Design considerations for comfortable motorcycle riding posture: Ergonomics perspective

Thesis submitted in partial fulfillment for the

requirements for the degree of

Doctor of Philosophy

in

Design

by

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Guwahati – 781039, INDIA

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Declaration

I hereby declare that the work contained in this thesis entitled “Design considerations for comfortable motorcycle riding posture: Ergonomics perspective” is my work and done under the guidance of Dr. Sougata Karmakar, Associate Professor at the Department of Design, Indian Institute of Technology Guwahati, Assam, India. To the best of my knowledge, it contains no materials previously published or written by another person or substantial properties of the material which has been accepted for the award of any other degree or diploma at Indian Institute of Technology Guwahati or any other educational institution, except where due acknowledgment is made in the thesis. Any contribution made to this research by others, with whom I have worked at Indian Institute of Technology Guwahati or elsewhere, explicitly acknowledge in the thesis. I declare that the intellectual content of this thesis represents my work and words. I have adequately cited and referred to the original work where others’ ideas, work, and words have been included. I also declare that I have adhered to all principals of academic honesty and integrity and not misrepresented or fabricated or falsified any idea/ data/ fact/ source in my submission.

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Date: 22/05/2021

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Certificate

This is to certify that the work contained in this thesis titled “Design considerations for comfortable motorcycle riding posture: Ergonomics perspective” submitted by Mr. Arunachalam M to the Indian Institute of Technology Guwahati for the award of the degree of Doctor of Philosophy has been carried out under my supervision. This work has not been submitted elsewhere for the award of any other degree or diploma.

Place: IIT Guwahati

Date: 22/05/2021

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Arunachalam M

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Summary of the thesis

With the exponential growth of the population, the number of motorcycle users in India is increasing rapidly. This number was reported as 40 million by 2014 (Jog, 2016). Injures and accidental death due to motorcycle mishaps are in an upward trend in recent years in comparison to other modes of transportation. One major aspect associated with these accidents is the ignorance of proper consideration of human factor issues in motorcycle design. Out of various human factor issues, prevalent postural distress (Velagapudi et al., 2015; Jamson et al., 2009) among the Indian riders might be an important root-cause of these road accidents. Thus, it is essential for designers/ engineers to find the comfortable riding posture (CRP - which was perceived to be comfortable or no discomfort by the rider) and optimum riding position during the conceptual phase of motorcycle-design. Moreover, it is worthy to note that there are various databases on the CRP (based on comfort joint angles), anthropometry and range of motion (ROM) for four-wheeler drivers, but there is no reported similar database for motorcyclist in Indian context. Thus, it is very important for automobile industries to develop the databases on standard motorcycle rider's anthropometry and ROM, since standard motorcycles are more widely as mode of commute by the Indian riders.

The problem was addressed with the systematic approaches:

(a) Development of an instrument for measuring key dimensions of standard motorcycles.

(b) Considering the dimensional variations of standard motorcycles, the adjustable motorcycle test-rig and experimental set-up were constructed.

(c) With the help of an adjustable test-rig, CRP, and optimum riding position were estimated from the representative sample of the Indian motorcycle riders using perceived comfort/ discomfort ratings, image process techniques and Taguchi optimization techniques. The measurements were also tested for trustworthiness using alternate-form and intra-/inter observer reliability technique.

(d) Statistical analyses were used to establish the association between the rider's physical attributes (anthropometric, and ROM) and CRP and Comfortable riding position (RP - Position which was perceived to be comfortable or no discomfort by the rider).

It is expected that the findings on rider's anthropometry, ROM, CRP and optimum riding position will be immensely useful for automobile industries to design a new or redesigning of existing motorcycle to ensuring better comfort. Design of motorcycle based on the anthropometric and ROM data for defining optimal riding position and thereby comfortable riding posture would certainly reduce muscular discomfort/ pain of the motorcyclists.

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Chapter – 1: Introduction

Abstract:

A motorcycle is the vehicle of choice for most Indians in their daily commute to work. The motorcycles segment with 80% market share, is the leader of the Indian Automobile market owing to a growing middle class and a young population. Moreover, ever increasing interest of the companies in exploring the rural markets further aided the growth of the sector. Among various human factor issues, the prevalent postural distress among Indian riders might be an important root-cause for the motorcycling fatigue and motorcycle accidents. Unfortunately, this may be due to ignorance of target user's human factor engineering in the motorcycle design. The solution could provide better comfort at the design process (in conceptual stage) of a motorcycle to reduce discomfort. The present research scope in the domain of motorcyclist's posture evaluation includes the development of country/region-specific dataset for rider's anthropometry, range of motion and comfort joint angle etc. for the design of motorcycles. The present research would serve as a meaningful and valuable resource for the researchers engaged in automotive sectors with a special interest in motorcycle design.

1.1 **Overview of the motorcycles and its users in India**

The surveys by People Research on India's Consumer Economy (PRICE) (Shukla, 2016) revealed that one in three individuals in India owns a motorcycle. As a fact, for most Indians, motorcycles are considered the conveyance of choice in their day to day commuting. In India, 22% of people use a public bus, and 11% people use a metro or local train to reach their workplace. The proportion of the population that uses auto-rickshaws is higher than those uses personal vehicles and that uses rent cabs to commute in cities. A total of 37% of people use two-wheelers (scooters/ motorcycles) to reach their workplace (Bhattacharya, 2016). Furthermore, motorcycle use includes daily long-way commuting for traveling to offices and other work-related purposes that involve speed and time constraints such as fast food delivery, speed post, and police patrols. Moreover, a motorcycle is a necessary and an effective mode of personal transportation in India.

1.1.1 Motorcycles in India

The classification nomenclature of motorcycles are not uniform/ similar globally (Hale et al., 2007). However, the Society of Automotive Engineers (SAE J213, 2004) provides a classification method with symbols. This recommended practice offers uniform definitions for motorcycle classification. Nevertheless, this classification method could be difficult to understand for a common man when buying a motorcycle. Moreover, this method is used only by designers/ engineers in industries and not by users.

Figure 1. 1: Various type of motorcycles in India

Generally, in India, motorcycles are classified (into scooters, standard/ economy, sport, and cruiser) based on design styles and appearance (including engine capacity) (Jeyakumar and Gandhinathan, 2014). According to Jeyakumar and Gandhinathan (2014), motorcycles can be categorized into 4 (as shown in Figure 1.1) (1) scooters: engine (capacity <125 cc) mounted at the rear side and supports the upright riding posture, (2) standard/ economy motorcycle: engine (capacity 110–125 cc) mounted at the front side and supports the upright riding posture, (3) sports motorcycles: engine (capacity >250 cc) mounted at the front side and supports the forward lean riding posture, (4) cruiser motorcycles: engine (capacity >150 cc) mounted at the front side and supports the backward lean with leg forward riding posture.

According to the Society of Indian Automobile manufactures (SIAM members 2019), the need for standard motorcycles (with engine capacity of 110cc to 125cc) is 72%; the sports motorcycles (with engine capacity of 125cc to 250cc) is 27% ; and the cruiser motorcycle (with engine capacity of above 250cc) is 1%. Also, sales and exports trends of motorcycles are higher than the other motor vehicles (passenger car and commercial vehicle). This sector contributed to 2.5% (US$ 67 billion) to the country’s Gross Domestic Product (GDP) (US$ 2,652 billion) in 2016-17 (Miglani, 2019). Thus, these shows the noteworthiness of standard motorcycles, which front-mounted engine (capacity of 110cc to 125cc). In addition, several initiatives by the Government of India and the major automobile players in the Indian market expect to make India a leader in the motorcycle market in the world by 2020.

During these years, top sold standard motorcycles in India are Bajaj CT 100, Pulsar 150, TVS Jupiter, TVS XL Super, Star city, CB shine, Hero glamour, Passion pro, HF Deluxe, Hero achiever, and Splendour pro. These models belong to Hero, Honda, TVS, and Bajaj motorcycle companies, which are India's largest motorcycle manufacturers and remain the top brand in the motorcycle industry despite the fierce competition.

1.1.2 Motorcycle users in India

Usually, Regional Transport Office (RTO) of various states in India provides two types of licenses to the two-wheeler users. The first type is “with gear” (WG) license holders who are eligible to use both motorcycle and scooter. The second type is without gear (WOG) license holders who are eligible to use only scooters. Due to the unavailability of the actual number of two-wheeler (motorcycle/ scooter) users or separate number of WG and WOG license holders, it could be approximated equal to the number of two-wheeler (WG and WOG) license holders in India. Thus, the total count of two-wheeler users is 400 million (MRTH, 2018).

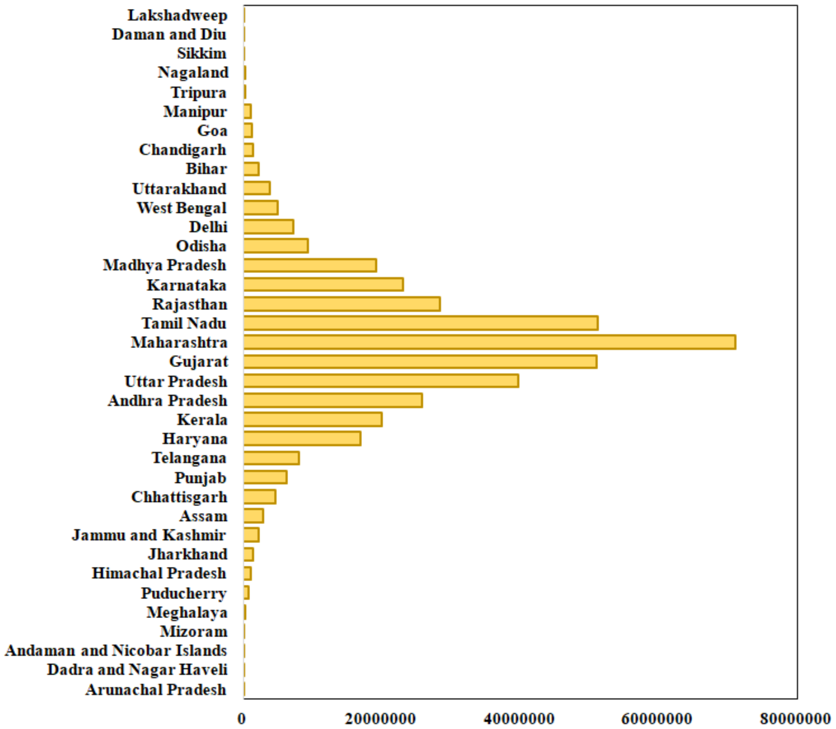

Figure 1. 2: State-wise motorcycle users in India (Source: Ministry of Road Transport and Highways 2010-2018)

The top 20 States and Union Territories (UT) with motorcycle users (Figure 1.2) include Maharashtra (7,10,22,105), Tamil Nadu (5,12,80,182), Gujarat (5,10,21,754), Uttar Pradesh (3,98,13,466), Rajasthan (2,84,93,271), Andhra Pradesh (2,58,71,776), Karnataka (2,30,62,078), Kerala (2,01,11,533), Madhya Pradesh (1,92,58,813), Haryana (1,69,89,710), Odisha (93,17,258), Telangana (80,31,016), Delhi (72,89,796), Punjab (63,05,321), West Bengal (50,06,875), Chhattisgarh (47,32,315), Uttarakhand (38,67,305), Assam (28,27,885), Bihar (23,16,713), and Jammu and Kashmir (21,88,280). While the bottom states/UT with motorcycle users include Chandigarh, Jharkhand, Goa, Himachal Pradesh, Manipur, Pondicherry, Tripura, Meghalaya, Nagaland, Mizoram, Sikkim, Andaman and Nicobar Islands, Daman and Diu, Dadra and Nagar Haveli, Lakshadweep, and Arunachal Pradesh.

According to the Indian Government survey conducted by the Ministry of Road Transport and Highways in 2018 (MRTH, 2018), the number of female (8%) two-wheeler (motorcycle/ scooter) users is very lower than that of the male counterpart (92%). Majority of the users are in the age range of 19–44 years. The RTO data was further analyzed by the present researcher using the regression method to understand the user trends (Figure 1.3). From Figure 1.3, it is understood that the percentage of female riders out of total riders (both male and female) are showing a decreasing trend with a negative slope (-0.43). It means that the increase in the numbers of male rider populations is relatively higher than female riders. Furthermore, most female users hold WOG licenses (i.e., they can use only scooters). By contrast, an increasing trend of male users is evident currently in India, and most of them hold WG licenses (i.e., they can use both motorcycles and scooters).

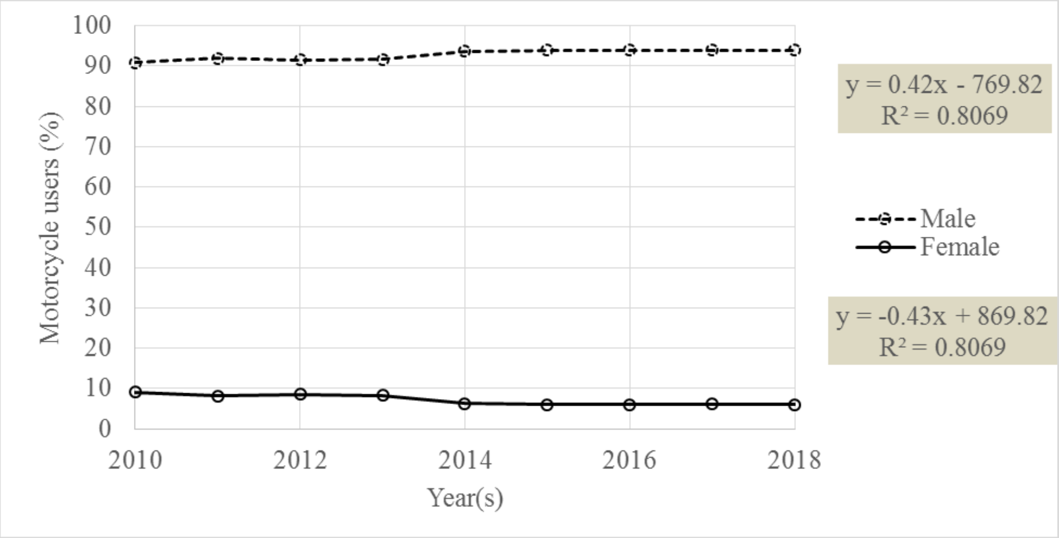

Figure 1. 3: Year(s) vs. percentage of female and male two-wheeler users in India

Altogether, the results of the data analysis showed that male motorcycle users (motorcyclist) with the age of 19–44 years are the most common users of standard motorcycles in India. Hence, the present study focuses on the predominant users (i.e. male riders with the age of 19-44 years) that could be appropriate for user-centered design approach of standard motorcycle in Indian scenario.

1.2 Literature review on motorcycle riding posture

Generally, a major cause of unnatural death is road mishap. As per reports, the incidence of fatalities with motorcycle is more as compared to any other automotive vehicles (Chang and Yeh, 2007; Ma'arof et al., 2015; Mohan et al., 2017; Robielos et al., 2012). The presumable causes of road causalities could be associated with motorcycles, its environment, and riders (Dhanabal et al., 2016).

Postural fatigue during riding a motorcycle, lack of skills, and drunken driving may be considered human factors linked with motorcycle causalities. Generation of awareness regarding riding safety and strict implementation of government laws can control drunken driving to some extent but proper training and practice can only improve lack of riding skills. The causes of postural fatigue during riding include damaged roads, bad weather conditions, and high vibration impact from the motorcycle, inappropriate riding posture, mental load, attitude and physiological aspects of the rider. In this context, it is extremely difficult to identify the most potential factor affecting the riding posture and thereby discomfort/ fatigue (Ma'arof et al., 2015). Despite of the fact that the motorcycle accidents are multi-dimensional phenomena, distressed riding posture is one of the primary reasons for the rider's muscular fatigue that leads to accidents (Balasubramanian and Jagannath, 2014; Dutta et al., 2014; Velagapudi et al., 2010).

To understand and define a comfortable and/or optimal motorcycle riding posture, researchers should know different postures adopted by riders for different motorcycles; factors affecting/ responsible for the adopted postures of motorcyclists; available tools and techniques for posture evaluation of the riders; available databases on motorcyclist physical characteristics (e.g.; anthropometry; total range of motion) and body joint angles during perceived comfort/ discomfort; posture prediction; and means for reducing postural discomfort produced during motorcycling. As the information regarding aforementioned topics is discrete in nature and not well documented in a single resource, the present research attempted to collect all the relevant information of the motorcyclist's posture and present it through a systematic review under different headings and subheadings to make this topic a meaningful and valuable one for the designers/ engineers/ researchers engaged in automotive sectors with a special interest in the motorcycle design.

The study of various factors affecting/ responsible for the motorcyclist's posture is essential to obtain a holistic view of the riding posture and how various human factors (e.g., physical characteristics, riding experience, duration of riding, cognitive load of riders), design characteristics of motorcycle and environmental variables (road, weather, and traffic conditions) affect the riding posture. If these factors negatively influence the rider's posture during riding, there is a probability of the rider perceiving postural discomfort. The long-term and short-term distress with respect to the posture, followed by muscular fatigue may lead to complications in simple maneuverability of the motorcycle, alteration in behavior and attention diversion while riding (Balasubramanian and Jagannath, 2014; Dutta et al., 2014; Velagapudi et al., 2010). All these factors are generally responsible for motorcycle accidents (Haworth and Rowden, 2006).

1.2.1 Rider (or motorcyclist) factors related with riding posture

Physical characteristics of the rider (age, anthropometrics, gender, etc.), riding experience, and riding duration are the main factors of the posture adopted during riding. Among these factors, anthropometrics (human body dimension) is a crucial factor considered when designing motorcycles.

The anthropometric dimensions required for the motorcycle design have been rarely reported from different countries. Many of the general population databases have not been mentioned about the number of drivers/riders in the sample size. It was observed that six key body dimensions were commonly taken into consideration while designing a motorcycle. These six anthropometric variables include knee height, stature, acromion to grip length, inner leg or crotch height buttock-knee length, and hip breadth (Paiman et al., 2014; Robertson and Minter, 1996; Stedmon et al., 2008). Moreover, secondary anthropometric dimensions such as thigh circumference, trunk height, knee opening dimensions, and popliteal to buttock length were also considered by few designers/ researchers (Paiman et al., 2014). Furthermore, few major anthropometric details, for example, acromion to the grip length and buttock-knee length, which are vital for the motorcycle design, are missing. Some attempts have been made to develop anthropometric datasets in a few countries such as the UK (Robertson and Minter, 1996; Stedmon et al., 2008), Nigeria (Lawrence, 2013), Malaysia (Paiman et al., 2014), and India (Amrutkar and Rajhans, 2011; Shamasundara and Ogale, 1999; Chakrabarti, 1997; Kulkarni et al., 2011). The country and region focused anthropometric dimensions of motorcyclists are vital for designing a two-wheelers for the User-Centered Design approach. In many of the countries, there is a lack of anthropometric database containing the key anthropometric dimensions. The use of general population's anthropometric dimensions as a replacement of the motorcyclist population might cause critical problems. For instance, anthropometric details can directly influence the falling height during an accident, as the center of mass factor differs between individuals (Lloyd, 2016). Moreover, researchers Robertson and Minter, 1996; Stedmon et al., 2008 have found that the anthropometric data of motorcyclists is significantly different from general population in UK.

The body mass index (BMI) of riders is a key factor of their lifestyle. BMI is associated/ correlated with the female driver's posture and is similarly considered for males (Karmegam et al., 2013). The force exerted by motorcyclists during riding increases with the flexion angle of their joint angles irrespective of their weight. However, lower weight (70 kg) riders may have relatively lesser angular change than the higher weight (100 kg) riders. The rider's weight is a crucial factor in determining their postural comfort (Ma'arof et al., 2012). Teenage motorcyclists having few years of riding experiences are prone to traffic errors and violations of traffic rules, irrespective of motorcycle types. The age and riding experiences has negative correlation with speeding behaviours of riders (Özkan et al., 2012). Robertson, 1987 stated that there are no significant differences in the patterns of postural discomfort for rider due to variation of age.

The riders experience is one of the influencing factors for response time to road condition (Praveen et al., 2009). This finding supports with Njå and Nesvåg, (2007) that speed, gender, age, lack of concentration are plausible causes that delays response time to control the motorcycle in traffic situation. Riding experiences of female and male motorcyclists have a positive correlation with perceived postural comfort. The correlation strength is mentioned as 0.9% to 2.6% for female and 1% to 3.2% for male (Karmegam et al., 2013). The riding hours and female motorcyclist's postural discomfort has a positive correlation, whereas in the case of male motorcyclists this correlation is marginal (Karmegam et al., 2013).

The seat reference point (SRP) is a position seen at the farthermost frontward and lowest point on a motorcycle seat. The SRP differs across seat types as well as models of motorcycle. The SRP could be considered an appropriate representation of the minimum seat height and the probable forward movement for posture adjustment for motorcyclists (Robertson, 1987). The rider's seating location is crucial for the position of displays and controls (Stedmon et al., 2011). The rider's seating location varies according to their sitting behavioral pattern, and it may also change with the seat depth and pan area during riding. Few studies have been carried out by the researcher on motorcyclist's seating comfort and contact surface pressure between rider and motorcycle (Koyano et al., 2003; Shafiei et al., 2015; Velagapudi and Ray, 2015). Literature survey reveals that there are negligible publications related to study of rider's seating behavior. None of the researcher investigated effect of seating behavioral pattern on rider's postural comfort and the strength of correlation between them

Riders wear protective clothing such as jackets/ full sleeve shirts, boots, and helmets. In certain countries including India, wearing a helmet is compulsory for riders' safety (Lin and Kraus, 2009; The Motor Vehicles Act, 1988). The cognitive performance of riders wearing a helmet is marginally affected (Bogerd et al., 2014; Liu et al., 1991). The motorcyclist's neck moment helps to come out of difficultly in viewing adjustable side mirrors (Ma'arof and Ahmad, 2012). In developed countries such as the USA and UK, protective riding jackets are mandatory. Many studies have assessed the thermal comfort of riders wearing a jacket (Bogerd et al., 2015; Farrington et al., 2004; Zwolińska, 2013). The jacket protects riders from poor weather conditions including the cold winter (Woods, 1986), which is a complete opposite to the scenario during the summer season (De-Rome et al., 2016). Many a times, tight clothing can reduce the ease of control operation and makes it difficult to view mirrors. The heavy boots may restrict foot movement (Robertson and Minter, 1996). None of the earlier studies have reported the correlation between the postural discomfort/comfort and rider's clothing (Ma'arof et al., 2012; Robertson et al., 2009).

