcycle model for the optimal riding positions obtained from this study. The recommended value of $R_1 = 48$ cm was in the range of 42–58 cm and 30–59 cm, proposed by Kolekar and Rajhans (2011) and JASO T003:2009, respectively. Similarly, for R_2, the present study suggested 65 cm, falls in the range of 50–70 cm and 32–90 cm proposed by Kolekar and Rajhans (2011) and JASO T003:2009, respectively. The recommended value of $R_3 = 34$ cm in the current study falls into the recommended range (20–53 cm), suggested by JASO T003:2009. However, it was relatively different from the dimensions proposed by Kolekar and Rajhans (2011). Our study proposes $R_4 = 17$ cm, different from the early recommendations by Kolekar and Rajhans (2011) and JASO T003:2009. This difference might appear due to the use of different handlebar designs in the present study.

The vertical distance of H-point from the ground, MR_1, considered to be one of the critical measurements in the vehicle design process (Roe et al., 1999) was 91 cm (with SD: 4 cm) in the present experiment. According to the early study of B. V. Shamasundara and M. S. Ogale (1999) on preference posture of 1410 Indian motorcyclist, the MR_1 was found in the range between 53 and 65 cm. Contrarily, our research found a range from 75 to 96 cm. Also, MR_2 of the current research (range from 11 to 35 cm) differed from the study range (from 17 to 40 cm) observed by B. V. Shamasundara and M. S. Ogale (1999). This discrepancy could be due to the instruction given to subjects and the adjustability feature provide during the experiment. However, the range of L-handlebar width (distance between the G′-points on the right and left-handle grips) reported by B. V. Shamasundara and M. S. Ogale (1999) from 54 to 76 cm was found almost similar to our current research (72–82 cm).

According to JASO T003:2009, T (distance between the G-points on the right and left handle grips) would be in the range from 35 to 80 cm and H (vertical distance between D-point to the ground) would be the maximum height of 90 cm. These recommendations closely mismatched with the current study results as 81 cm and 72 cm, respectively. The mean of O (distance between the F-points on the right and left footrest) was found to be 59 cm, which falls into the range (from 54 to 59.5 cm) obtained in the early study of Arunachalam et al. (2017).

4.1. Future scope - implementation of measurements in the motorcycle design process

Two-wheeler companies have a high number of customers at their disposal. Among them, most of the customers stated unsatisfied with their two-wheeler (Sai Praveen and Ray, 2015). Thus, the current research may help to transform immediate accessible information for better motorcycle design, in turn, user comfort. Moreover, we anticipate that motorcycle designers may now adopt similar methodology to address the discomfort among motorcycle users. Indian motorcycle manufacturers should be encouraged to implement the findings of currents study in their product development stage of upcoming motorcycle models. It will undoubtedly help in improving the ergonomics design of Indian motorcycle models.

As there is no clearly defined comfort range of motion database to ensure comfortable riding posture for Indian male motorcycle riders, it is currently not possible to evaluate motorcycle design in virtual environment using popular DHM software (e.g. RAMSIS, CATIA, Jack, SAMMIE and Santos) available in the market. The current comfort joint angle database for Indian male motorcycle riders would enable DHM software manufacturer to incorporate the same for ergonomic assessment of the riding posture of Indian male motorcyclists and thereby would facilitate redesign/modification of motorcycle design in CAD software.

Limited source and time constraints forced us to limit the sample size to 120, in agreement with the recommended sample size while conducting anthropometry studies (ISO, 2012, p. 15,535). Since a decreasing trend of female motorcyclists has been evident in the current

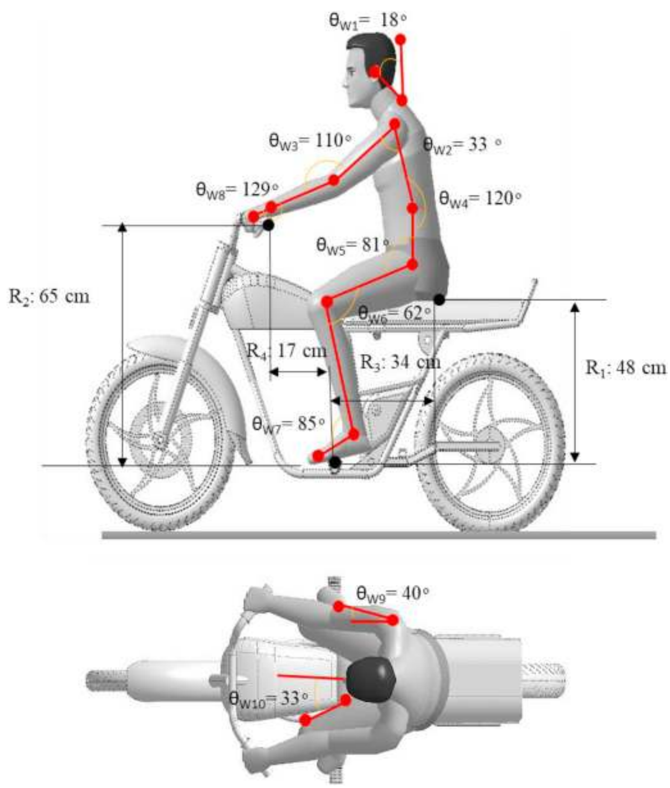

Fig. 9. Suggested mean comfortable joint angles and best possible riding positions for standard motorcycles.

Indian scenario (Government of India, 2018), the current study considers only males. However, the authors recommend considering female subjects in future research to achieve precision in the optimal riding position and postures. Though the present investigation only considered Indian subjects (motorcycle users), this limitation does not seem to affect if similar methods will be adopted for research in other parts of the world.

There was another critical limitation in the Taguchi DOE that the L9 orthogonal array was considered instead of an L27 orthogonal array to reduce the number of test runs due to the involvement of human subjects and manual arrangements in the motorcycle test rig. Unlike real dynamic riding conditions (road/vibration etc.), this was a laboratory study. However, we anticipate furthering this longitudinal work in dynamic situations (riding on a flat road).

5. Conclusion

The study experimentally acquired comfort joint angles using the image processing technique. It effectively measured the riding position perceived comfortable by the subjects. In the process of identifying the optimal riding position, Taguchi DOE was used. The experiment identified comfort postural angles and best possible riding positions (as shown in Fig. 9). Subsequently, the confirmation test supports the findings of the optimal riding position. This was the first attempt to find the comfortable riding posture and optimum riding position for a particular class/type of motorcycle in Indian context with important 10 body-joint angles. The result can further be utilized in improving the motorcycle design for comfortable riding experience. More inclusive design solutions, where users can adapt their vehicle to their own physical characteristics and preferences could be the ultimate futuristic solution to achieve the goal. The comparison results concluded that most of the comfort joint angles in the present research were considerably different from the observations made by earlier studies of scooter/sport motorcycles. However, the optimum riding position was found within the recommended standards. Further field trials will be needed to evaluate optimum results in real dynamic riding conditions (paved road).

CRediT authorship contribution statement

Muthiah Arunachalam: Data curation, Formal analysis, Finding acquisition, Methodology, and Writing – original draftWriting- original. **Ashish Kumar Singh:** Validation, and Writing – review & editingWriting-reviewing & editing. **Sougata Karmakar:** Conceptualization, Project administration, 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. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ergon.2021.103135.

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