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.).

Majority of the earlier researchers have kept aside rider's physical characteristics and other issues (seating behavior, type of clothing, and experience, driving duration) that might be considered as lead players in deciding the postural discomfort/comfort of the riders. Thus, exploration in these aspects is essential to ensure comfortable riding posture.

1.2.2 Design features of motorcycle and posture

The motorcycle is a fixed or non-adjustable mobile-workstation (vehicle) (COPE, 2002; Ma'arof and Ahmad, 2012; Robertson et al., 2009). Except side view mirrors, all other components (like seat and handlebar) are fixed in nature (SAE J1050, 2009). Other automobiles, such as trucks, off-road vehicles, and cars, provide varying arrangements to accommodate drivers for performing their activities with minimal postural discomfort. The motorcyclist has to perform tasks (like operation of throttle, front/rear brake, levering etc.) in a contained riding posture providing few forward motions with respect to motorcycles (Ma'arof and Ahmad, 2012). The rider's posture depends on the motorcycle's interface components (i.e., handlebar grip, seat or saddle, and footrest). The dimension/ size of these components and location/ placement are crucial for determining rider's postures (Faris et al., 2011; McInally, 2003; Rashid et al., 2014). Nevertheless, the fuel tank dimensions may also important and significant for determining the riding posture (Fauzi et al., 2015). Thus, all the interface components should be designed considering ergonomic principles.

Over the years, design of motorcycles have been improved in terms of safety features, reduction in vibration and shock, and coping up with unfavorable environmental conditions, etc. But, thorough investigations are required to minimize the postural discomfort of the riders (Ma'arof et al., 2014). Postural comfort can be achieved by providing adjustability features in the footrest and handle grip (Kolekar and Rajhans, 2011).

1.2.3 Impact of environmental variables on motorcyclist's posture

Under any circumstances, motorcyclists have to perform various functions such as stop, accelerate, or decelerate operations. Motorcyclists adopt their postures to stabilize motorcycles during acceleration/ deceleration or braking (Zhu et al., 2012). The deceleration/ acceleration pattern of riders depends on weather and road conditions and traffic flow. Rider's personal stress and riding behavior are also highly associated with speeding or risky driving (Watson et al., 2007). The cruiser motorcycles have commonly longer (larger) geometry as compared to other types. Postures of cruiser motorcyclists is prudently leaning backward supported, where body weight is transferred towards motorcycle's C.G during braking control behavior (Lenkeit et al., 2011). Whereas, in the case of electric scooters, braking control behavior is different from other motorcycles (Abumi and Murakami, 2015; Lai et al., 2003). The electric scooter's control task (deceleration or braking) may affect motorcyclists' upper limb leaning moments to retain balance (Abumi and Murakami, 2015). Consequently, their postural change is relatively higher than other types of motorcycles like cruiser. The deceleration/ braking behavior wasn't found correlated with individual rider factors (e.g. age, BMI, riding hours and riding experience etc.) (Lenkeit et al., 2011).

The road conditions such as flat/ plain and bumpy slope may also affect the motorcyclist's posture. The suspension system may absorb the impact of bumpy roads and vibration caused by unfavorable roads. The worst bumpy terrains including sandy, bumpy, or gravel roads may make damper systems inefficient. Some researchers investigated the efficiencies of different damper absorbers on whole-body vibrations during unfavorable road condition (Israr et al., 2007; Kharat and Dhande, 2015; Mirbod et al., 1997; Mohamad et al., 2014; Quadros et al., 2013; Shivakumara and Sridhar, 2010; Tathe and Wani, 2013). The effect of vibrations on motorcyclists depended on not only suspension systems but also motorcycle aerodynamics, gyroscopic, and tire type (De-Molina, 1989; Moreno et al., 2011). Riders' age, size and weight are used for prediction of vibration exposure of the motorcyclist. According to Robertson (1987), there is no significant difference in the patterns of postural discomfort among classes of motorcycle and engine capacities.

Diyana et al., 2017, showed that prolong static sitting and exposure to vibrations from motorcycles may cause musculoskeletal disorders, especially in the neck, shoulder, and lower back. Furthermore, motorcycle features were highly responsible than human factors for postural discomfort. Therefore, designing a motorcycle with effective features may be a feasible solution to address the unfavorable effects of traffic and road conditions on riders. For instance, Agostoni et al. (2012) made design interventions on a motorcycle's handlebar to reduce transmission of vibration to the rider's hand and arm. Although the effect of weather/night-day conditions on driving posture and performance have been studied by Bella et al., 2014 in case of four-wheeler vehicles but similar studies on motorcyclist postural change has not been reported by the researchers.

1.2.4 Posture analysis of motorcyclists

The purpose of posture analysis is to assess the degree of comfort/discomfort of the motorcyclists and recommend design interventions enhance comfort during riding. The analysis may be performed using DHM (Digital Human Modelling) in virtual environment, subjective assessment using questionnaire and objective evaluation using equipment/ assessment tools. The postural distress can be evaluated using various equipment e.g. electromyography (EMG), heart rate monitor, goniometer etc. and postural evaluation tools such as Rapid Upper Limb Assessment (RULA), Rapid Entire Body Assessment (RABE), Ovako Working posture Assessment System (OWAS), stain index, Quick Exposure Checklist (QEC) and so on.

1.2.4.1 Comfort/Discomfort analyses using DHM

DHM approach is cost-effective and performed to evaluate the rider's posture before developing physical mock-ups or prototypes (Kumar et al., 2013). Its pre-requisites includes CAD models of human, CAD model of vehicle and interfacing them following various references points (Jung et al., 2009). Reference points for vehicles (motorcycle/ car) are hip-joint point (H-point) (JASO T006:2007, 2007), seating-reference point (SgRP) (SAE J1100, 2009), and accelerator-heel point (AHP). These reference points are usually utilized in ergonomics evaluation of passenger vehicle (motorcycle/car) and proactive design (Bhise, 2011; Cucinotta et al., 2019; Macey and Wardle, 2009).

In DHM software platforms, posture analysis can be performed by defining comfort range of joint angles within the total range of motion (ROM). Some of the DHM software (e.g. Jack) consist of default ROM values which were used in industrial applications (Delleman et al., 2004). Researchers are consistently pursuing DHM based researches towards improving automobile design and ensuring more comfortable driving postures (Andreoni et al., 2002; Schmidt et al., 2014). Degree of comfort/ discomfort differs from posture to posture (Apostolico et al., 2014; Kölsch et al., 2003). As there is no ROM database specifically for motorcyclist population, ROM database of general population (Chakrabarti and NID, 1997) is commonly consulted for motorcyclist posture evaluation.

Similar to ROM, the rider's comfort joint angle details have not been studied. However, some of the researchers defined the scooter-rider's posture with eight joint angles (Figure 1.4). Researchers used goniometer and faro-arm equipment to measure the rider's joint angles while riding scooter (Barone and Curcio, 2004; Barone and Lo Iacono, 2015; Chou and Hsiao, 2005; Lawrence, 2013). Since these studies involved different type of scooters/ motorcycles as well as different study population, results of motorcyclist's comfort joint angle reported by various researchers differ by about 10-degree.

The ROM and comfort joint angle databases of motorcyclists have not been developed for many countries. Adoption of such databases from one country may not be appropriate for designing motorcycles in another country Moreover, most of the DOF data are missing data in the country-specific databases. Hence, there is urgent need of developing country-specific databases for ROM and comfort joint angle that could be utilized for defining appropriate representative manikin for motorcyclist for a particular country. This manikin will help in proactive evaluation of motorcyclist's posture to estimate level of comfort/ discomfort.

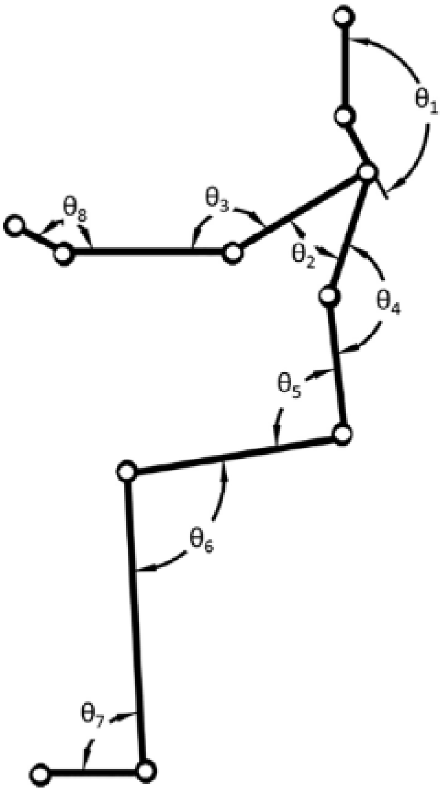

Figure 1. 4: postural Joint angles studied by the researches for scooter

1.2.4.2 Postural discomfort/comfort studies using equipment, posture evaluation tools and questionnaires

In general, REBA (Hignett and McAtamney, 2000), OWAS (Karhu et al., 1977), RULA (McAtamney and Corlett, 1993), workplace ergonomic risk assessment (WERA), QEC (David et al., 2008), and MODSI (simple model for comprehensive risk evaluation of musculoskeletal disorders) (Manero Alfert et al., 2011) are the most commonly used postural evaluation tools in the industry and academia. Limitations and assumptions were diverse for these tools. Few earlier studies related to posture evaluation of vehicle driver/ motorcycle rider have used QEC, RULA, REBA and WERA as posture evaluation tools (Ma'arof et al., 2012; Ramasamy et al., 2017; Stedmon, 2018). These investigations failed to explain the reason for using/ selecting a particular posture evaluation tools in that study. These tools are commonly involve extension/flexion of major body parts (neck, legs, etc.). However, other degree of freedom e.g. the adduction/ abduction of thigh/ arm which is very crucial for defining motorcyclist's posture were not considered in these tools during posture evaluation (Manzato et al., 2013; Massaro et al., 2012). Thus, the efficiency of these postural analysis tools in the rider's posture assessment is questionable.

Research articles revealed that researchers used customized closed-ended type questionnaire for studying motorcyclist's discomfort/comfort. Earlier reported studies deployed a RGB pain scale, a Likert rating scale of 5 or 7 points (Karmegam et al., 2013, 2009; Karuppiah et al., 2012; Sai Praveen and Ray, 2015), and a Borg's scale (Karuppiah et al., 2012; Mathurkar, 2016). Discomfort and comfort are two opposite measures, which should be recorded with a 11 point-Likert rating scale for an effective measurement (Fatollahzadeh, 2006). Apart from the Likert rating scale, discomfort/comfort ranking system and visual discomfort/comfort scale were also frequently applied in pain assessments (Haefeli and Elfering, 2006). (Haefeli and Elfering, 2006). Not all these interval scales are effective to measure the discomfort and comfort. The questionnaire which comprises free modulus measure method of measurement system is efficient enough and reduces the biases of interval scale system (Kee and Karwowski, 2001).

1.2.4.3 Postural comfort/discomfort studies using equipment

Apart from questionnaire studies, posture comfort level can be studied by bio-signal based equipment like electromyography (EMG) and heart rate (HR) monitor (Delleman et al., 2004). The HR monitor is used to find posture discomfort in terms of physiological distress and thereby altered HR (Talib et al., 2015). The riding duration and rider's heartbeats per minute (bpm) are considered to determine motorcyclist performance and postural comfort. As the heart rate is affected by psycho-social factors, estimation of postural comfort/ discomfort based on heart rate is sometimes mistaken (Palatini and Julius, 1999; Talib et al., 2015; Wu et al., 2004). Hence, HR is not considered as appropriate equipment for posture studies. Therefore, Fauzi et al., 2015 proposed that EMG and HR may be used together during posture studies.

EMG signals were used to estimate postural fatigue based on the performance of the rider's skeleton muscles. EMG studies were more effective than HR investigation. Many researchers have assessed rider's postural discomfort/comfort in terms of EMG activity of various muscles (Balasubramanian and Jagannath, 2014; Ma et al., 2003; Marina et al., 2011; Rashid et al., 2015a, 2015b; Velagapudi et al., 2010). Variables and muscles considered were more or less similar in such studies. Mean power frequency (MPF), RMS amplitude, maximal voluntary contraction (MVC), and median frequency (MF) are the variables considered for these studies. The muscle groups involved while riding are upper trapezius, erector spinae, triceps brachii, extensor, carpi radialis, latissimus dorsi, gastrocnemius, sternocleidomastoid, and biceps femoris.

1.3 Summary of literature review and research gap diagram

Available information related to motorcyclist's posture has been presented above in the four sub-heading entitled as (a) Rider (or motorcyclist) factors related with riding posture, (b) Design features of motorcycle and posture, (c) Impact of environmental variables on motorcyclist's posture and (d) Posture analysis of motorcyclists.

Literature review includes all possible influencing factors, which directly or indirectly affect rider's posture. Based on available literature, present researcher has tried to demonstrate the impact of various human factors (physical characteristics, riding experience, duration of riding, cognitive load etc. of the rider), design characteristics of motorcycle (dimension and location of interface components, motorcycle age, suspension systems, type of tyres, aerodynamic form etc.), and environmental variables (road, weather and traffic conditions) on rider's perceived comfort.

Also, it is evident from the literature that very limited researches have been carried out towards proactive posture evaluation of motorcyclists in CAD environment. Present research has highlighted various research gaps pertaining to user-centred design of motorcycles. Ergonomic aspects should be considered in the early stages of motorcycle design process to ensure better riding posture. Country specific anthropometric, ROM and comfort joint angle databases for motorcyclist are still lacking for most of the countries. This hinders the proactive assessment of motorcycles during the design process. Thus, future research scope in the domain of motorcyclist's posture evaluation include development of such anthropometric, ROM and comfort joint angle databases. Some literature showed the posture evaluation of vehicle driver/ motorcycle rider using the QEC, RULA, REBA and WERA as posture evaluation tools. However, the competence of these tools in the motorcyclist's posture assessment is still doubtful. Out of various objective evaluation (indirect) methods of postural comfort/discomfort, electromyography (EMG) study has been found as the most reliable one due to its independency on psychosocial factors.

Based on the aforementioned literature review, various research gaps identified for exploration is illustrated in Figure 1.5. Research questions corresponding to these research gaps have been denoted as “RQ” (1–7 in Figure 1.5). All research questions are presented in subsection 1.5.

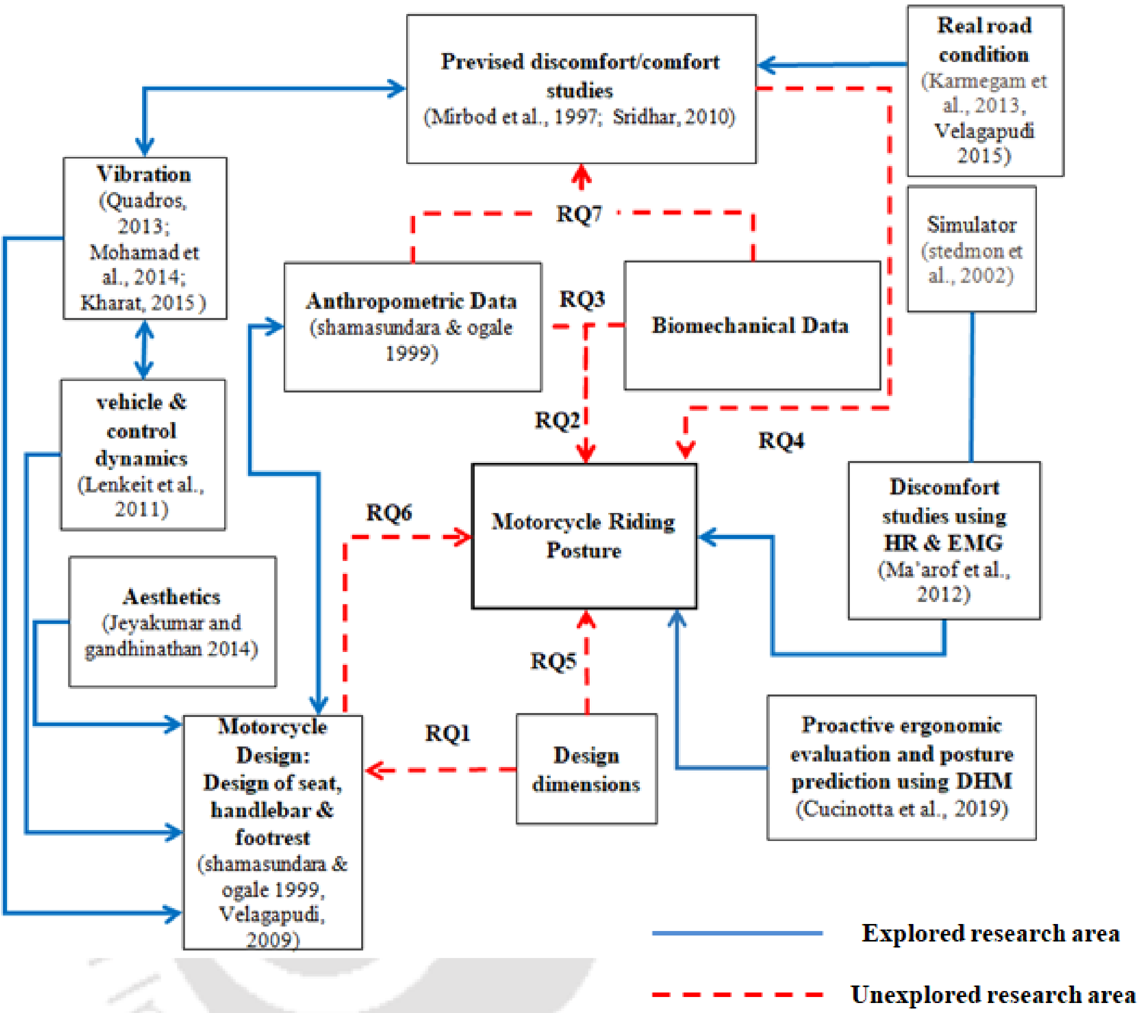

Figure 1. 5: Identified research gaps for the present research topic

1.4 Motivation and Justification for choosing the present research

Worldwide, a few comfort joint angle databases are available for motorcycle riders (mopeds/ motorcycle). However, no published paper/ patent regarding the optimal riding position of standard motorcycle is available to ensure comfortable posture. Furthermore, Velagapudi et al., 2015 stated that 85% of the study subjects (221 Indian riders) feel discomfort on road motorcycling. Motorcycling fatigue could be a key factor for motorcycle accidents in India (Arunachalam et al., 2020). In addition, it is evident from the literature review there is lack of postural studies related to motorcycle riders. Thus, this research work contributes to fill, research gaps available in standard motorcycle’s posture in context of Indian male riders.

1.5 Research questions (RQ)

RQ1: What are the standard or traditional dimensions practiced/ followed for designing three interface points (handlebar, seat, and footrest) in a motorcycle?

RQ2: What are the key anthropometric and ROM variables that define the physical characteristics of Indian male motorcyclists?

RQ3: What is the percentage difference of anthropometry and ROM variables between the Indian male motorcyclists and other international/ national databases (motorcyclist/ driver and the general Indian population)?

RQ4: How can we define the comfortable riding posture [†](CRP) for a motorcyclist in terms of comfort joint angles?

RQ5: How can we define the optimum riding position in terms of interface point’s (handlebar/ grip, seat, and footrest) dimensions of a motorcycle?

RQ6: Which are the principal factors (from a larger set of variables) that explaining/ representing most of the variance of comfortable riding posture (CRP) and comfortable riding position [‡](RP)?

RQ7: How are the association of anthropometric, and range of motion variables with CRP and RP?

1.6 Problem statement

One major aspect associated with various road-accidents is the ignorance of proper consideration of human factors in motorcycle designs. Among various human factors, prevalent postural distress in Indian riders might be the root cause of road accidents. Worldwide, few comfort joint angle databases of the motorcycle (mopeds/motor-motorcycle) riders are available (Barone and Curcio, 2004, Chou and Hsiao, 2005). Existing studies only have dealt with flexion/ extension angles of the body joints. Adduction/ abduction and rotational angles have not been considered in the reported studies; however, these angles are also crucial for defining postural comfort. No published literature and patent regarding an optimal position for a standard motorcycle to ensure postural comfort is available.

[†] CRP – Posture which was perceived to be comfortable or no discomfort by the rider.

[‡] RP – Position which was perceived to be comfortable or no discomfort by the rider.

Hence, study is planned to investigate the postural comfort of motorcycle riders, specifically for the riders of standard motorcycle which are most commonly used in India. During motorcycle riding, the rider's posture undergoes dynamic changes due to various factors including road conditions, traffic conditions, and vehicle characteristics. To delimit the research in the aforementioned direction, the static riding posture under controlled laboratory conditions has been considered to avoid the complex involvement of numerous influencing factors.

About 85% of Indian riders feel discomfort on real roads (Velagapudi et al., 2015). This postural discomfort may be caused by incompatibility between the rider's anthropometry and motorcycle's dimensions. This incompatibility might have impact on body joint angles, which deviate from comfort range of movement. In Indian scenario, there is requirement of developing comfort joint angle database for motorcycle riders to provide design guidelines to determine optimal riding position (handlebar point, footrest point and seat point) for motorcycle.

1.7 Aim

To find the association between the rider's physical attributes (anthropometry and ROM) and comfortable riding posture (CRP) or comfortable riding position (RP) for ergonomic design of the standard motorcycle.

1.8 Objectives

Obj 1. To study the dimensional variations in three interface parts/points (handlebar/ grip, seat, and footrest) in existing motorcycles.

Obj 2. To study the most influential anthropometric and ROM variables that define the physical characteristics of Indian male motorcyclists.

Obj 3. To identify the optimum riding position in terms of interface point's (handlebar/ grip, seat, and footrest) dimensions of a motorcycle.

Obj 4. To define the motorcyclist's comfortable riding posture (CRP) in terms of comfort joint angles.

Obj 5. To determine the principal factors (from a larger set) contain most of the information in explaining/ representing CRP (joint angles) and RP (comfortable riding position).

Obj 6. To study the relationship of anthropometry and range of motion variables with the comfort table rider posture, as well as with comfortable riding position.

1.9 Hypothesis

Based on research questions, a hypothesis formulated which was further into two working hypotheses,

Hypothesis: The comfortable riding posture (CRP) and comfortable riding position (RP) might be significantly associated with anthropometric and ROM variables of the motorcyclists.

Working Hypotheses 1:

Null Hypothesis 1 (H_1): The CRP is not significantly associated with the anthropometric and ROM variables of the motorcyclists.
Alternative Hypothesis 1a (H_{1a}): The CRP is significantly associated with the anthropometric and ROM variables of the motorcyclists.

Working hypotheses 2:

Null hypothesis 2 (H_2): The RP is not significantly associated with the anthropometric and ROM variables of the motorcyclists.
Alternative hypothesis 2 (H_{2a}): The RP is significantly associated with the anthropometric and ROM variables of the motorcyclists.

1.10 Expected outcome

I. Database of the key dimensions of the motorcycles popularly used in India.
II. Indian motorcyclists' anthropometric and range of motion database.
III. Defining the comfortable riding posture based on perceived comfort joint angles of the Indian male motorcyclists.
IV. Defining the optimal riding position in terms of interface point's (handlebar/ grip, seat, and footrest) dimensions

1.11 Framework of the thesis

Based on the study workflow, the thesis report is divided into six chapters. Figure 1.6 illustrates a brief workflow. The overview of the research questions, objectives, and hypotheses addressed in the individual chapters, is depicted in Table 1.1. Subsection 1.11.1 presents the summary of each chapter.

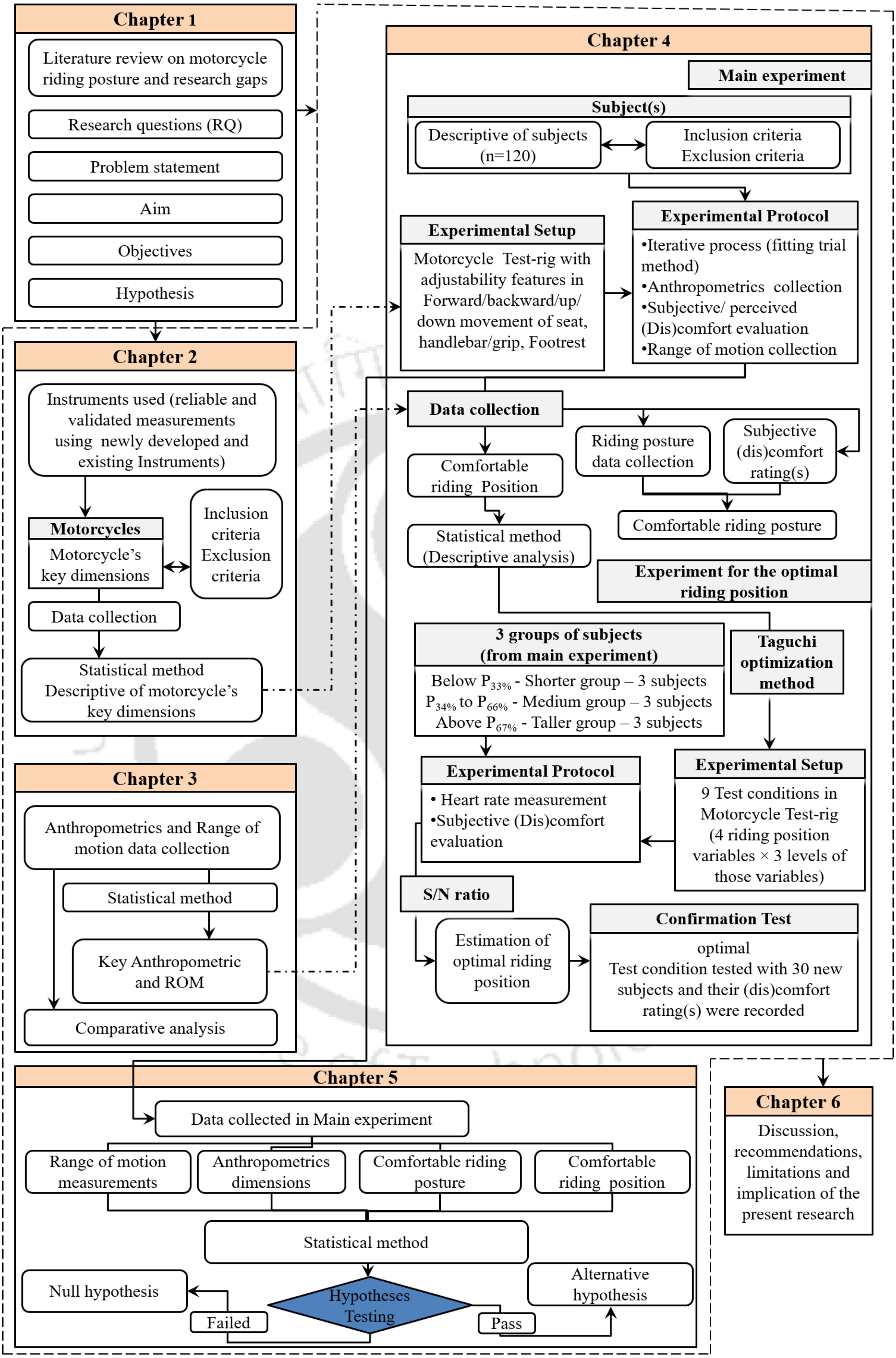

Figure 1. 6: Thesis workflow and content of various chapters

Table 1.1: Research questions, objectives, hypothesis - organized in various chapters and publications

Chapter No.	Research Questions	Objectives	Hypothesis	Publications
II	**RQ1:** What are the standard or traditional dimensions practiced/ followed for designing three interface points (handlebar, seat, and footrest) in a motorcycle?	**Obj 1.** To study the dimensional variations in three interface parts/points (handlebar/ grip, seat, and footrest) in existing motorcycles	Gathering information related to motorcycle's key dimensions which supported to prove Hypothesis **H_{1a}** and **H_{2a}** ↓	Arunachalam, M., Mondal, C., Karmakar, S. (2020). Field measurement of the motorcycle's key dimensions using simple method and in-house fabricated instrument. Instrumentation Mesure Métrologie, Vol. 19, No. 4, pp. 263-272.
III	**RQ2:** What are the key anthropometric and ROM variables that define the physical characteristics of Indian male motorcyclists? **RQ3:** What is the percentage difference of anthropometry and ROM variables between the Indian male motorcyclists and other international/ national databases (motorcyclist/ driver and the general Indian population)?	**Obj 2.** To study the most influential anthropometric and ROM variables that define the physical characteristics of Indian male motorcyclists	Gathering data related to anthropometric dimensions and ROM measurements which was used as the independent variables to prove Hypothesis **H_{1a}** and **H_{2a}** ↓	Arunachalam, M., Ashish Kumar Singh and Karmakar, S. "Determination of the key anthropometric and range of motion measurements for the ergonomic design of motorcycle." Measurement, 159, 1-18 (2020.
IV	**RQ4:** How can we define the comfortable riding posture (CRP) for a motorcyclist in terms of comfort joint angles? **RQ5:** How can we define the optimum riding position in terms of interface point's (handlebar/ grip, seat, and footrest) dimensions of a motorcycle?	**Obj 3**. To identify the optimum riding position in terms of interface point's (handlebar/ grip, seat, and footrest) dimensions of a motorcycle **Obj 4**. To define the motorcyclist's comfortable riding posture (CRP) in terms of comfort joint angles.	Gathering measurements related to CRP/ RP which was used as the dependent variables to prove Hypothesis **H_{1a}** and **H_{2a}** ↓	Arunachalam, M., Mondal, C., Singh, G. and Karmakar, S. "Motorcycle riding posture: A Review." Measurement, 134, 390-399 (2019). [SCIE/Scopus Indexed] Arunachalam, M., Singh, A.K. and Karmakar, S., 2021. Perceived comfortable posture and optimum riding position of Indian male motorcyclists for the short-duration riding of standard motorcycles. International Journal of Industrial Ergonomics, 83, 103135. Arunachalam, M., Singh, A.K. and Karmakar, S., 2021. Exploring the association of riders' physical attributes with comfortable riding posture and optimal riding position. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering. [In Press].
V	**RQ6:** Which are the principal factors (from a larger set of variables) that explaining/ representing most of the variance of comfortable riding posture (CRP) and comfortable riding position (RP)? **RQ7:** How are the association of anthropometric, and range of motion variables with CRP and RP?	**Obj 5.** To determine the principal factors (from a larger set) contain most of the information in explaining/ representing CRP (joint angles) and RP (comfortable riding position) **Obj 6.** To study the relationship of anthropometry and range of motion variables with the comfort table rider posture, as well as with comfortable riding position	**Testing of Hypothesis 1 (H_{1a}):** The CRP is significantly associated with the anthropometric and ROM variables of the motorcyclists. **Testing of Hypothesis 2 (H_{2a}):** The RP is significantly associated with the anthropometric and ROM variables of the motorcyclists.	

1.11.1 Brief of chapters

A brief summary of the study divided into six chapters in the thesis is as follows:

Chapter–1: Introduction (present chapter)

The first chapter focuses on the importance of two-wheelers in daily life activities in India, classification of two-wheelers, exports/ sells trends of motorcycle industries, and its effect on India's GDP, prospects of motorcycle users (motorcyclist) in India. It describes the problem related to the motorcyclists' posture, which is one of the indicators of motorcycling fatigue and fatalities. It reviews the existing literature related to motorcyclist posture and summarizes the research gaps. The research questions, aim of present research, objectives to achieve the aim, hypotheses, and framework of the thesis are also presented in this chapter.

Chapter–2: Field measurement of the motorcycle's key dimensions using simple method and instrument

The second chapter describes the comprehensive observation of motorcycle's key dimensions obtained using simple method and new instrument. This chapter describes the need for developing a new instrument for measuring the key dimensions of motorcycle. The design-development process and calibration of new instruments are comprehensively disclosed here. The new (in-house fabricated) instrument was tested and validated using an accuracy analysis before data collection from fields (motorcycle showrooms).

Chapter–3: Determination of key anthropometric and range of motion measurements for the ergonomic design of motorcycles

The third chapter describes the investigation details of motorcyclist's anthropometric and ROM measurements. This chapter covers tools, techniques, and methodology used for anthropometric and ROM measurements during the survey. The precision of the measurement techniques was ensured through reliability tests. The sample size estimation and number of subjects from each state has been defined. The dimensional reduction analyses led to achieve one of the objectives which also helped to answer the research question. A comparative analysis has been performed to understand the difference between general and motorcycle population. These results and findings has been explained and discussed with other similar studies.

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Chapter–4: Comfortable posture and optimum riding position for designing a motorcycle

The fourth chapter presents the assessment details of motorcyclist's comfortable riding posture and position. This investigation was performed through the experimental protocol in a test rig, which provides a wide range of adjustability in handlebar, footrest, and seat. Image processing technique was used to extract the information regarding riding postures and positions. Comfort and discomfort rating scales were used to observe perceived discomfort/comfort during experimental trials. All the measurements and observations were assessed for trustworthiness using reliability methods. The comfortable riding posture (CRP) were estimated using a rating weighted procedure. The Taguchi design of experiment was followed to obtain the optimal riding position. The findings of present research were compared, explained, and discussed with the observations of other earlier researches.

Chapter–5: Association between comfortable riding posture/position and anthropometric and range of motion among motorcyclists

The fifth chapter contains the investigation pertaining to the study of relationship of anthropometry and ROM variable with the comfortable rider posture (CRP), as well as with comfortable riding position (RP). This investigation used earlier (chapter 3 and 4) experimental data and observations to test the hypotheses. The data analysis method involved principal component analysis, Pearson correlation analysis, and multiple regression methods. Relationships between the CRP/RP and rider's physical attributes (anthropometric and ROM) were revealed. Findings of present research could eventually be applied to motorcycle design by the engineers/ designers to improve user satisfaction.

Chapter–6: Discussion, recommendations, and implication of the present research

The sixth chapter provides the novelties and key findings of this thesis. The fulfillment of objectives and testing of hypotheses were also depicted here. This chapter covers the recommendations and suggestions for motorcycle designers from the perspective of ergonomics and outlines the limitations and future scope of the study.

Chapter – 2: Field measurement of the motorcycle's key dimensions using simple method and instrument

Abstract

Background: Out of many plausible causative factors for the spike in accidents, un-headgear, drunk-ride, and lack of riding skills are reported to be the significant reasons for motorcycle mishaps. While the implementation of strict rules and regulations may control many of these issues, riding skills can only be improved through better availability of training facilities. The use of the simulator for training purposes is minimal due to a lack of awareness along with the high cost of the commercially available simulator. Non-availability of the dimensional database (of different types of motorbikes), which are essential for simulator design. Moreover, the available measuring techniques and devices are not only costly but also unable to satisfy diverse requirements of motorcycle measurement. Objective: The present research aimed to study the dimensional difference in three interface parts/points (of handlebar/ grip, seat, and footrest) and prepare the dimensional database of motorcycles using a newly developed measuring instrument. Method: Following the adaptive design method, the alpha prototype of new measuring instrument was developed. The instrument was calibrated and used for measuring the dimensions associated with the handlebar, seat, and footrest of the motorcycles. Also, detailed dimensions (like angular measurement, diameter) of handlebar, seat, and footrest were measured using sliding callipers and protractors. Results: Totally, 23 motorcycles' 18 critical dimensions of handlebar, seat, and footrest were found. Conclusions: The developed dimensional database of the different motorcycles could be useful for constructing a adjustable-motorcycle simulator.

2.1 Introduction

A total of 49% of all road traffic deaths occur among motorcyclists, cyclists, and pedestrians (Bacci, 2017). Of the aforementioned 49% of road traffic deaths, 23% are motorcycles, which means 125 billion people die every year. Especially in South Asia and the Western of WHO regions, motorcycle traffic deaths are 34% higher than other areas like Europe, the Americas, Africa, and Eastern Mediterranean (World Health Organization, 2015). The number of motorcycle users is increasing rapidly worldwide, especially in South Asia. In South Asia, the rate of motorcycle-related accidental deaths and injuries is considerably higher than that of accidents related to other road vehicles (World Health Organization, 2015).

The cause of death among aged 15-29 years and 3 out of 4 road deaths are among men. The causes of traffic deaths include drunken driving, lack of driving skills, high-speed driving, and lack of helmet use. The main causes of motorcycle accidents are the lack of helmet use, lack of riding skills, and drunk riding. Few of these reasons are strictly enforced by law in south-Asian counties like India, chain, Malaysia, etc. The use of law enforcement in drink and driving death rates reduced by 20%. While the implementation of strict rules and regulations may control many of these issues, riding skills can only be improved through better availability of training facilities.

Motorcycle riding skills can be enhanced using a motorcycle simulator. However, due to lack of awareness and the high cost of commercial motorcycle simulators, the use of simulator training is limited in the South Asia. The Postura Motergo (Ma'arof et al., 2015), MORIS Motorcycle Simulator, Honda Smart Trainer, and University of Padova Motorcycle Simulator are used in Malaysia and India for motorcycle training. Moreover, it has also been found that there is a lack of credible information like research publications on motorcycle dimensions.

Non-availability of the dimensional database (of different types of motorbikes), which is essential for simulator design, is the main hindrance of developing the low-cost locally manufactured simulators. Moreover, the available measuring techniques and devices are not only costly but also unable to satisfy diverse requirements of motorcycle measurement. Hence, the present research aimed to develop an easily portable and affordable measuring device for motorcycles and to use the same for preparing the dimensional database of different standard motorcycles. These measurements will help to address the research question (RQ).

RQ1: What are the standard or traditional dimensions practiced/ followed for designing three interface points (handlebar, seat, and footrest) in a motorcycle?

2.2 **Method**

The study method followed the consequent steps to accomplish the objectives

I. Selection of key dimensions of the motorcycle

II. Market and literature survey on existing instruments to measure the key dimensions

III. Design and development of new device via the adaptive design process

IV. Testing of the new device for accuracy on the field through the standardized operation/measurement procedure

V. Descriptive statistical analysis using IBM SPSS 24.0 for all the key dimensions

2.2.1 Key dimensions and landmark's definition

According to ISO 11432: 2002 standards, Plans, and axis of the motorcycle are defined as shown in Figure 2.1, which must be considered during the measurement of the motorcycle's key dimensions.

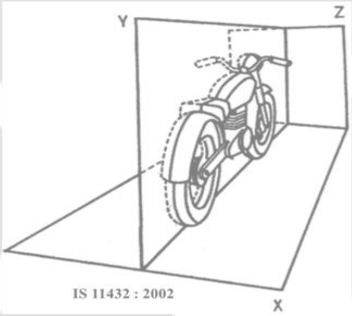


Figure 2. 1: Definition of planes and axis of the motorcycle

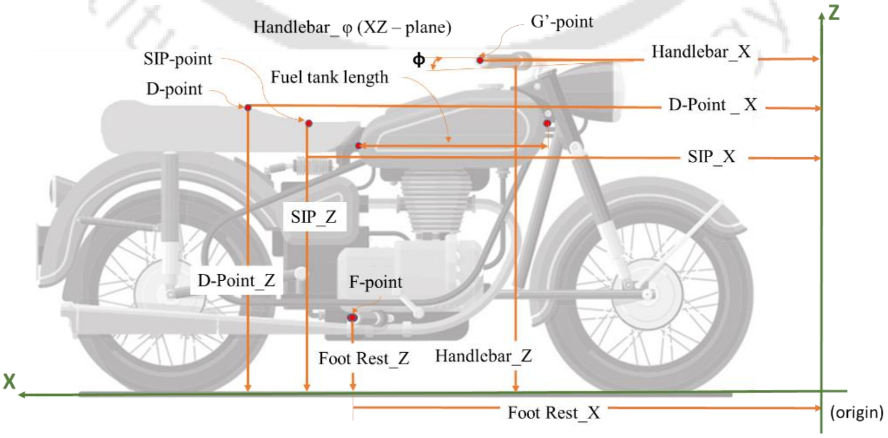
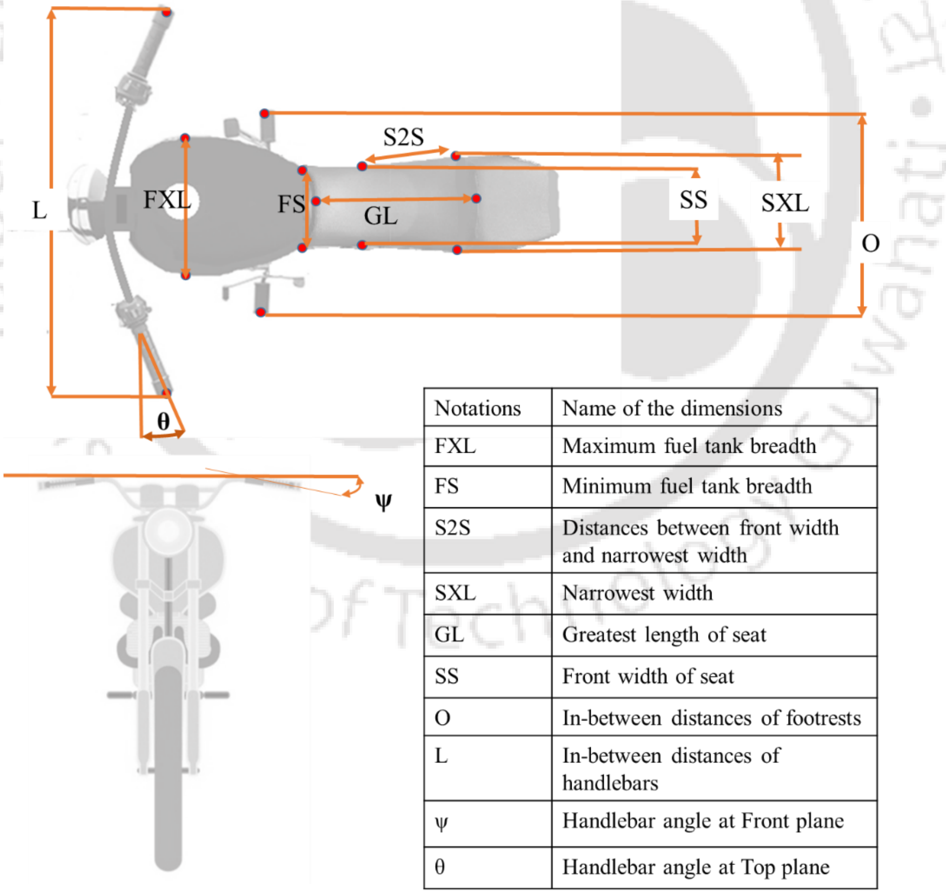


Figure 2. 2: Definition of motorcycle's key dimensions at the XZ plane. Note: Interface points - G'-point (Handlebar), SIP and D-point (Seat) and F-point (Footrest)

Eight key dimensions were measured at the xz plane (Figure 2.2), which are recognized from the early published research articles (Hale et al., 2007; Kolekar and Rajhans, 2011)(Sabbah and Bubb, 2008). These dimensions were measured via landmarks such as SIP (also called SRP), D-Point, origin point, and Footrest (F-point). These landmarks locations were defined as below by the previous research articles. The seat reference point (SIP or SRP) is a notional location corresponding to the furthest forward position on the seat and the lowest point on the seat (Robertson and Porter, 1987). F-point is located at the central and the farthest end of the usable portion of the footrest from the longitudinal median plane of the motorcycle. G'-point is located at the central and the farthest end of the usable portion of the handlebar/grip. 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 (JASO T003:2009). Fuel tank length was measured between the extreme corner points of the fuel tank at the xz plane. The origin point is located at a distance of 100cm along the X-axis and 35cm from the floor (ground) (as per Hale et al., 2007; Sabbah and Bubb, 2008).



Notations	Name of the dimensions
FXL	Maximum fuel tank breadth
FS	Minimum fuel tank breadth
S2S	Distances between front width and narrowest width
SXL	Narrowest width
GL	Greatest length of seat
SS	Front width of seat
O	In-between distances of footrests
L	In-between distances of handlebars
ψ	Handlebar angle at Front plane
θ	Handlebar angle at Top plane

Figure 2. 3: Definition of motorcycle's key dimensions of handlebar, seat, fuel tank and footrest

Since the remaining ten dimensions (as shown in Figure 2.3) also require for the basic construction of motorcycle simulators (Ma'arof et al. 2015). The dimensions were measured using a standard procedure which recognized in the previously published research articles (Mansfield and James, 2001) (JASO T102-84, 1975; SAE J 1241, 2012; SAE J30, 1998). These dimensions were measured through landmarks in handlebar, seat, fuel tank, and footrest. The measurement protocol of these dimensions was followed as per the aforesaid research articles. Large sliding calliper (GPM anthropological instruments model 101; range: 0 –150cm and accuracy of ± 0.01cm) was used to measure the FXL, FS, S2S, SXL, SS, L and O. Tape (Size: 150cm x 13cm (L*W)) was used to measure the GL and angular (ϕ, θ and ψ) measurement were recorded using large protractor (Model name: Thermo – Protractor and Size 28 × 28cm).

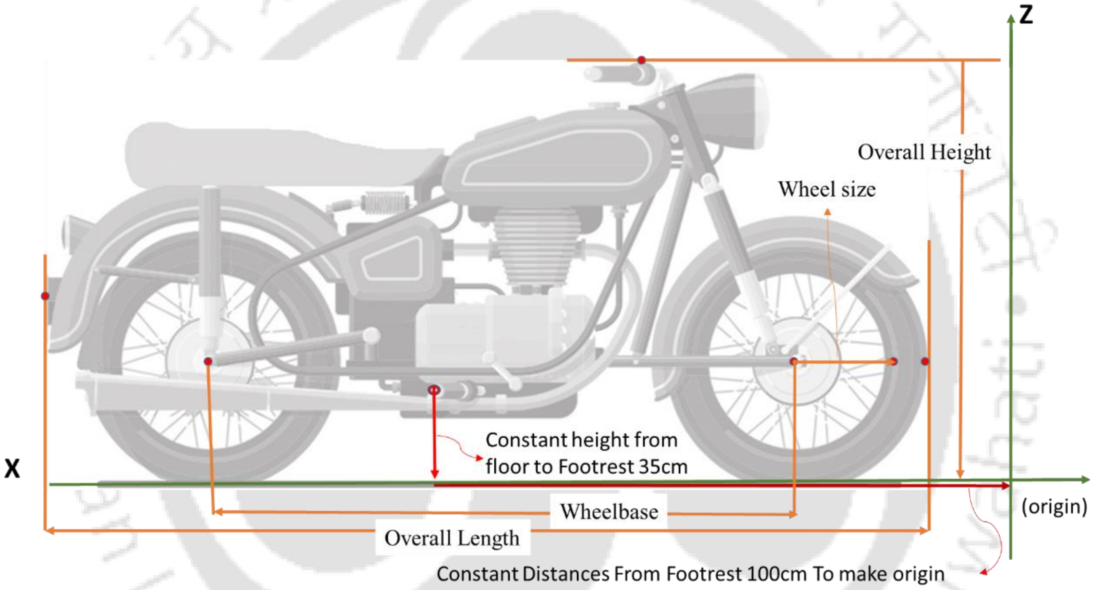


Figure 2. 4: General dimensions of motorcycles

The measuring technique/instruments should comply with the following requirements, which may use to measure the eight dimensions (at XZ plane). These requirements led to identifying a proper measuring technique/instruments for motorcycle key.

The requirements of the motorcycle's key dimensional measurements are as follows: All motorcycles should be measured in the coordinate system (xz) and maintains a common origin point (0, 0) since the general dimensions are provided in motorcycle company websites. The measuring technique/instruments may consider the wheelbase, overall length, overall breadth, overall height, and wheel size as their calibration dimensions (as shown in Figure 2.4). Most of the motorcycle's maximal volume observed to be 183cm × 91.5cm × 152.4cm (L×B×H).

Thus, these dimensions must accomplish by the measuring technique/instruments as the minimal working space. Further, some of the general criteria/requirements may help for a hassle-free field study such as portable, affordable, less time consumption for measurements that allows outdoor usage and accuracy level can high (at least 0.1% of mentioned workspace volume). Moreover, these requirements help in the guideline to identify the best suitable measurement technique/instruments to measure the eight dimensions (at XZ plane of motorcycles).

2.2.2 Market and literature survey on existing instruments to measure the motorcycle's (eight) dimensions (at XZ plane)

The measuring techniques are commonly used in mechanical industries for digitizing heritage components, reverse engineering of products, or inspect product quality improvement in metrology. Generally, measuring techniques classified as non-contact and contact measurement techniques. According to the characteristics of the product or components under measurement, it could be suggested the appropriate instruments or method.

Currently, the available measuring techniques and methods for reverse engineering of this kind of product (motorcycle) are: 3D (three-Dimensional) scanner, coordinate measuring machine (CMM), and computed tomography (CT) X-ray 3D.

3D scanner: The 3D scanner employ several technologies like laser line system, structured light system, multi-view camera system, and millimetre waves (Daanen and Ter Haar, 2013) (Olds and Honey, 2006).

In the laser line system employed 3D scanners, it is mandatory to move the sensor to observe the product. It provokes a higher level of errors (Mahmud et al., 2011). These systems are easily portable with few tripods and cost around 10000 US$ (Daanen and Ter Haar 2013). The working space provides (20cm×20cm×20cm) by this system, were not sufficient for motorcycle measurements (Borghese et al., 1998).

The structured light 3D scanner is working in a stereovision system. This same working principle as like as humans detects a map of the world (Stančić et al., 2013). Generally, a structured light system uses only one camera and projected stripes for observing the 3D object surface. This system is easily movable, portable, less expensive, and faster scanning than other

3D scanners (Rocchini et al., 2001). Nevertheless, these systems are having a problem with the shadow in outdoor environments while detecting the pixels points (640×480px). Thus, this problem may provoke false detections due to reflecting from a nearby reflective surface (Stančić et al. 2013). Therefore, this system is not satisfied enough to use in motorcycle measurement applications.

A multi-view camera is another method of observing 3D clod points extract from a 3D object using one or more cameras at different viewpoints (Daanen and Ter Haar 2013). In this method, experimental observation made by handle-held device (camera or iPhone/smartphone) person around 360 degrees around the object with a different angle of focus to capture more number of pictures at each approximant position. The captured images are converted into CAD files (.stl and .obj) using online open sources software (Kolev et al., 2014) (Baltsavias et al., 2005) (Böhler and Marbs, 2004) (Muratov et al., 2016) (Nocerino et al., 2017). This method of scanning technics is quite cheaper, portable, and affordable than other 3D scanning devices. This method satisfies all our motorcycle-measuring requirements. However, this technology has disadvantages of poor capturing data for specific surface materials which are highly specular (Cui and Stricker, 2011). Besides, this method can be performed in close-range photography, which may be possible for small heritage products, not for a huge motorcycle (Böhler and Marbs, 2004; Kolev et al., 2014).

The millimetre-wave method works under the principle of distinction between active and passive millimetre-wave scanners. The millimetre-wave passed through the object or human while passive scanners process the emitted waves from objects or humans to observe the cloud 3D points (Daanen and Ter Haar, 2013). This method usually used in textile industries or airports for luggage and passenger scanning. This kind of scanners is not meant for mechanical industry usage. However, it has the advantage of scanning through clothes or covered material.

Coordinate measuring machines (CMM): A contact or non-contact probe fixed with a movable 3-axis arm obtains the 3D cloud points of objectives. A computer operator or program maybe control this instrument and to measure an object (Crampton, 2008). This instrument has a higher level of application in mechanical industries (Achelker et al., 2014). Since it can provide a higher level of measuring accuracy with a contact probe, neither then non-contact laser probes and easily portable (Barbero and Ureta, 2011; FaroArm 2019). However, this instrument has constrained workspace for measurement, which may not be suitable for motorcycle measurement. Also, these instruments are costly and measure selective co-ordinate point measurements, which may cause an information gap between two cloud points (Gapinski et al., 2013)(FaroArm 2019).

Computed tomography (CT) X-ray 3D: This scanning method made by X-raying the 3D object. It is popularly called a CT scan in the medical field. This instrument works under residual radiation passing through a 3D object is detected as an X-ray image (Gapinski et al., 2013). This scanning method has the advantage of scanning external/internal shape and geometry, defects of object's materials. However, this scanning method has the same drawbacks as CMM (Tóth and Živčák, 2014). Thus, this scanning method also not suitable for motorcycle measurement applications.

All Available 3D coordinate measuring techniques and instruments/devices are not only costly but also unable to satisfy diverse requirements of motorcycle measurement. Hence, the present research objective to develop a portable and affordable measuring device for measuring the eight key dimensions (at XZ plane) of motorcycle and using the same for preparing the dimensional database of different motorcycles.

2.2.3 Design process

Generally, the design process can be classified into three types (1) originality (2) adaptive and (3) variant design process (Otto and Wood, 2003). The selection of design process could be depending upon the requirements and the existing products (instruments) in the market. From the market survey, it was observed that none of the available devices were fulfilled the conditions, which was the demand for the current case of a motorcycle. However, Chou and Hsiao, (2005) used a laser based instruments to measure the 2D coordinates of the scooter riders at 2D (XY) plane. Further, this technique is fulfilling the requirement of the present study. Thus, the principle of design has been inspired by this study for further modification using the adaptive design process to fulfill our present study requirements and completely satisfy the IS 11432: 2002 which govern the rules regarding the motorcycle's plans/orientations and overall dimensions.

The principle of adaptive design was used for developing a laser-pointer-based measuring instrument (Figure 2.5). The developed instrument comprised five major parts: the x-axis rail frame, sliding base (x-axis), Rod stick (z-axis), laser pointer holder, and laser pointer. The sliding support allows the z-axis rod stick to move through the x-axis rail frame. The laser pointer is fixed in the laser holder, which can move across the z-axis rod stick during measurements. The rail frame (x-axis) and rod stick (z-axis) adhere to rulers.

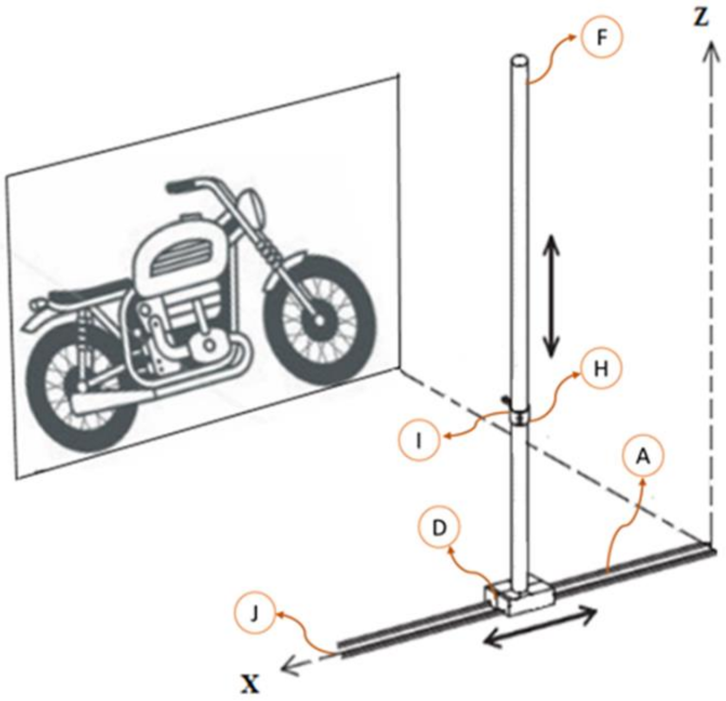


Figure 2.5: Working principles of design and its parts. Note: Part notations and names - A: X-axis rails frame; D: Sliding base (X-axis); F: Rod-stick (as Z-axis); H: Laser pointer holder; I: Laser pointer; J: Floor

By using the aforementioned working principles, a concept model was designed using the CAD model for the further design processes. Figure 2.6 displays the proposed concept based on the aforementioned working principles of the measurement device. The functional description of the proposed device is as follows:

A. The X-axis rail frame (C-section) is to maintain the straight runway path in X-axis. It is 250cm long, which can help to measure all of the dimensions (including calibration dimensions).
B. The support wheel is attached with rod-stick holder and movable along with rod-stick holder. It helps to maintain balance/stability for the rod-stick Z-axis frames self-weight during measurement and gives us an error-free measure.
C. Connector (bolt and nuts) was used in integrating the 250cm X-axis rails frame. Its help in portability of the measuring instrument during transportation for outdoor measurement.

D. Rod-stick holder is integrating the rod-stick Z-axis frame and X-axis rails frame for uniform measurement.
E. Inside connector has been provided to integrate the pieces of rod-stick Z-axis frames. It helps in portability of the measuring instrument during transportation for outdoor measurement.
F. Rod-stick holder frames are gunned with a ruler-tape of 200cm.
G. The laser holder supports the movement along with the rod-stick Z-axis frames for the Z-axis measurements. Also, it's provide space to hold the laser pointer.
H. Laser pointer could use for pointing the motorcycle's landmarks during measurements. Since laser beams travel through fog/air medium in a straight line, it has been used to locate the landmark of the motorcycle.
I. A rigidity platform has been provided to give stability and maintain the parallel plane during measurement. This detachable wooden block has been used for platform rigidity.

Overall, the proposed concept can address all the requirements of this study. Thus, to fabricate a functional (alpha) prototype of proposed concept (new instrument), a bill of materials (BOM) was generated for the prototype. The prototype cost was estimated according to the local shops. The total fabrication cost (GTFC) estimated for the prototype was 42 $ (INR 3000). It can breakdown into labour charge is 14 $ (INR 1000), material price is 14 $ (INR 1000), and fabrication cost is 14 $ (INR 1000). The alpha prototype of new Instrument found to be cheaper as compared to other measuring instruments in the market.

Before prototyping the proposed concept (new instrument), the finite element analysis (FEA) test was performed using COMSOL 4.3 to identify the deflection caused by the self-weight of the Z-axis rod-stick frame and provoke the errors during measurement. The material selected for the proposed concept was aluminium (aluminium channels 1000 series). The FEA test discloses that the self-weight displacement of the Z-axis rod stick was 0.004cm in X-direction, and total deflection was 0.014cm. These displacement results were found to be negligible.

A BOM was prepared using ISO A4 drawing sheets to purchase the materials. An alpha prototype was fabricated in the workshop of IIT Guwahati. The developed prototype was examined for calibrations and initial error by using rulers and scales. A portable bag was made to carry the new instrument (alpha prototype) for field study.

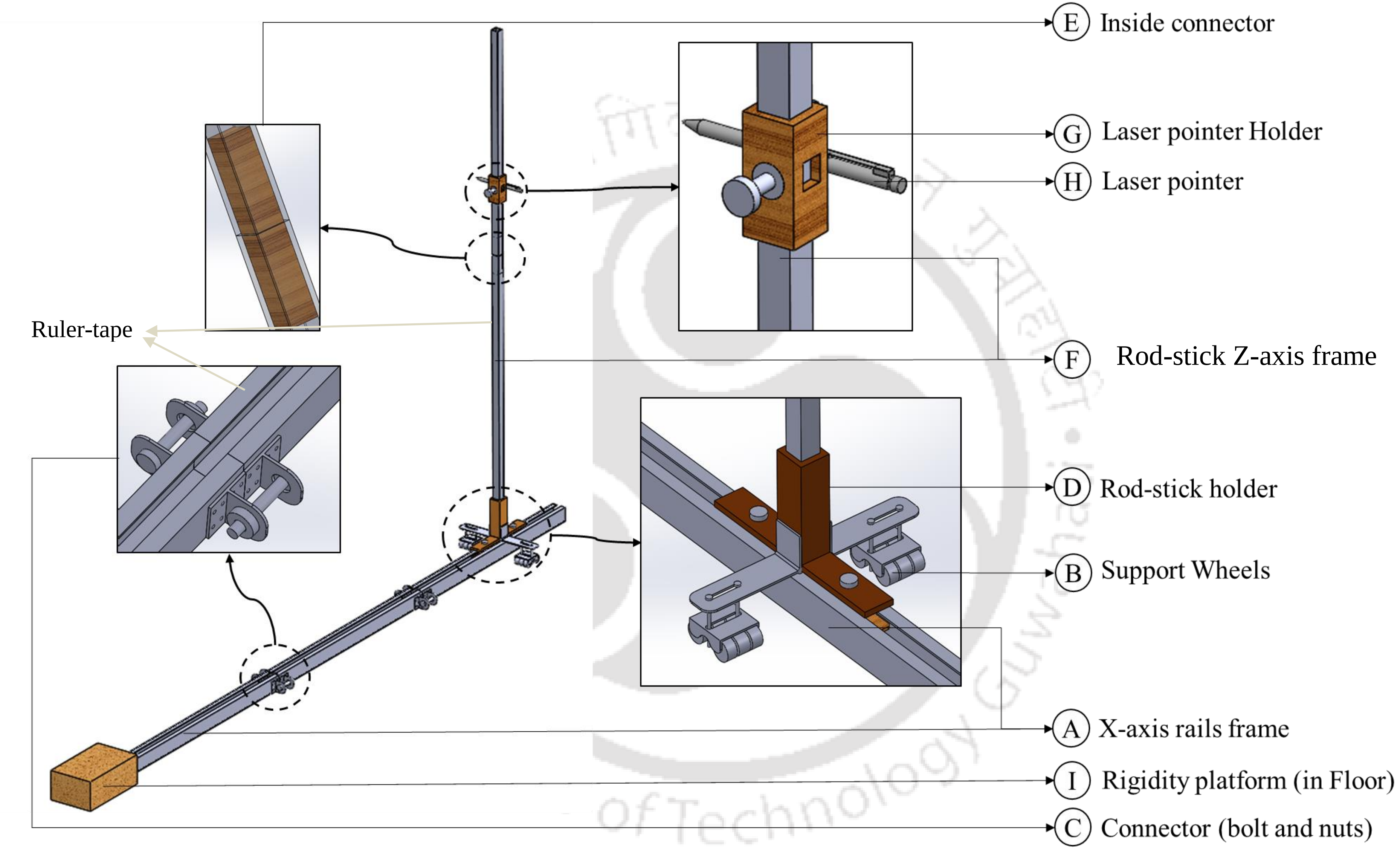


Figure 2. 6: Proposed measuring instrument and its main parts

2.2.4 On-field measurement using the newly developed measuring instrument

Figure 2. 7: Measurement setup with a new measuring instrument

23 (standard or economic segment) motorcycle's key dimensions were measured in the motorcycle showrooms (as show in Figure 2.7). The 23 motorcycles include the popular motorcycle models (as listed in Table 2.1). Before start measuring the key dimensions at the xz- plane, a newly developed measuring instrument was calibrated using know dimensions (i.e. wheelbase, overall length, and overall height).

The key dimensions were measured according to a standard operating procedure (SOP). A SOP is mandatory for any kind of instrument to calibrate and used it. Thus, this developed instrument are also supposed to have it. The newly developed instrument would be fellows below-mentioned SOP.

I. *Initialling the new measuring instrument (as show in figure 2.7)*

- Install the new instrument in the right side of motorcycle and make sure that the 100cm indicates the footrest.
- Two white washers should keep under the both tyres for uniform level rising of footrest to 35cm height (Z-axis distance).

- Keep two-bubble level meter along the tyres to create flat surface. A equal and minimal 1m distance should maintained between the flat surface of bubble level meter and new measuring instrument (X-axis rails Frame)
- Insert the Sliding base in the X-axis rails Frame and the Rod-stick as Y-axis Frame in the Sliding base. The laser mount can fix on Rod-stick as Z-axis Frame.
- Separately, keep the bubble level mater on the X-axis rails and the Rod-stick Z-axis to check the spirit level of vertical and horizontal axis. This step is to do after and before each measuring process. If spirit level is not proper, then the level can correct by adjusting the X-axis rails and the Rod-stick Z-axis alignments.
- Once, the above installation procedure is done. The calibration process starts. However, before start, The X-axis and Z-axis distance of footrest are supposed to correct as exactly 100cm and 35cm respectively.

II. To start the readings

- Calibration dimensions measured like wheelbase, tyre size, Overall length and wheelbase as per IS 11432: 2002 instructions. Each calibration dimensions measured twice for better clarification.
- Following with calibration process, Handlebar$_{xz}$, footrest$_{xz}$, D-point$_{xz}$, are measured. The first step in the SOP involved fixing the centre of the footrest (F-point) 100cm from the origin along the x-axis and 35cm from the origin along the z-axis. Step 2 involved measuring the know/calibration dimensions (e.g., the wheelbase, overall height, and overall length) as per the IS 11432: 2002 guidelines. Each calibration dimension was measured twice to achieve higher accuracy. Following the calibration process, the landmarks of the seat and handlebar were located precisely using red-landmarks. Moreover, the eight key dimensions (in the xz plane) were measured using the new instrument from the origin. After these measurements, dimensions of the seat, handlebar, footrest, and fuel tank (i.e. FS, FXL, SXL, S2S, GL, SS, ϕ, O, L, ψ, and θ) were measured using a large protractor and large sliding calliper. The whole duration of the field measurement for a motorcycle was 1 hour.

2.3 **Results and discussion**

2.3.1. Accuracy analysis of newly developed measuring instrument

Accuracy analysis was conducted on the data collected by the new instrument for the 23 motorcycles. Data collection was performed according to the SOP. The overall length, wheelbase, and overall height were subjected to comparative analysis. The actual values of the aforementioned dimensions were obtained from motorcycle company websites. The measured values of the aforementioned dimensions were obtained during the first measurement trial. The accuracy was assessed in terms of relative error percentage (Error%), alternative reliability (Pearson correlation), and Bland–Altman plot. The relative error between the actual and measured dimensions was calculated using the following equation 1:

$$Error\% = \frac{Actual - measured}{Actual} \times 100 \quad (1)$$

Where “Actual” represents the real dimension of the motorcycle's wheelbase, overall height, and overall length and “Measured” represents the observed dimension of the motorcycle's wheelbase, overall height, and overall length measured using the new instrument.

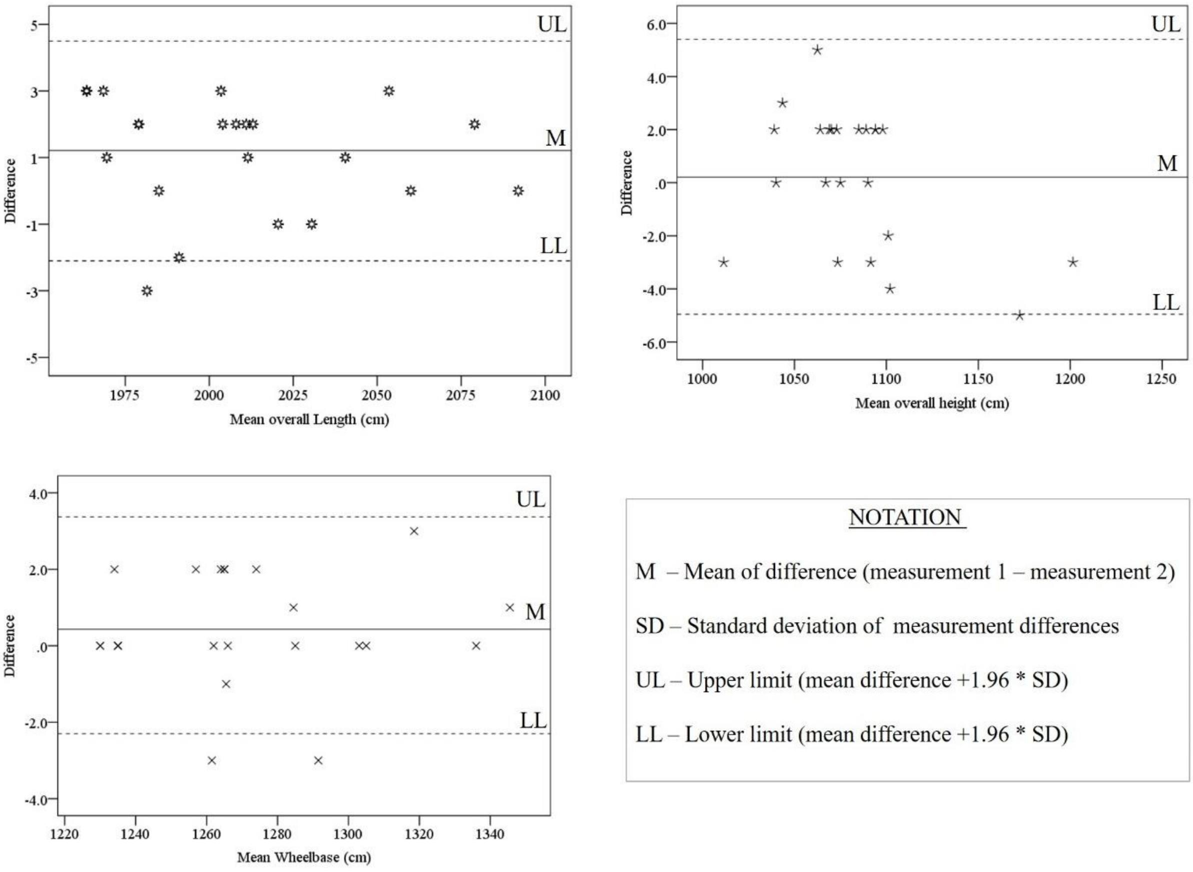
Table 2.1 presents the relative errors (Error %) of the wheelbase, overall height, and overall length. The Error% of the overall length, overall height, and wheelbase were estimated to be −0.152% to 0.153%, −0.297% to 0.287%, and 0% to 0.238%, respectively. Among these error%, overall length error% was found to be relatively lesser than the overall height and wheelbase. Overall, relative errors estimated at a maximum of 0.5%. This error% of all the dimensions were within the tolerances limit of ±0.5%. Also, the errors of each motorcycle's dimensions estimated to be negotiable and low.

The comparative analysis was performed using Bland Altman plot techniques, which is less expensive to compare two measurement systems (Bland and Altman, 1999). In the aforementioned plot, the differences between the measurements of two systems (measurement 1 – measurement 2) were plotted against their mean (as shown in Figure 2.8). This plot was drawn using SPSS for overall length, overall height, and wheelbase dimension to evaluate the accuracy of the newly developed instrument.

Table 2. 1: Percentage of relative error of new instrument (Unit: cm; unless specified)

Models of motorcycles	Overall length			Overall Height			Wheelbase		
	Actual	Measured	Error%	Actual	Measured	Error%	Actual	Measured	Error%
Baja CT 100	196.5	196.2	0.153	107.2	107.5	-0.280	123.5	123.5	0.000
Pulsar 150	2055	205.2	0.146	117	117.5	-0.427	132	131.7	0.227
Discover 150	203	203.1	-0.049	106.5	106	0.469	130.5	130.5	0.000
XCD 125	198	197.8	0.101	120	120.3	-0.250	127.5	127.3	0.157
Apache	208	207.8	0.096	110	110.2	-0.182	130.3	130.3	0.000
Victor	198	198.3	-0.152	109	108.8	0.183	126	126.3	0.238
Phoenix	198.5	198.5	0.000	106.5	106.3	0.188	126.5	126.3	0.158
Star city	199	199.2	-0.101	101	101.3	-0.297	126.2	126.2	0.000
CD shine	201.4	201.2	0.099	107.1	106.9	0.187	126.6	126.4	0.158
CD livo	202	202.1	-0.050	109.9	109.7	0.182	128.5	128.5	0.000
CB 125 shine	201.2	201.1	0.050	109	109.3	-0.275	126.6	126.4	0.158
CB unicorn	209.2	209.2	0.000	110	110.4	-0.364	133.6	1336	0.000
Dream yoga	200.5	200.3	0.100	109.5	109.3	0.183	128.5	128.4	0.078
Splendor	197	196.9	0.051	104	103.8	0.192	123	123	0.000
Hero glamor	200.5	200.2	0.150	107	106.8	0.187	126.5	126.6	0.079
passion pro	198	197.8	0.101	107.5	107.5	0.000	123.5	123.5	0.000
ismart	196.5	196.2	0.153	109.5	109.3	0.183	123.5	123.3	0.162
Splendor pro	197	196.7	0.152	104	104	0.000	123	123	0.000
Dream neo	200.9	200.7	0.100	107.4	107.2	0.186	125.8	125.6	0.159
Optimax 125	201.2	201	0.099	109	109	0.000	126.6	126.6	0.000
HF Deluxe	196.5	196.2	0.153	104.5	104.2	0.287	123.5	123.5	0.000
Honda Hornet	204.1	204	0.049	106.7	106.7	0.000	134.6	134.5	0.074
Achiever	206	206	0.000	108.6	108.4	0.184	129	129.3	0.233

The Bland–Altman plot of the overall length indicated that only one outlier measurement fall beyond the upper and lower limits of the differences. For the wheelbase, two outlier measurements fell beyond the lower limit of the differences. However, for the overall height, no outliers were found. Moreover, most of the measurements were within the confidence interval (between the upper and lower limits) in the Bland–Altman plots. Therefore, the dimensions measured by the newly developed instrument would be reliable and trustworthy.



NOTATION

M – Mean of difference (measurement 1 – measurement 2)

SD – Standard deviation of measurement differences

UL – Upper limit (mean difference +1.96 * SD)

LL – Lower limit (mean difference +1.96 * SD)

Figure 2. 8: Bland Altman plot – (a) overall length; (b) overall height and (c) wheelbase

The alternative reliability was evaluated using the Pearson correlation coefficient. This coefficient was estimated between the actual and measured dimensions of the overall length, overall height, and wheelbase. The correlation coefficients of the overall length, overall height, and wheelbase were estimated to be 0.999, 0.998, and 0.999, respectively. These correlation coefficients are within the reliability limit of 0.980. Thus, the new instrument was reliable.

2.3.2. Descriptive analysis of key dimensions

All 23 standard motorcycle's key dimensions at the XZ plane were shown in Table 2.2. Further, it was analyzed using IBM SPSS 24.0. The descriptive statistics were presented through the mean, standard deviation (SD), maximum, and minimum of 23 motorcycle models. Tables 2.3 present the descriptive statistics of key dimensions of among all the 23 motorcycles.

Table 2. 2: Raw dimensions of 23 standard Motorcycle's key dimensions at the XZ plane (Unit: cm)

Models of Motorcycles	G'-point		SIP		D-point	
	X	Z	X	Z	X	Z
Baja CT 100	84	107.5	120	73	147	89
Pulsar 150	71	104.5	117	83	138	92
Discover 150	85	108.8	130	87	155	92
XCD 125	83	107	128	88	148	92
Apache	59	97	120	90	132	110
Victor	81	107	149	88	125	86
Phoenix	77	112	128	89	150	94
Star city	80	107.5	126	87	144	92
CD shine	76	107	125	83	143	87
CD livo	80	108.5	129	86	151	91
CB 125 shine	78	105.5	124	83	143	86
CB unicorn	74	108	124	84	149	89
Dream yoga	77	107.5	124	89	145	94
Splendor	80	103	126	81	147	86
Hero glamor	77	111.8	124	86	145	93
passion pro	82	106	117	89	139	91
ismart	76	109.5	121	86	139	93
Splendor pro	79	106.5	119	85	142	89
Dream neo	77	107.5	124	89	145	94
Optimax 125	78	105.5	124	83	143	86
HF Deluxe	80	103	126	81	147	86
Honda Hornet	56	103	105	84	130.5	92
Achiever	80	108.5	129	86	151	91

Note G'-point at handlebar; SIP and D-point at the seat. During these measurements, footrest fix at the distance of 100cm from the x-axis origin and 35cm from the z-axis origin

Table 2. 3: Descriptive statistics of the standard motorcycle dimensions (Unit: cm; unless specified)

Key dimensions	Minimum	Maximum	Mean	SD
Handlebar_X	56	85	77	6.9
Handlebar_Z	97	112	106.6	3.2
SIP_X	10.5	149	124.3	7.6
SIP_Z	73	90	85.2	3.8
D-point_X	125	155	143.4	7.1
D-point_Z	86	110	91.1	5
Handlebar_ф (Unit: °)	0	8	3	2
Fuel tank length	34	52	44.7	5.3
Maximum fuel tank breadth (FXL)	28	42	33.2	3.5
Minimum fuel tank breadth (FS)	13	25	18.8	3.1
Distance between front width and narrow width (S2S)	11	18	15	2
Narrowest width (SXL)	19	23	21.4	1.3
Greatest length of seat (GL)	31	41	35.8	2.2
Front width of seat (SS)	14	19	16.2	1.5
Distance between the footrests (O)	54	59	56.6	2
Distance between the Handlebars (L)	69	77	73.2	2.4
Handlebar angle at Front Plane (ψ) (Unit: °)	10	11	7	3
Handlebar angle at Top Plane (θ) (Unit: °)	25	15	20	5

Note: During these measurements, footrest fix at the distance of 100cm from the x-axis origin and 35cm from the z-axis origin

The G'- points of the handlebar were found, between the variation range, from 56cm to 99cm for forward/backward direction, from 97cm to 115.5cm for the vertical direction, and 69cm to 77cm for In-between distance of Handlebar (L). The variations of In-between distance of footrests (O) were found between 54cm to 59cm. The D-point of the seat were found, between the variation ranges, from 125cm to 155cm for forward/backward direction, 86cm to 110cm for the vertical direction. Regarding SIP-point of the seat, the variation range were found between 105cm to 149cm for forward/backward direction and from 73cm to 90cm for the vertical direction.

The 23 standard motorcycles models had the following seat dimensions: front width (SS), mean = 16cm and SD = ± 2cm; narrowest width (SXL), mean = 21cm and SD = ± 2cm; distance between the front width and narrowest width (S2S), mean = 15cm and SD = ± 2cm; and GL, mean = 36cm and SD = ± 2.2cm. The minimum and maximum fuel tank breadths were varied between 13cm to 25cm and 28cm to 42cm, respectively. The fuel tank length was varied between 34cm to 52cm. The mean (M) and SD of the measured handlebar angles were as follows: ϕ, M = 3° and SD = 2°; ψ, M = 7° and SD = 3°; and θ, M = 20° and SD = 5°.

Most of the dimensional variations were very minimal. The maximum SD was found in SIP_X (seat dimension). However, all the observations were in-line with existing standards JASO T003:2009, 2009; JASO T102-84, 1975. The study has some of the limitations that the overall relative error estimates as a maximum of 0.5%. The errors are quite higher than other equipment. However, this instrument was specially made for motorcycle key dimensions measurement. Since, the new instrument was manually operated. Most of the errors could be caused by the human. Hence, the error could be reduced in further research through the following strategies: (1) Replacement of part/design feature which cause the human-error; (2) Restructuring the operation procedure which might prevalent the human behavioural-error; and (3) Automate the measurement procedure to reduce the human-error.

2.4 Conclusion

The newly developed laser-pointer-based measuring instrument was lightweight (main structure were aluminium, 7kg), with easy assemble/dismantle features (sliding channel, clamp and nut-bolt mechanism), low cost (estimated ~ 3000 INR or $41) and capable of measuring the key dimensions within the volume of 183cm × 91.5cm × 152.4cm (length x. breadth x height). Among relative errors, the maximum value was found to be 0.153% for overall length, 0.287% for overall-height, and 0.238% for the wheelbase. Also, the Bland Altman plot and Pearson correlation coefficient results were found trustworthy. It is expected that the dimensional database of standard motorcycles and thereby corresponding dimensional variability among the different motorcycles would be useful for deciding the dimensions of the motorcycle simulator or test-rig development.

Chapter – 3: Determination of the key anthropometrics and range of motion measurements for the ergonomic design of motorcycle

Abstract

A motorcycle is one of the popular personal-modes of transportations. It commonly refers to all type of two-wheelers (sports/ cruiser/ standard/ scooters) that works and powers by electricity or fossil fuel. Motorcycles are the most common mode of commuting in India, and 92% of motorcycle users are male. To develop a suitable motorcycle design for Indian motorcyclists, databases related to the range of motion (ROM) and anthropometry of Indian motorcyclists must be established. The existing databases are either lacking relevant information or may be different from the target users (Indian male motorcyclists). Objective: The purpose of the study was to find the most potential anthropometry and ROM variables of Indian motorcyclists and compare them across (inter)national databases. Method: Twenty-nine (29) anthropometric and twenty (20) ROM measurements were obtained from 120 male (aged 19–44 years) subjects using a standard anthropometric kit (Lafayette Instrument, USA). Dimensional reduction analysis and estimation of percentage differences were computed, and the measurements were validated using Intra-observer and Inter-observer reliability techniques. Results: An extensive anthropometry and ROM database in terms of mean, standard deviation, range, and percentile values were also documented. The results indicated that ROM and anthropometric measurement indicators such as the "motion in the sagittal plane" and "body length indicator" represent the physical attributes of male Indian motorcyclists. In the comparative analyses, percentage difference for ROM measurements ranging from -33% to 53% and for anthropometry dimensions varied from -20% to 16%. Conclusions: This study indicates that databases of the ROM and anthropometry of Indian motorcyclists must be established to achieve an ergonomic design for Indian motorcycles.

3.1 **Introduction**

Ergonomics plays a vital role in the motorcycle design process for effective user-centered design towards successful, marketable products (motorcycles). The ergonomics of the motorcycles are evaluated using Digital Human Modelling (DHM) tools, which are commercially available (like CATIA, Jack, SANTOS, etc.) (Cucinotta et al., 2019; Tony et al., 2020). These DHM tools facilitate a designer to rapidly simulate and visualize 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.

Currently, few anthropometrics databases of motorcyclists exist as published research papers. To the best of our knowledge, no ROM database has been established for motorcyclists. However, few motorcyclist anthropometrics studies were reported from the UK (Robertson and Minter, 1996) and Nigeria (Lawrence, 2013).

Although car drivers population are higher than the motorcyclist in global, higher motorcyclist are there in Southern Asian countries (Gastner et al., 2018). Among the South Asian countries, India has a higher number of motorcyclist population when compared with other automotive users (SIAM, 2018). The reason for the high motorcycle users in low-middle-income countries like India could be the cost of affordability. Although India has a large number of motorcyclists, comprehensive anthropometric and ROM databases have not been established for Indian motorcyclists. However, some Indian anthropometric studies (Kulkarni et al., 2011; Shamasundara and Ogale, 1999) reported a mixed survey of the motorcycle, car, and truck driver population. Amrutkar and Rajhans (2011) performed an anthropometric study on 70 adult motorcyclists (aged 18 to 25 years) from 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 aforementioned studies did not specify the exact number of male and female motorcyclists. Moreover, they did not provide due importance to male motorcyclists (92% of Indian motorcycle license holders are men; Government of India, 2018) when developing anthropometric databases for Indian drivers of two- or 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. The aforementioned studies collected measured different sets of variables; thus, no uniformity was maintained in these studies. Therefore, numerous times, it was not feasible to compare this database with other 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 questionable. Consequently, motorcycle designers have to use the Indian general-population database (Chakrabarti, 1997) to design motorcycles for the Indian market.

Developing comprehensive general-population databases are important for any country to prepare estimates and analyse 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. 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.

Studies (Cucinotta et al., 2019; Robertson and Minter, 1996) have indicated that the establishment of anthropometric and ROM databases is essential for evaluating the ergonomics of motorcycle design. 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. (Dawal et al., 2015; Kolekar and Rajhans, 2011). Moreover, applying anthropometric and ROM data from other countries during the design of motorcycles for Indian riders might lead to dimensional (mis)match (Chakrabarti, 1997).

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 (Robertson and Minter, 1996). 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):

RQ2: What are the key anthropometric and ROM variables that define the physical characteristics of Indian male motorcyclists?

RQ3: What is the percentage difference of anthropometric and ROM variables between the Indian male motorcyclists and other international/ national databases (motorcyclist/ driver and the general Indian population)?

3.2 **Methods and Materials**

3.2.1 Subjects

The motorcyclist population of India (29 states and nine union territories) is estimated as four hundred seven million in 2016 (Government of India, 2018). 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 calculated using ISO 15535:2012 (ISO, 2012). This guideline indicates the general requirements for estimating the sample size when performing an anthropometric study. While calculating a minimum number of samples based on the formula (equation 1), the recommended sample size for the study was determined as (n ≥) 117.

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

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 ($\bar{x} = 167.5$cm), 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 (Kulkarni et al., 2011).

The anthropometric and ROM measurements were conducted using stratified random sampling, and one hundred twenty male subjects were randomly selected from Institute (IIT Guwahati). One hundred twenty subjects 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 Indian motorcyclists from 20 major states. The research subjects were divided into six zonal groups: central, southern, northeastern, western, northern, and eastern India. The aforementioned six zones were assumed to have equal proportions of male motorcyclists; hence, we equally segmented the sample population into each zonal group (15%–17% for each group). The motorcyclists (subjects) with pre-existing health problems, such as musculoskeletal disorders, hypermobility, and bone fractures, were excluded in the initial screening.

3.2.2 Selection of ROM measurements and body dimensions

The study measured twenty-nine anthropometrics (including BMI (body mass index) and four skinfolds), and twenty ROM of measurements (see Figure 3.1 and 3.2) recognized from the previously published research articles (Arunachalam et al., 2019; Kolekar and Rajhans, 2011; Lecoublet et al., 2019; Paiman et al., 2014; Robertson and Minter, 1996). The procedure of ROM and anthropometrics measurements were followed as per the earlier available research paper, ISO standards, and books (Chakrabarti, 1997; ISO, 2008; Jamaiyah, 2010; Marfell-Jones et al., 2012; Pheasant, S, 2016; Chertman et al., 2010; Norkin and White, 2016; Shariff et al., 2019). Details such as the orientation of particular segments (e.g., the leg, arm, and head), the position of the subject (e.g., standing and sitting), and the plane of measurement (e.g., dorsal or Frankfurt) were followed as per aforementioned research articles. The anatomical landmarks used for 29 anthropometric dimensions and 20 ROM measurements are presented in **Appendices A and B,** respectively.

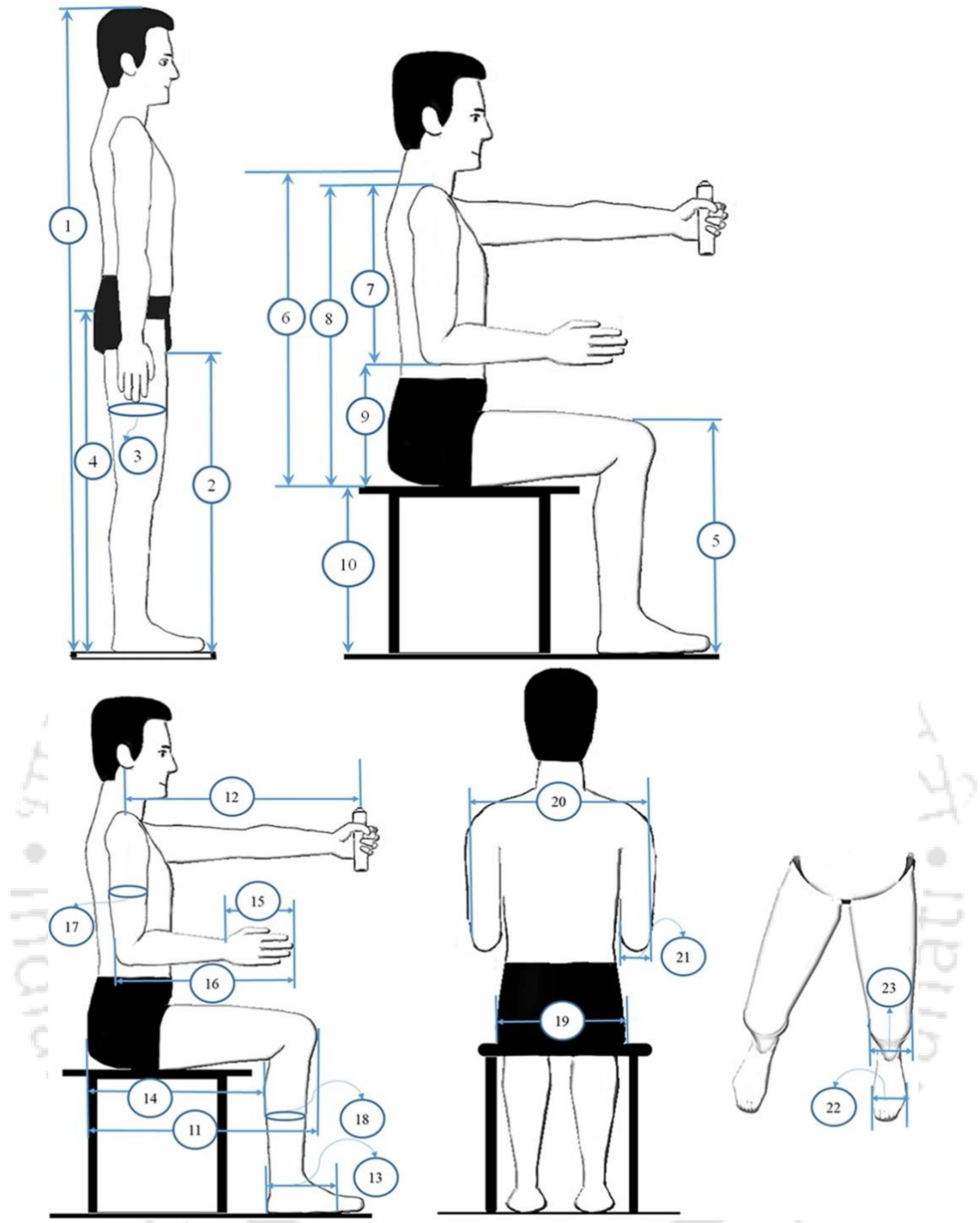


Figure 3. 1: Anthropometrics measurements

Note: Circled numerics represent the following anthropometric nomenclatures and acronyms:[1] Stature (S); [2] Crotch height (CH); [3] thigh circumference (TC); [4] Buttock extension (BE); [5] Knee height (KH); [6] Cervical height sitting (CHS); [7] Shoulder-elbow length (SEL); [8] Shoulder height sitting SHS); [9] Elbow height, Sitting (EHS); [10] Lower leg length (LLL); [11] Buttock-knee length (BKL); [12] Acromion grip length (AL); [13] Ball of foot length (BFL); [14] Buttock-Popliteal length (PL); [15] Hand length (HL); [16] Elbow-Hand Length (EHL); [17] Upper arm circumference (UC); [18] Calf circumference (CC); [19] Hip breadth, sitting (HBS); [20] Elbow to elbow breadth (EEB); [21] Humerus breadth (HB); [22] Foot breadth (FB); [23] Femur breadth (FrB).

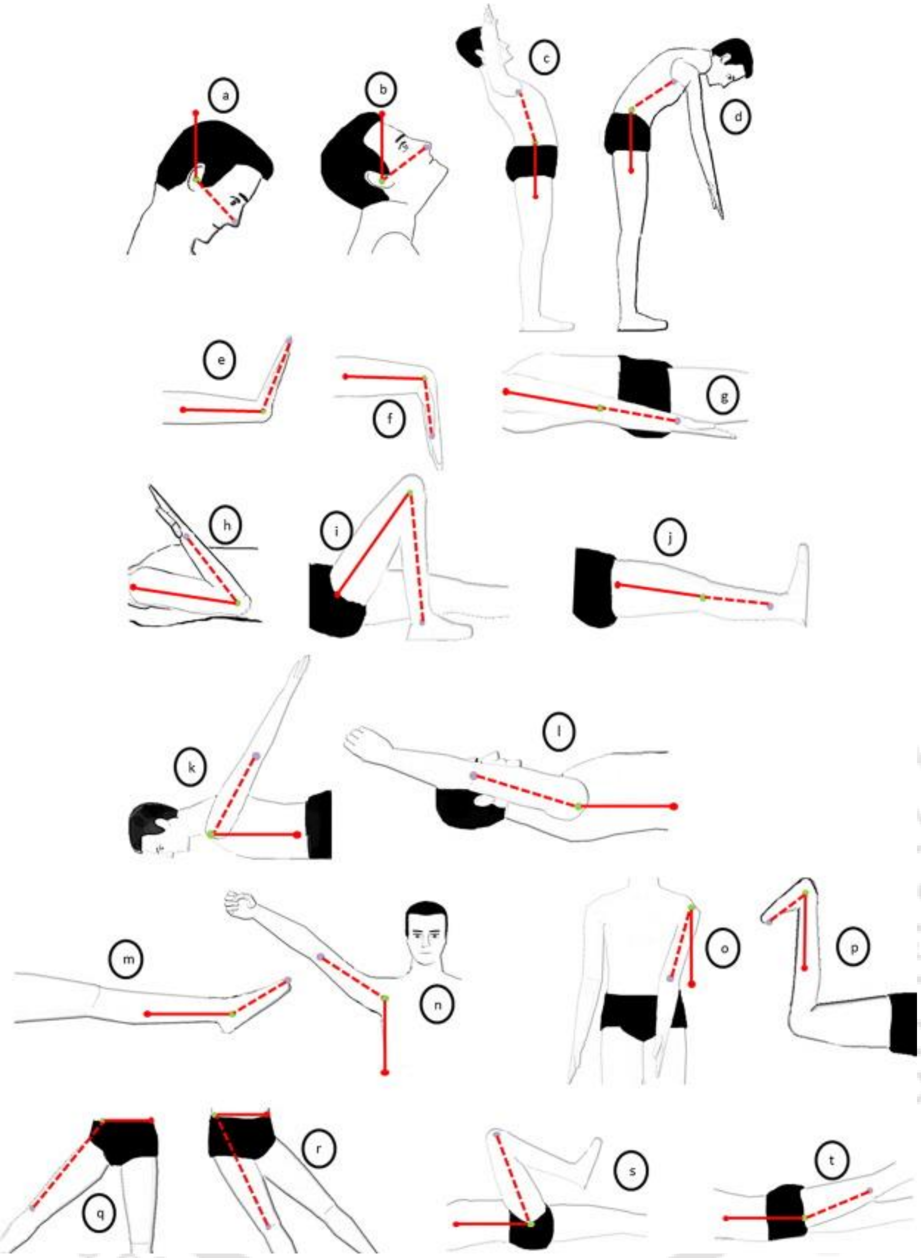


Figure 3. 2: Anatomical landmarks for ROM measurements

Note: Circled alphabets represent the following ROM nomenclatures and acronyms. Redline - the stationary-arm or distal arm of the goniometer, and the red dotted line - movable-arm or Proximal arm of the goniometer: [a] Neck Flexion (NF); [b] Neck Extension (NE); [c] Lumbar Extension (LE); [d] Lumbar Flexion (LF); [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); [l] Shoulder Flexion (SF); [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).

3.2.3 Measuring instruments and apparatus

The anthropometric dimensions and ROM were measured manually by using a set of apparatuses (Figure 3.3). Figure 3I- VI displays the different instruments used in this study, namely the anthropometer (GPM 101 anthropological, Make: Switzerland), expandable rods (can expand up to 210cm), plastic tape (200cm), base plate, sliding caliper, and portable weight balance scale (Model: GVC 9837, Maximum 136 kg capacity, Make: GVC, India) used for physical measurements. The ROM was measured using a 360° full-circle goniometer (length of the stationary and moving arms was 30 cm) (Figure 3VII). A slim skinfold caliper (range: 0 –8cm) (figure 3VIII) was used to measure the skinfold thickness. A table and adjustable stole (figure 3IX) were used during the supine position measurements and sitting posture, respectively.

Figure 3. 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.

3.3 Experiment Procedures

Two observers/researchers 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 subjects 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 (World Medical Association, 2001). Prior to the data collection session, general information, such as the state of origin, age, and motorcycle riding experience of the subjects, was recorded in data collection sheets.

In this study, the measurement information was acquired after five subsequent sessions:

(1) Anthropometric dimensions in the standing posture

(2) Anthropometric dimensions in the sitting posture

(3) ROM measurements in the standing posture

(4) ROM measurements in the sitting posture

(5) ROM measurements in the supine posture

The subjects were requested to wear shorts during the measurement process. The duration of the whole measurement procedure for each subject was about 1 hour.

3.3.1 Reliability of ROM measurements and anthropometric dimensions

Before the anthropometric and ROM measurements on 120 subjects, Intra-observer and Inter-observer reliability tests were performed on randomly chosen 10 subjects 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 and manual errors (Sutalaksana and Widyanti, 2016).

During the Intra-observer reliability assessment, initially, observer-1 measured all ROM and anthropometric dimensions on ten subjects during the first week. After a week, all the measurements were repeated on the same subjects 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 subjects during the same day.

The aforementioned reliability and error were determined using the intraobserver and interobserver %TEM (equation 2) and R or the ICC (equation 3) (Jamaiyah, 2010; Stomfai et al., 2011). Equations 2 and 3 were included in the worksheet and used to estimate %TEM and R, respectively, for the anthropometric and ROM measurements.

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

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

Where N = number of subjects, D = difference between measurements, M = means of measurement, SD = standard deviation of the measurement.

3.4 **Data analysis**

The anthropometric and ROM measurements of 120 subjects manually transferred from the datasheet to IBM SPSS version 25.0 software for data analysis. 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 (PC) analysis (PCA) is commonly known for dimensional reduction of a more extensive set of variables into a smaller subset (Pearson, 1901; Tavana et al., 2016). These statistical methods were used on twenty ROM and twenty-nine anthropometric measurements to discover the answers to our research questions. 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 correlation among 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 analyses were performed by calculating the percentage difference between the earlier studies from the (inter)national database and the present study. Particularly, a national database on general (Chakrabarti, 1997) and automotive/truck drivers population of India (Shamasundara and Ogale, 1999; Kulkarni et al., 2011; Amrutkar and Rajhans, 2011) the international motorcyclist database from Nigeria (Imaekhai Lawrence 2013) and U.K (Robertson and Minter, 1996), were used for the comparative analysis. The percentage of differences was estimated using equation 4, which was formulated on the basis of previous studies (Imrhan et al., 2009; Oviedo-Trespalacios et al., 2017).

$$\%\mathrm{D}=\left(\left(\mathrm{PM}_j-\mathrm{PRM}_j\right)/\mathrm{PM}_j\right)\times 100 \qquad (4)$$

Where %D is the percentage differences,

$\mathrm{PRM_j}$ is the mean of the $\mathrm{j^{th}}$ variable of anthropometric or ROM from the previous study, and

$\mathrm{PM_j}$ is the mean of the $\mathrm{j^{th}}$ variable of anthropometric or ROM from the present study.

Since the standard deviation of the ROM and anthropometry dimensions were not presented in some studies (Chakrabarti, 1997; Kulkarni et al., 2011), we have used percentage differences estimation instead of other statistical tests (e.g., independent t-test used in Adnan and Dawal, 2019; Lee et al., 2019) for the comparative analysis.

3.5 **Results and Discussion**

3.5.1 Descriptive analysis of anthropometrics and ROM measurements

The 120 male subjects holding a valid license with a mean age of 29 years (SD 8.8 years) were included for physical measurements. These subjects had reported a mean riding experience of 10 years with SD 4 years. Table 3.1 and 3.2 shows the descriptive results of 29 anthropometric and 20 ROM measurements among all the subjects.

Table 3. 1: Descriptive results of anthropometric measurements (n=120) (Unit: cm unless specified)

					Percentile		
Anthropometric measurements	Min	Max	Mean	SD	5th	50th	95th
W - Weight (in kg)	38	96	68	11	51	68	84
S - Stature	154	188	169	7	158	168	183
BMI - Body mass index (Kg/m^2)	14	32	24	4	18	24	29
CH- Crotch height	67	95	78	5	69	77	86
BE- Buttock extension	58	98	84	6	72	86	94
CHS -Cervical height sitting	58	71	64	3	59	64	69
SHS -Shoulder height sitting	51	65	58	3	52	57	63
EHS -Elbow height, Sitting	16	28	22	3	18	22	27
KH-Knee height	46	84	55	4	49	55	60
LLL -Lower leg length	37	71	45	4	39	44	50
SEL -Shoulder-elbow length	30	41	35	2	31	35	40
EHL- Elbow-hand length	42	54	47	3	43	48	52
BKL -Buttock-knee length	50	68	59	4	53	59	66
PL -Buttock-popliteal length	40	57	49	4	42	49	56
AL -Acromion grip length	53	75	63	4	55	63	70
BFL -Ball of foot length	10	21	18	2	16	18	20
HL- Hand length	15	21	18	1	15	18	20
FB -Foot-breadth	8	12	10	1	9	10	11
EEB -Elbow-Elbow breadth	33	53	43	4	37	44	49
HBS- Hip breadth, sitting	27	43	34	3	29	34	38
TC -Thigh circumference	34	57	45	5	38	45	54
T -Triceps skinfold (mm)	4	14	8	2	5	8	12
SS -Subscapular skinfold (mm)	5	15	10	2	6	10	13
SR-Supraspinal skinfold (mm)	5	16	11	2	7	10	15
MC -Medial calf skinfold (mm)	5	14	10	2	7	10	13
CC -Calf circumference	21	52	33	5	27	33	41
UC -Upper arm circumference	19	34	29	3	23	29	33
FrB-Femur breadth	6	11	9	1	8	9	10
HB -Humerus breadth	6	9	7	1	6	7	8

Table 3. 2: Descriptive analysis results of ROM measurements (n=120) (Unit: ◦)

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

3.5.2 Reliability of anthropometric and ROM measurements

Table 3.3 presents the intraobserver and interobserver technical errors of the anthropometric dimensions. The ICC and %TEM of the anthropometric measurements varied from 0.99 to 0.97 and from 1.8% to 0.05%, respectively. Moreover, the ICC and %TEM of the skinfold thickness measurements ranged from 0.98 to 0.99 and from 2.06% to 4.56%, respectively, for both of observer technical errors. Researchers (Crenna et al., 2014; Jamaiyah, 2010; Stomfai et al., 2011) in earlier studies agreed that the measurements could be considered reliable and error-free for higher than 0.95 reliability values.

Table 3. 3: Anthropometric measurements Inter- /Intra-observer technical errors

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

Table 3.4 presents the intraobserver and interobserver technical errors for the ROM measurements. The ICC and %TEM of the ROM measurements varied from 0.96 to 0.99 and from 0.9% to 1.7%, respectively, for both observer technical errors. Soucie et al. (2011) indicated that ROM measurements are expected error-free when the reliability coefficient exceeds 0.96. Since the ICC measurements in the pilot study (10 subjects) were higher than the suggested values in the previous literature, the overall result implies that the anthropometric and ROM measurements would be trustworthy for the further survey, including more subjects.

Table 3. 4: ROM measurements – Inter and Intra-observer technical errors

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

3.5.3 Dimensional reduction using principal component analysis (PCA)

3.5.3.1 Principal components (PC) of anthropometry measurements

Five PCs (PC_1 to PC_5) were obtained from 29 anthropometric variables by conducting PCA. A scree plot was used to identify potential PCs (Figure 3.4). The scree plot indicated that effective PCs had eigenvalues larger than 1. The KMO value of the sampling sufficiency was 0.79 (ranged from 0.70 to 0.79). Thus, the present study had a “middling” sample size (Cerny and Kaiser, 1977). Bartlett’s test of sphericity was also found to be significant ($p < 0.001$), which indicates that the sample size was acceptable (Kuo et al., 2019). The correlation coefficients among all anthropometric variables ranged between −0.7 and 0.7 (as shown in **Appendix C, Table C1**), which indicates a strong relationship among the anthropometric variables.

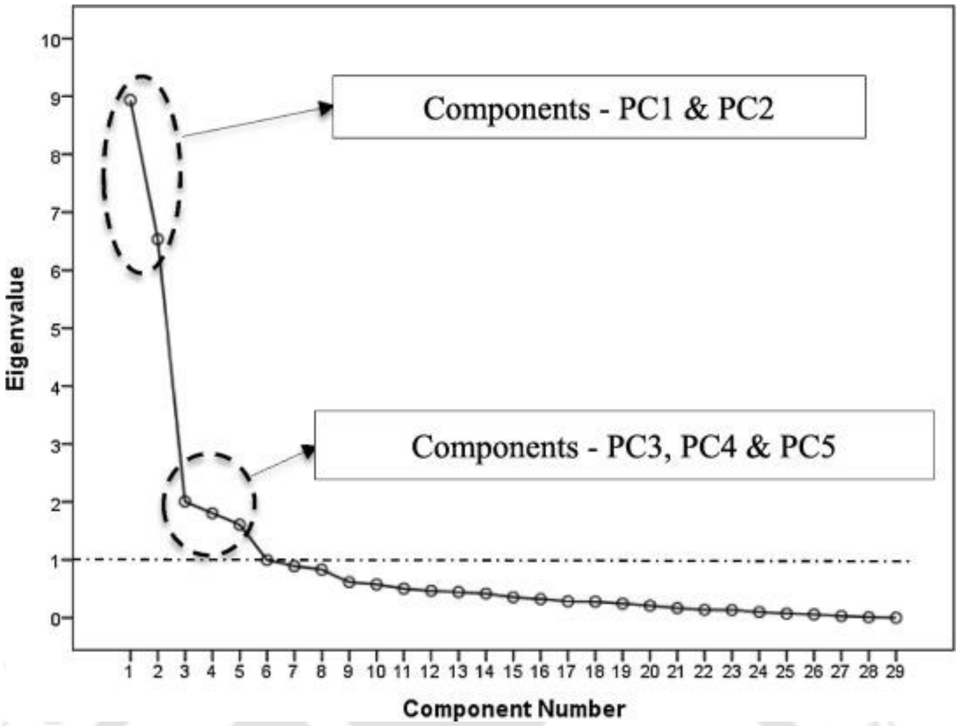


Figure 3. 4: Anthropometry dimensions - Scree plot

After varimax orthogonal rotation, five PCs of the anthropometric measurements accounted for 71.95% of the total variance in the original variables (see Table 3.5). PC_1 comprises 14 variables (Table 3.6) and explains 30.8% of the total variance (eigenvalue was 8.9). PC_1 was named as "*body length indicator*". PC_2 comprised ten variables and named as "*volume indicator*". It explained for 22.5% of the variance (eigenvalue was 6.5). PC_3 comprised five variables that explained 6.9% of the total variance (eigenvalue was 2). This PC was named as "*body fat indicator*". PC_4 comprised three variables that explained 6.2% of the total variance (eigenvalue was 1.7). This PC was named as "*Sitting height indicator*". PC_5 comprised of three variables that explained 5.5% of the total variance (eigenvalue was 1.6). PC_5 was named as "*Body bilateral length indicator*".

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, buttock extension, crotch height, shoulder–elbow length, sitting cervical height, lower-leg length, knee height, elbow–hand length, shoulder–elbow length, buttock–popliteal length, buttock–knee-length, ball-of-foot length, hand length, and acromion grip length. By contrast, PC_4 (*body bilateral length indicator*) and PC_5 (*body fat indicator*) exhibited a low explanation for the variance in the anthropometric attributes of Indian male motorcyclists.

Table 3. 5: Total variance explained for anthropometric variables

	Initial Eigenvalues			Rotation sums of squared loadings		
Component	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	.991	3.418	75.370			
7	.885	3.053	78.423			
8	.828	2.857	81.279			
9	.614	2.117	83.396			
10	.574	1.980	85.376			
11	.503	1.736	87.112			
12	.466	1.606	88.717			
13	.443	1.529	90.246			
14	.417	1.439	91.686			
15	.354	1.222	92.908			
16	.323	1.113	94.020			
17	.284	.980	95.000			
18	.280	.964	95.964			
19	.245	.846	96.810			
20	.211	.729	97.539			
21	.167	.576	98.116			
22	.138	.476	98.592			
23	.135	.465	99.058			
24	.099	.341	99.399			
25	.073	.252	99.651			
26	.057	.198	99.849			
27	.032	.109	99.958			
28	.011	.037	99.995			
29	.001	.005	100.000			

Table 3. 6: Results of factor analysis for anthropometric variables

	Component(s)				
	1	2	3	4	5
W - Weight		.877			
S - Stature	.910				
BMI - Body mass index		.847			
CH- Crotch height	.652				
BE- Buttock extension	.779				
CHS -Cervical height sitting	.569			.708	
SHS -Shoulder height sitting	.541			.797	
EHS -Elbow height, Sitting				.936	
KH-Knee height	.622				-.448
LLL -Lower leg length	.647				
SEL -Shoulder-elbow length	.881				
EHL- Elbow-hand length	.872				
BKL -Buttock-knee length	.849				
PL -Buttock-popliteal length	.796				
AL -Acromion grip length	.721				
BFL -Ball of foot length	.671				
HL- Hand length	.777				
FB -Foot-breadth					-.768
EEB -Elbow-Elbow breadth		.676	.411		
HBS- Hip breadth, sitting		.811			
TC -Thigh circumference		.802			
T -Triceps skinfold			.847		
SS -Subscapular skinfold		.572	.470		
SR-Supraspinal skinfold		.590	.561		
MC -Medial calf skinfold			.786		
CC -Calf circumference		.792			
UC -Upper arm circumference		.696			
FrB-Femur breadth		.657			
W - Weight					.762

Note. Eigenvectors lower than 0.4 were hidden in the table

In line with our results, the study by Dasgupta et al. (2012) on Indian automotive male drivers (car/truck/motorcycle) revealed that the length related dimensions (stature and elbow-hand height) were expressing higher physical characteristics than other anthropometric dimensions. On the contrary, Majumder (2014) 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. (2012) performed PCA on anthropometry measurements of U.S drivers (cab and truck) and compared their results with U.S general population. Haslegrave (1980) 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.

3.5.3.2 Principal components (PC) of ROM measurements

Seven PCs were obtained from 20 ROM measurements after conducting PCA. All the PCs had eigenvalues higher than 1 (Figure 3.5). The KMO measure of the sampling adequacy was estimated at 0.61. This value falls in the range between 0.60 to 0.69 and called a "mediocre" sample size (Cerny and Kaiser, 1977). The Bartlett's test of sphericity was also found to be significant ($p < 0.001$), which indicates that the sample size was acceptable (Kuo et al., 2019). The correlation coefficients among the ROM variables were within a range of −0.5 to 0.5 (shown in **Appendix C, Table C2**), which indicates a modest relationship among the ROM variables.

After performing varimax orthogonal rotation for the ROM variables, the seven PCs explained 62.23% of the total variance in the original variables (see Table 3.7). PC_1 comprised six variables (see Table 3.8) and explained 14.2% of the total variance (eigenvalue was 2.8). This PC was named as "*motion at the sagittal plane*". PC_2 comprised four variables and named as "*motion at the transverse plane*". This PC explained 11.2% of the total variance (eigenvalue was 2.2). PC_3 comprised three variables and explained 10.5% of the total variance (eigenvalue was 2.1). These variables were named as "*Upperlimb Motions at Sagittal plane*". PC_4 comprises two variables and explained 7.5% of the total variance (Eigenvalues was 1.5). These variables was named as "*lower limb Motions at the Sagittal plane*". PC_5 comprise two variables and explained 6.5% of the total variance (Eigenvalues was 1.3). These variables were named as "*lower limb Motion at Transverse plane*". PC_6 comprised two variables and explained 6.3% of the total variance (Eigenvalues is 1.26). These variables were named as "*Spine Motion at Sagittal plane*". PC_7 comprises two variables and explained 5.7% of the total variance (Eigenvalues was 1.14). These variables were named as "*Knee-elbow Motion at Sagittal plane*".

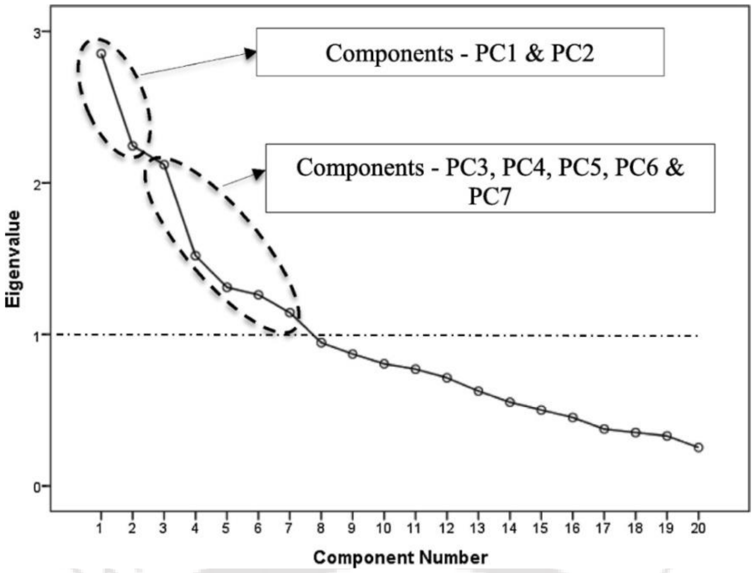


Figure 3. 5: ROM measurements - Scree plot

Table 3. 7: Total variance explained for ROM measurements

	Initial Eigenvalues			Rotation Sums of Squared Loadings		
Component	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	.946	4.731	66.965			
9	.871	4.353	71.318			
10	.806	4.031	75.349			
11	.771	3.856	79.205			
12	.714	3.568	82.773			
13	.626	3.131	85.904			
14	.553	2.764	88.669			
15	.501	2.506	91.175			
16	.452	2.262	93.436			
17	.376	1.878	95.315			
18	.353	1.765	97.080			
19	.330	1.651	98.731			
20	.254	1.269	100.000			

Table 3. 8: Results of factor analysis for ROM measurements

	Component						
	1	2	3	4	5	6	7
NF-Neck Flexion		-.713					
NE-Neck Extension		-.782					
LF-Lumbar Flexion						.758	
LE-Lumbar Extension						.788	
WF -Wrist Flexion	.679						
WE-Wrist Extension	.571						
KF- Knee Flexion							.621
KE -Knee Extension	-.423						
HF-Hip Flexion				.757			
HE- Hip Extension				.608			
HAb -Hip Abduction					.486		
HA-Hip Abduction		.649					
EE -Elbow Extension							.648
EF- Elbow Flexion	.495						
SF-Shoulder Flexion			-.772				
SA-Shoulder Abduction	-.528		.462				
SAb-Shoulder Abbuction		.472					
SE-Shoulder Extension	.748						
AP- Ankle Plantarflexion					.824		
AD-Ankle Doris flexion			.632				

Note. Eigenvectors lower than 0.4 were hidden in the table

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 no dominant 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 **Table C2** (see **Annexure C**) 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 (1966) 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 (1969) study on the U.S student population was unable to acquire any single general characteristic (dominant PC) for joint flexibility.

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

Table 3.9 presents a comparison of the anthropometric variables between the database of this study and (a) the general-population database of India (Chakrabarti, 1997); b) Indian drivers (Kulkarni et al., 2011); c) Indian drivers (Shamasundara and Ogale, 1999); d) Motorcyclists from Pune city, India (Amrutkar and Rajhans, 2011); e) British motorcyclists (Robertson and Minter, 1996); f) Nigerian motorcyclists (Imaekhai Lawrence, 2013). 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 (Chakrabarti, 1997) reveals high dimensional differences of 16%. As we can see from Table 3.9, most of the variables clustered between -1% to 16% dimensional difference. The stature and weight of motorcyclists, which are among the crucial anthropometric dimensions (Dasgupta et al., 2012), 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 (Guan et al., 2012 and Robertson and Minter, 1996), showing similar kinds of differences between the general and motorcycle/car driver population.

The comparative analysis with the driver population of India (Kulkarni et al., 2011; Shamasundara and Ogale, 1999) illustrates that the dimensional differences were ranged from -11% to 1%. The dimensional difference 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.

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When comparing present study with the anthropometric data of 70 motorcyclists from Pune (city of India) extracted from Amrutkar and Rajhans (2011), we found that the percentage differences were ranging from -11% to 11%. In particular, the knee height, buttock–popliteal length, lower-leg length, and shoulder–elbow length exhibited differences of more than 6% between the aforementioned two databases. Similar levels of percentage differences were found when the database of the present study was compared with India's general population (Chakrabarti, 1997). Moreover, it shows that the anthropometric dimensions of the Indian motorcyclist population (considering six zones) were higher than the dimensions of both generals (Chakrabarti, 1997) and specific city (Pune) (Amrutkar and Rajhans, 2011) population of India. Perhaps this could be the reason of comparing different type of sampling studies i.e. biased-sampling/ specific-location of the country and unbiased-sampling/ considering six zones of the country.

The Indian (present study) and British motorcyclist (Robertson and Minter, 1996) 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 -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

The dimensional differences between Nigerian (Imaekhai Lawrence, 2013) 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, most of the Indian driver's anthropometry were more or less similar to Indian motorcyclists (present study).

Table 3. 9: Comparative analysis - Anthropometric dimensions

		National database								International			
	Present study	Chakrabarti, 1997		Kulkarni et al., 2011		Shamasundara and Ogale, 1999		Amrutkar and Rajhans, 2011		Robertson and Minter, 1996		Imaekhai Lawrence 2013	
Gender and origin/ type of population	Male motorcyclist India	General male Indian		Indian drivers male		Indian drivers male		Motorcyclist of (Pune) city, India		Male motorcyclist UK		Male motorcyclist Nigeria	
Sample size (only male)	120	710		N/M		1091		N/M		108		160	
Anthropometric Dimension		M	%D	M	%D	M	%D	M	%D	M	%D	M	%D
W -Weight(in kg)	68	57	16	64	6	NA		NA		82	-20	N/A	
S - Stature	169	165	2	167	1	167	1	NA		177	-5	166	2
CH - Crotch height)	78	77	2	73	6	NA		76	2	82	-4	NA	
BE- Buttock extension	84	84	0	NA		NA		83	1	NA		NA	
EHS- Elbow height, Sitting	22	22	2	NA		NA		21	4	NA		NA	
KH -Knee height	55	52	6	NA		*49*	-11	51	7	54	2	52	6
LLL- Lower leg length	45	43	5	NA		NA		42	7	NA		42	7
SEL -Shoulder-elbow length	35	32	10	NA		*35*	-1	31	11	NA		NA	
EHL -Elbow-hand length	47	NA		NA		*46*	-2	NA		NA		NA	
BKL- Buttock-knee length	59	56	6	NA		NA		NA		63	-7	55	7
PL -Buttock-Popliteal length	49	46	7	NA		NA		45	8	NA		45	8
AL -Acromion grip length	63	NA		NA		NA		NA		66	-5	69	-9
BFL -Ball of foot length	18	NA		NA		NA		20	-11	NA		NA	
HL-Hand length	18	18	-1	NA		*19*	-3	18	1	NA		NA	
FB-Foot-breadth	10	NA		NA		*10*	-1	9	7	NA		NA	
EEB- Elbow-Elbow breadth	43	41	4	NA		NA		40	7	NA		NA	
HBS-Hip breadth, sitting	34	33	2	NA		*35*	-2	NA		38	-11	NA	

Note: M is mean values (All unit are in cm) of anthropometric dimensions; %D = Percentage differences; *Italic* style numbers are 50th percentiles values of anthropometric dimensions; NA - Not mentioned

Table 3. 10: Comparative analysis - ROM measurements

Gender and origin/type of population	Present study - Male Indian Motorcyclist	Chakrabarti, 1997 - General Male Indian	
Sample size	120	961	
ROM measurements	M	M	%D
NF -Neck Flexion	37	45	-21
NE -Neck Extension	40	30	24
LF -Lumbar Flexion	104	90	14
LE -Lumbar Extension	21	10	53
WF- Wrist Flexion	75	80	-7
WE -Wrist Extension	69	65	5
EE -Elbow Extension	2	NA	
EF -Elbow Flexion	140	145	-3
SF -Shoulder Flexion	164	180	-10
SE- Shoulder Extension	44	45	-3
HE -Hip Extension	17	20	-17
HF- Hip Flexion	107	110	-3
KF- Knee Flexion	128	135	-6
KE- Knee Extension	2	NA	
AP- Ankle Plantarflexion	36	45	-26
AD- Ankle Doris flexion	19	40	-33

Note: M - Mean values (All unit are in °) of ROM measurements; %D = Percentage differences; NA – Not mentioned

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 (Chakrabarti, 1997). Table 3.10 shows the variation in mean ROM difference between Indian motorcyclists with the general population (Chakrabarti, 1997). The average angular difference was -29% ranged from -33% to 53%. 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 population 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.

3.6 **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 are major important anthropometrics) 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 percentage difference ranging from -33% to 53% for ROM measurements and -20% to 16% for anthropometry dimensions. Particularly, it should be noted that the dimensional difference for ROM measurements were higher than the anthropometrics.

It is evident from the present 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 present research could be used for the ergonomic design of motorcycles for Indian users unless a larger database is generated considering insights of the present study.

Chapter – 4: Comfortable posture and optimum riding position for designing a motorcycle

Abstract:

Background and Objective: The riding comfort is considered an essential aspect of the market success of any electric/fuel-powered motorcycle. Many research articles reported about the musculoskeletal discomfort persists among the motorcyclists. This study aims to identify a comfortable riding posture (CRP) and an optimum riding position for designing a motorcycle. Method: 120 subjects (aged between 19 and 40 years) were selected for the experiment to evaluate the comfortable riding positions (RP) and CRP. The data was acquired using a static simulator test-rig in conjunction with the image processing technique. The optimum riding position was determined using the Taguchi optimization method. Taguchi's L9 orthogonal array was used for reducing the number of experiments. Three levels of four variables (related to distances between landmark positions defined in JASO T003:2009 standards) were considered as the control variables. The output response included subjective discomfort/comfort rating for ten different joints. The measurements were verified and validated using repetitive test techniques that ensured the anticipated level of the subjective perceived discomfort/comfort ratings. Results: A set of 10 postural joint angles and ten optimum riding position measurements (relate to the position of the handlebar, the seat, and the footrest) were found. The mean CRP (joint angles) for the ten joints, which were obtained from subject’s perceived CRP. Taguchi optimization method determined the best riding positions for improving the motorcycle design. Conclusions: The study outcomes provide effectiveness in the riding comfort at the expense of minimal changes to the motorcycle design.

4.1 Introduction

The automobile 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 2.5% (US$ 67 billion) to the country's GDP (US$ 2,652 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, 2019).

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 from 120 U.K motorcyclists (110 male and ten female) using a self-reported questionnaire. He found that 78% of the motorcyclists felt discomfort while riding a motorcycle. Karmegam et al. (2009) and Karmegam et al. (2013) 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. Most 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, 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 610km. They observed 95% of the rider’s perceived discomfort in the recent past, while 87% of them perceived predominant discomfort in the lower back 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 (Dutta et al. 2014). Mohan and Raghuathan, (2017) and Anoop and Binoosh, (2019) observed that most of the Keralites (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.

Many 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 both 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 (Rashid et al., 2015; Rashid et al., 2018; Balasubramanian and Jagannath, 2014).

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.

The existing and widely used Japanese Automobile Standards (JASO T003:2009; JASO T005:2009; JASO T006:2007) recommends the dimensional adjustability range for the three interface parts/points (handlebar, seat, and footrest) in the motorcycle frame. The experts established these standards by conducting a photography survey of 12 young (17-year-old) Japanese male (stature: 171±2cm) in 7 (different engine capacity) motorcycles. For example, the recommended handlebar width (end-to-end distance between handles) should be between 35cm and 80cm (JASO T003:2009). This wide range (35cm to 80cm) of dimensions could determine the riding position for a motorcycle rider. 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.

Also, it would be challenging for a designer to choose an optimum handlebar width that shall be within the range from 35cm to 80cm (as per JASO T003:2009), achieving maximum riding comfort. Hence, the present research has been planned to clarify the aforementioned issues related to the comfortable riding posture and position. The findings of the present 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 CRP and optimal riding position for comfortable riding experience. The study aims to answer two research questions (RQ):

RQ4: How can we define the comfortable riding posture (CRP) for a motorcyclist in terms of comfort joint angles?

RQ5: How can we define the optimum riding position in terms of interface point's (handlebar/ grip, seat, and footrest) dimensions of a motorcycle?

4.2 Methods and Materials

4.2.1 Experimental setup

The study objectives were achieved through experimentations on a static simulator (in-house experimental set-up, see Figure 4.1), 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., 2018).

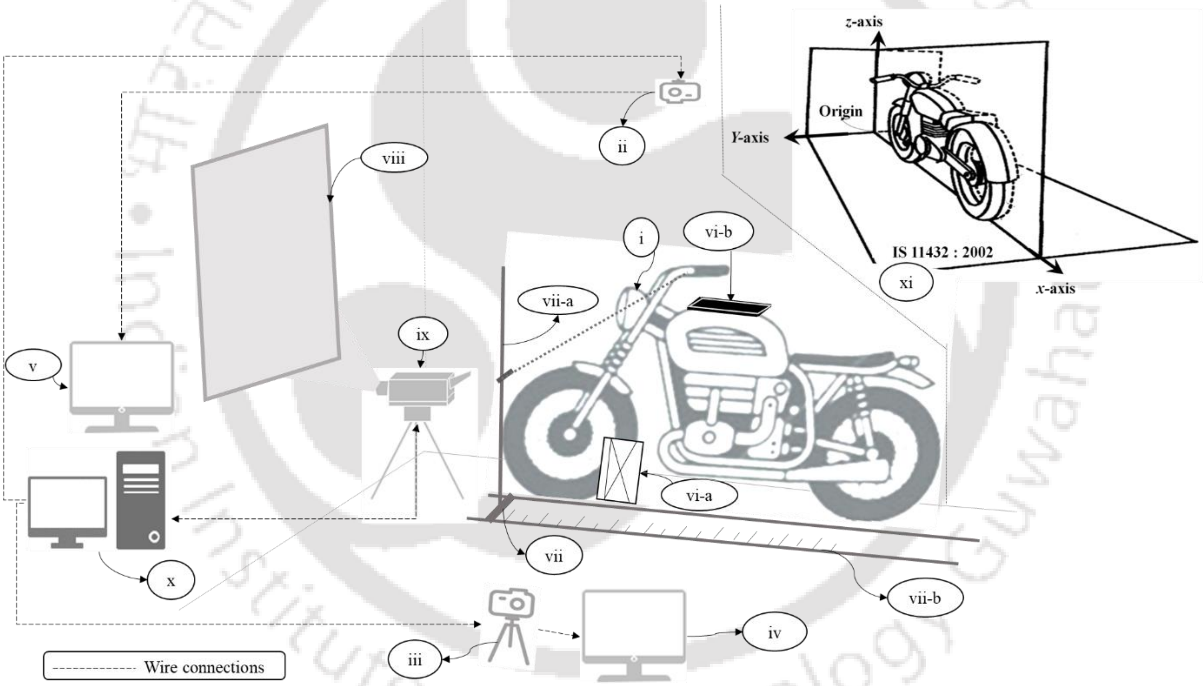

Figure 4. 1: Experimental mock-up - static simulator. Note: (i) Test-rig motorcycle; (ii) Camera – Top view; (iii) Camera-side view; (iv) Extended camera monitors for side view; (v) Extended camera monitors for top view; (vi-a) Calibration system of side view; (vi-b) Calibration system of top view; (vii) 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.

The experimental data of riding position and posture of the subjects were collected from a motorcycle test-rig (see Figure 4.1-i). This test-rig was 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 usable portion (F-point) of the footrest (of test-rig) was set at the distance of 100cm backward (along X-axis) and 35cm upwards (along the z-axis) and 0cm sidewise (along the y-axis) from the origin point (as shown in Figure 4.1-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 (120cm, 0cm, 366cm) from the origin to decrease the parallel axis error (Hung et al., 2004) (as shown in Figure 4.1-ii). Similarly, another camera was used to capture the side view (xz plane) of the subject. It was kept at the coordinates of (80cm, 457cm, 60cm) from the origin (see Figure 4.1-iii) to reduce the parallel axis error (Gavan et al., 1952). The extended camera monitor for both side and top view (see Figure 4.1-iv and 4.1-v) provided enlarged projections of the captured images and helped to ensure the precise focus on the subject. The calibration system of the side view kept along the xz plane of the motorcycle test-rig (as shown in Figure 4.1-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 Figure 4.1-vi-b). The role of the 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 Figure 4.1-vii). The setup had a vertical ruler with laser pointers for measuring the height of handle grip (as shown in Figure 4.1-vii-a) and seat from the floor (as shown in Figure 4.1-vii-b). The setup was installed parallel to the xz plane of the motorcycle test-rig at 91cm (3ft) distant from the frame (as shown in Figure 4.1-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), we created a riding simulation to provide a realistic riding experience to the subjects. Few short duration road-side simulation videos were played through the projector on the screen with the same procedure mentioned by Hsiao et al. (2015), Porter and Gyi, (1998), Barone and Curcio, (2004); Barone and Lo Iacono, (2015). The projector screen were kept at a distance of 182cm (6 ft) and 122cm (4 ft) from the motorcycle test-rig and the floor, respectively (as shown in Figure 4.1-viii and 4.1-ix). A master computer (HP ProDesk Intel i5-processor, windows 8.1) (as shown in Figure 4.1-x) was used to control the projector as well as both digital-cameras through wires (HDMI and USB).

4.2.1.1 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 motorcycle test-tig were determined based on a field survey (mentioned in the chapter 2) (Arunachalam et al., 2017) and JASO T003:2009, (2009) standards. Arunachalam et al. (2017) reported field measurements of handlebar/grip, footrest, and seat from 23 standard motorcycles (economy/executive) models in India.

The aforementioned study observed variations in handlebar (G'-point) from 56 to 99cm for forward-backward direction, 97 to 115.5cm for the vertical direction, and 69 to 77cm between handlebars (L). The variations of distances between footrests (O) were found to be 54 to 59cm. The seat (D-point) varied from 125 to 155cm for forward-backward direction, and 86 to 110cm for the vertical direction. During these measurements, the same coordinate system with origin point located in front of the motorcycle was followed as in the present study. All these measurements for the handlebar, footrest, and seat were found complied with the dimensional range recommended by the JASO T003:2009 standards.

According to the survey by Arunachalam et al. (2017), the handlebar inclination in most of the standard motorcycles was found at 20° which is similar to JASO T102-84, (1975) where 20° handlebar inclination was recommended along with handle grip length of 11cm, and handle grip width of 3.5cm (see Figure 2-a, right side corner). A commercially available smaller fuel tank (SAE J 1241, 2012; SAE J30, 1998) was deployed in the test-rig for maximum flexible lateral thigh moments (adduction/ abduction) of the subject. A normal footrest (pad) having a length of 8.5cm (standard, commercially available) was installed in the motorcycle test-tig.

The handlebar and footrest were provided some adjustability features to allow the rider/ subject to set these according to their requirement of perceived comfort. The range of adjustment was given to both handle grip and footrest by 5cm at their longitudinal centreline along the xy plane (Figure 4.2-a). Moreover, a range of 20cm in vertical (in xz plane) and 25cm in a horizontal direction for the handlebar were provided (Figure 4.2-b). The seat in the test rig could be adjust up to 25cm vertically in the xz plane as per the comfort of the rider.

The range of seat dimensions (see Figure 4.2-a, right side corner) was decided based on the measurement of 23 standard motorcycle models (See chapter 2, Table 2.3) (Arunachalam et al., 2017). The survey revealed that the motorcycles had the following seat dimensions: front width (mean: 14cm; SD: ± 2cm), narrowest width (mean: 21cm; SD: ± 2cm), the distance between the front width and narrowest width (mean: 15cm; SD: ± 2cm) and the widest length (mean: 36cm; SD: ± 9cm). Except for the SD of widest length dimension, all other seat dimensions had less variability. Therefore, the mean dimensions of the seat were considered for the experiment. The greatest length of the seat was decided as 45cm for providing a maximum sitting surface for a subject.

The seat used for the experiment had flat seat contour (no curvature or zero seat depth) with normal seat foam (open-cell polyurethane, density = 82 kg/mm3, hardness = 21 kgf; measured by Durometer with 30° included angle) (Velagapudi and Ray, 2019) as found in standard motorcycle model in India. The effect of different seat contours on sitting comfort yet to be studied for the economy/standard 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 ten minutes). Hence, the effect of seat design and contour was not taken into consideration in the present experiment of short-duration riding.

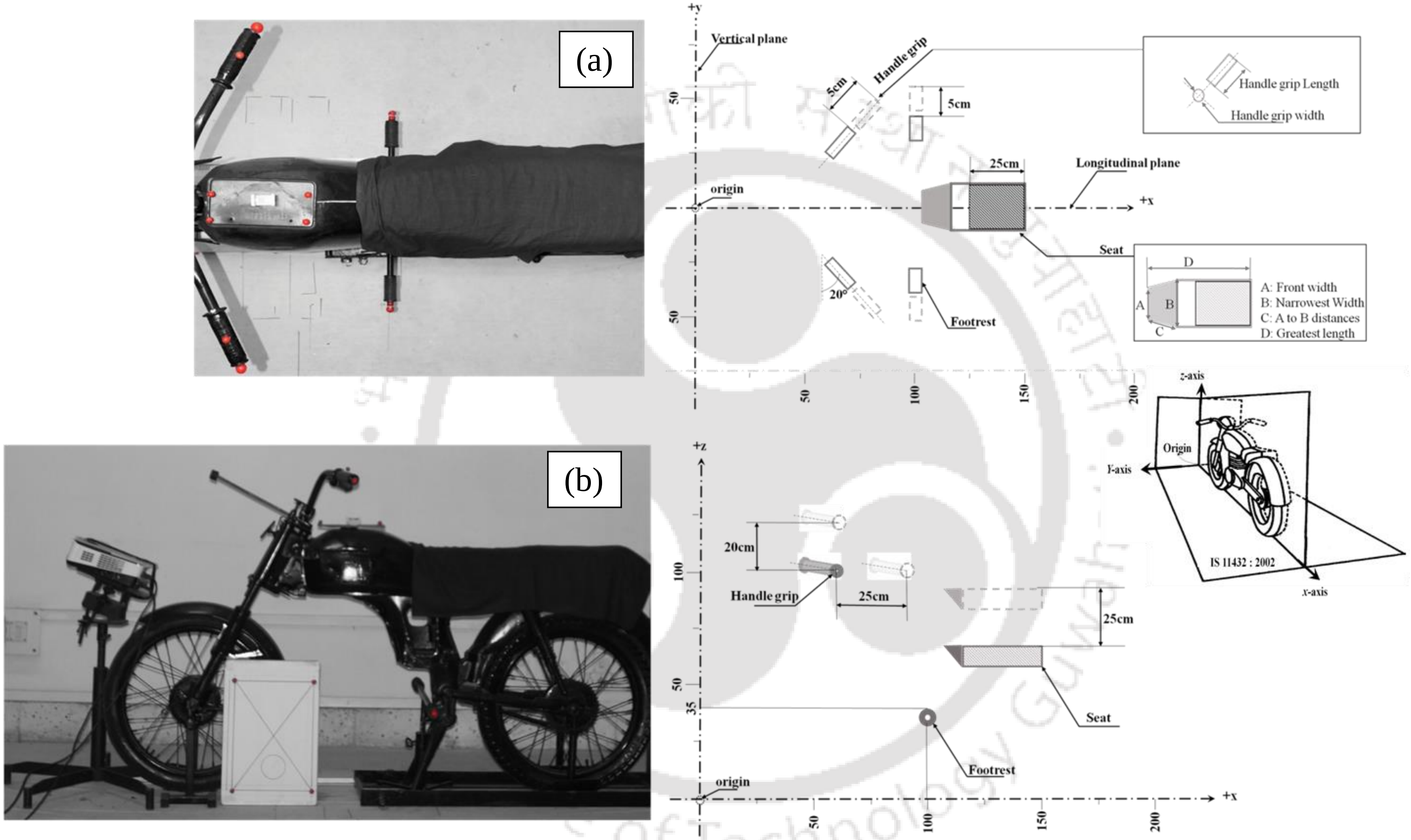

Figure 4. 2: Adjustable ranges of handle grip, footrest, and seat. (a) Topview adjustability features and (b) Side view adjustability features

4.2.2 Riding posture and position acquisition approach

4.2.2.1 Definition of riding position

The landmarks used to measure the riding position were shown in Figure 4.3. To locate landmarks on the test-rig, red spherical markers (Ø 19mm) were placed on the respective test-rig landmark 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 usable 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 handlebar/grip, while G'-point is located at the central and the farthest end of the usable portion of the handlebar/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.

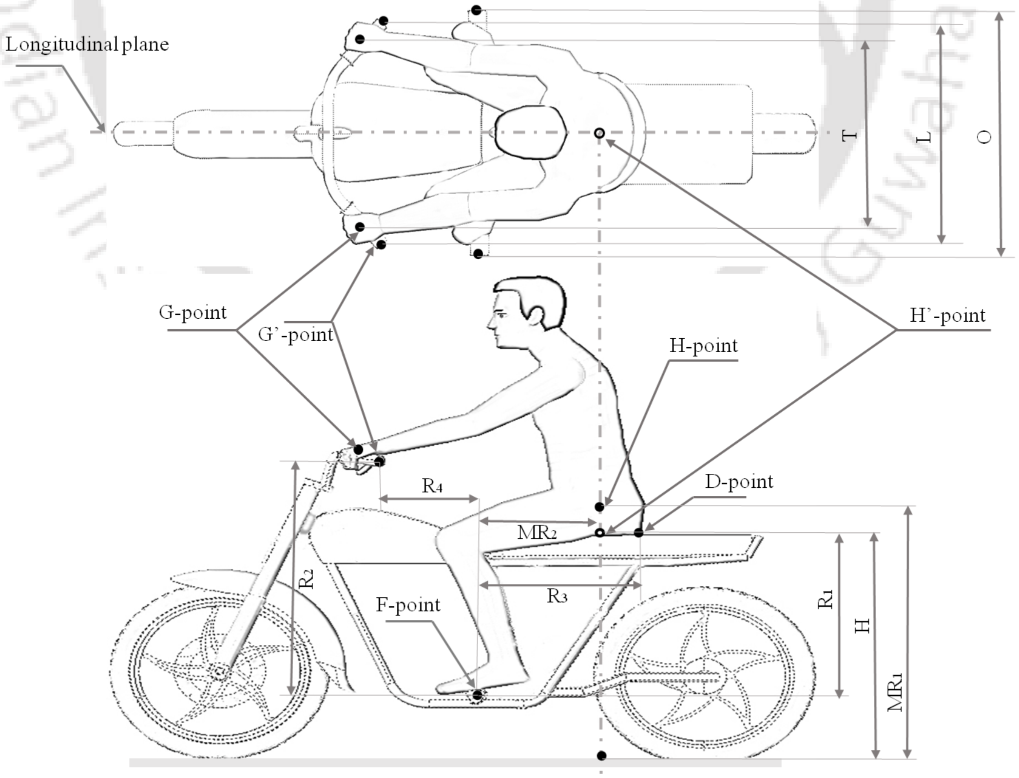

Figure 4. 3: Landmarks for measuring riding position

As evident from the Figure 4.3, these landmarks for riding position depends on the three key interface points, i.e., seat, handlebar/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 Shamasundara and Ogale, (1999). The F-point was fixed at a height 35cm from the ground and 100cm from the origin (see Figure 4.2-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 handlebar/grip
- L represents the distance between the G'-points on the right and left handlebar/grip
- 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 Figure 4.3) 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).

The ten body-joint angles (θ_1 to θ_{10}) in riding posture were defined through the subject's body landmark (as shown in Figure 4.4), 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 19mm) were affixed on the respective body locations to highlight the coordinate of the landmarks. The 2D coordinate (x, y) of these body landmarks were substituted in the equation (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).

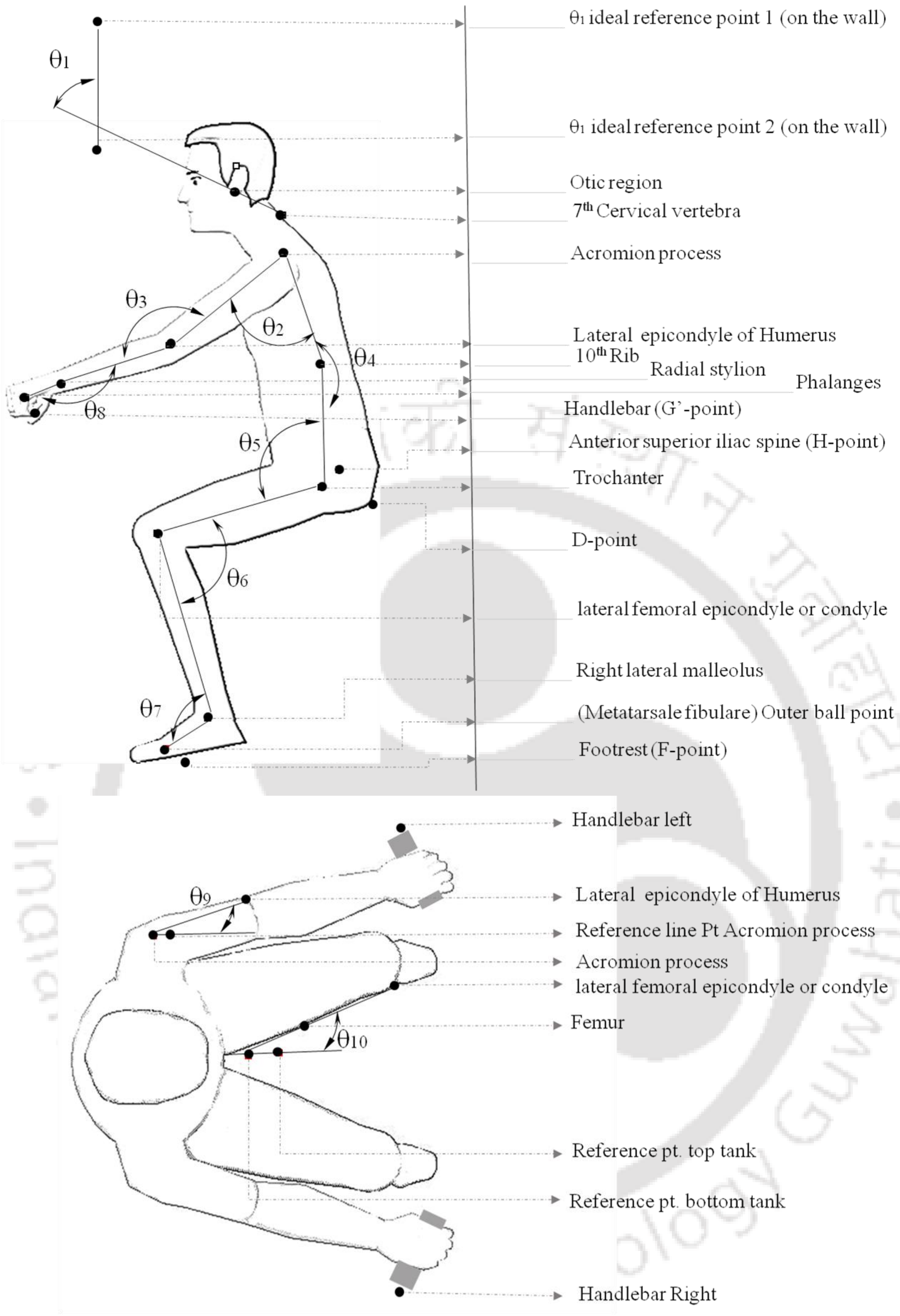

Figure 4. 4: Landmarks for measuring postural joint angles

Note: – Two red markers were affixed on the background wall of the subject (as shown in **Appendix D1)** to locate the θ_1 ideal reference points 1 and 2. Two red markers were affixed on the seat (as shown in **Appendix D2**) to locate the θ_{10} ideal reference points 1 and 2.

θ_2 to θ_9 can be determined by using equation 1. The coordinates of the lateral epicondyle of the humerus (x_1, z_1), acromion process (x_2, z_2), and 10th rib (x_3, z_3) were considered for computing θ_2 (shoulder angle). θ_3 (elbow angle) was computed from the coordinates of the acromion process (x_1, z_1), lateral epicondyle of the humerus (x_2, z_2), and radial styloid (x_3, z_3). θ_4 (lower-back angle) was estimated via the coordinates of trochanter (x_1, z_1), 10th rib (x_2, z_2), and acromion process (x_3, z_3). θ_5 (hip angle) was computed by the coordinates of 10th rib (x_1, z_1), trochanter (x_2, z_2), and lateral femoral epicondyle (x_3, z_3). θ_6 (knee angle) was estimated through the coordinates of trochanter (x_1, z_1), lateral femoral epicondyle (x_2, z_2), and right lateral malleolus (x_3, z_3). θ_7 (ankle angle) was computed via the coordinates of lateral femoral epicondyle (x_1, z_1), right lateral malleolus (x_2, z_2), and metatarsale fibulare (x_3, z_3). θ_8 (wrist angle) was estimated by the coordinates of phalanges (x_1, z_1), radial styloid (x_2, z_2), and lateral epicondyle of the humerus (x_3, z_3). θ_9 (shoulder abduction/ adduction angle) was computed by the coordinates of the lateral epicondyle of the humerus (x_1, y_1), acromion process (x_2, y_2), and extended point of acromion process (x_3, y_3). Figure 4.5a illustrates the estimation of the knee angle (θ_6) utilizing the respective coordinates for computing the slopes (tan α and tan β).

θ_1 and θ_{10} can be determined by equation 2. The coordinates considered to compute θ_1 (neck angle) were 7th cervical vertebra (x_1, z_1), θ_1 ideal reference point 1 (on the wall) (x_2, z_2), otic region (x_3, z_3) and θ_1 ideal reference point 2 (on the wall) (x_4, z_4). The coordinates considered to compute θ_{10} (hip abduction/adduction angle) were femur (x_1, z_1), θ_{10} ideal reference point 1 (on the seat) (x_2, z_2), lateral epicondyle of the humerus (x_3, z_3) and θ_{10} ideal reference point 2 (on the seat) (x_4, z_4). Figure 4.5b has been used to illustrate the application of equation 2 for the estimation of the hip abduction/ adduction angle (θ_{10}).

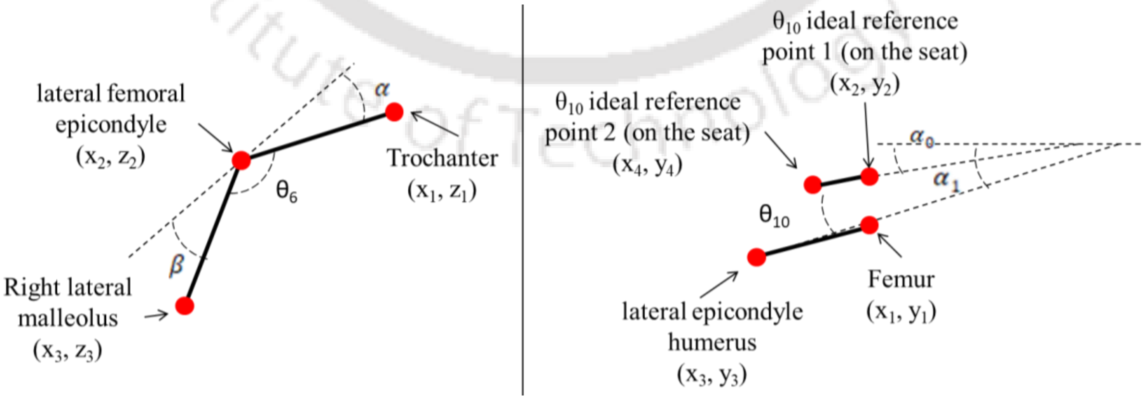

Figure 4. 5: Representation of (a) application of equation 1 for estimating knee angle (θ_6) and (b) application of equation 2 for estimating hip abduction/ adduction angle (θ_{10}).

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

Where, $\tan\alpha = \frac{y_1 - z_2}{x_1 - z_2}$

$\tan\beta = \frac{z_3 - z_2}{x_2 - x_3}$

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

Where,

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

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

4.2.2.2 Digital image processing (DIP)

The image processing technique was used to extract the desired information (2D coordinates of the landmarks) from the collected images. Generally, the DIP technique follows three subsequent steps: (1) Input - acquisition of the image (into the software); (2) Operation – manipulation and analysis to extract the information from the image; (3) Output – altered images with the desired information. Among these three steps, second (operation) being the most critical depends upon the captured digital image consisting of two-dimensional function (f) of pixel arrays (x, y). So, it could be represented as f (x, y), where x and y are the space (plane) coordinates. Figure 4.6 demonstrates an example of an image captured in color filtration mode and displaying the landmarks of a wooden manikin. These coordinates were identified through a code programmed in the MATLAB R2016a. The algorithm adopted for MATLAB program follows the below steps:

Input: Image (I), ɽ (threshold), p -› red components
Output: Co-ordinates (x, y)
Step – I: Read the Image I
Step – II: Convert the image to grayscale format
Step – III: Use the ɽ to covert the grayscale image to the binary image
Step – IV: Contract the center pixel of all black points in a binary image
Step –V: Create the label matrix with p red components
Step –VI: Label all the co-ordinates with red colors

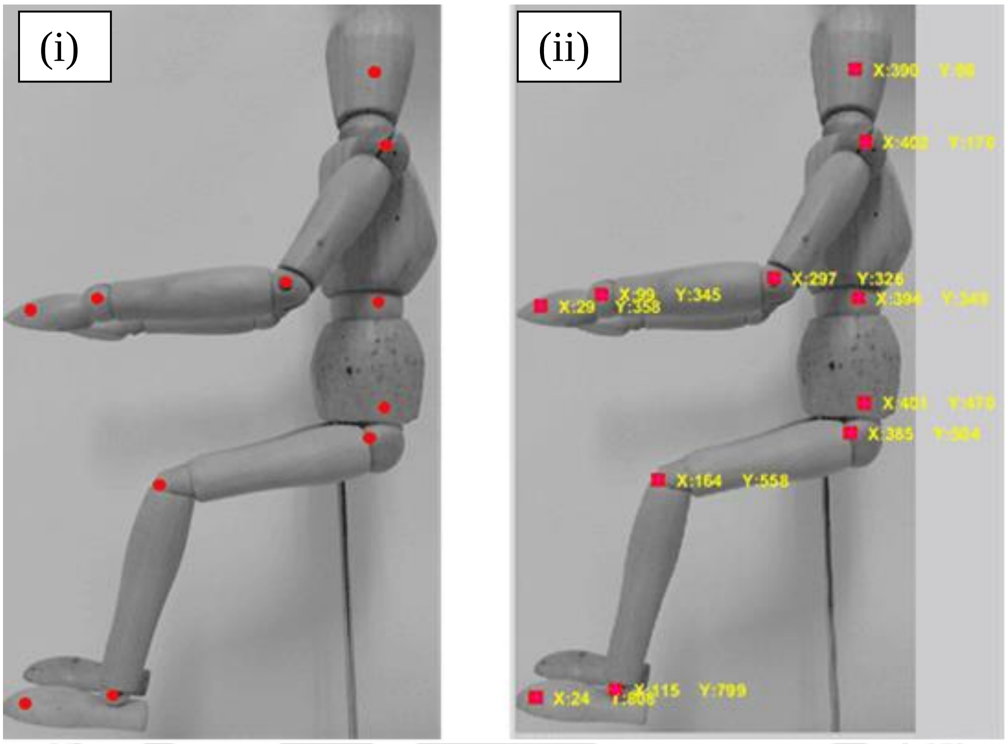

Figure 4. 6: Demo of Image processing – performed on a wooden manikin (i) Input image with red markers on body landmarks; (ii) Output image with respective coordinates (x, y).

This DIP technique was used to obtain the *(x, y)* coordinates of the landmarks (shown in Figures 4.3 and 4.4). 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 red spherical markers (Ø 19mm) placed on the body landmarks. These images were captured using side/top-view cameras with colour filtration mode to locate the landmarks in the images (shown in **Appendix D1 and D2**).

Image calibration:

These images were calibrated using two rectangular boards (Figure 4.1-vi-a and 4.1-vi-b) of known size were used to calibrate the captured images. The detailed procedure adopted while calibrating the images was elaborated in **Appendix E**. Calibration results of the images showed that the resolution of the side-view image was 5456 x 3064pixels. With an actual dimension of 34cm x 25cm, the average estimated resolution of the calibrated image of the rectangular board (side-view) was 389.59 x 280.88 pixels (SD = 11.93 x 8.5pixels) for all the 120 images (for 120 subjects). Therefore, each pixel of the side-view image was estimated at 0.087cm. Further, the mean and SD of the percentage of error deviation in angular (AEd%) and dimensional (Ed %) measurements calculated as 1 % (±1.96) and 0% (±0.26), respectively, for the side-view images.

Similarly, the resolution of the top-view image was 3872 x 2176pixels. With the actual dimension of 6cm x 19cm, the average estimated resolution of the calibrated image of the rectangular board (top-view) was 121.83 x 393.38pixels (SD = 24.02 x 70.69pixels). Therefore, each pixel of the top-view image was estimated at 0.049 cm. The mean and SD of Ed% and AEd% calculated as 1 % (±3.24) and 1.74% (±1.42), respectively, for the top-view images.

Overall, the calibration results (Ed% and AEd%) of the side and top-view images were found to be precise enough and within the recommended maximum error tolerance of ±3.24%, in-line with the previous literature (Gavan et al., 1952; Hsiao et al., 2015; Hung et al., 2004).

4.2.3 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 (CRP) (perceived discomfort/comfort)/ main experiment and (2) Experiment for estimating optimal riding position (using Taguchi methods). 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 in 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 4.2.2.1), 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 for 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).

4.2.3.1 Experiment for estimating comfortable riding posture (CRP)/ Main experiment

Sample size:

Among four hundred seven million motorcyclists in India, 92% are male motorcyclists within the age group of 19 to 44 years (Government of India, 2018). Therefore, the data collection and related measurements were focused on the aforesaid dominating users. Since the present experiment is the subsequent part of a longitudinal study (Arunachalam et al., 2020), the same 120 randomly selected male subjects aged between 19-44 years (M: 29 and SD: 8.8) were invited to participate. Referring to the minimal sample size estimation devised by the International Organization for standardization (ISO 15535:2012), equation 3 provided the calculated sample size for the study as (n ≥) 117.

$$n \geq \left(1.96 \times \frac{\left(\frac{SD}{M} \times 100\right)}{\alpha}\right)^2 \times (1.534)^2 \qquad (3)$$

Where, n = sample size and; SD = Standard Deviation and M = Mean; relative accuracy (α) = 1% (assuming 95% confidence level).

For unbiased estimation, the minimum sample size was decided by descriptive of stature data mean value ($\bar{x}$=167.5cm), SD (6.1 cm) referred from the reputed (SIZE India) database of Indian drivers (Kulkarni et al., 2011). Since driver's stature dimension is crucial anthropometric dimension for a PCA studies (Dasgupta et al. 2012), we have used stature to estimate the sample size in this study. Before starting the experiment, subjects were informed about the experimental protocol. It consisted of four subsequent steps: (1) Iterative process, (2) Anthropometric measurements, (3) Perceived discomfort/comfort evaluation, (4) Computing weighted comfort joint angle.

Iterative process:

Also called "method of fitting trials" (Jones, 1969), the iterative process helped the subjects to achieve a comfortable posture (CRP) through adjustment of the handgrip, seat, and footrest. Initially, the subjects were asked to sit on the motorcycle test-rig and attain a CRP. Subsequently, a (motorcycle simulation) video was played on the white screen for their continuous attention towards the experiment. After every 2 minutes, the subject was 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 again 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.

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.

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 discomfort/comfort evaluation), during this interval time, anthropometric data were recorded. Basic anthropometric variables like weight and stature were measured using the anthropometric kit and weighing machine, respectively. The mean (SD) of weight and stature of the 120 subjects were found as 68 (11) kg and 169 (7) cm, respectively.

Perceived discomfort/comfort evaluation:

This test was conducted to confirm whether the comfortable posture/position were best or not. Once the subject seated on the test-rig, approved as comfortable posture/position in the “iterative process”, the red markers were fixed at the landmarks (as mentioned in subsection 4.2.2.1) by the experimenter. A 5 min riding simulation video was played in front of the rider through the projector on the white screen. During the 5 minutes, subjects were informed to identify/ perceive discomfort/comfort at their body joints. The duration (5 min) was decided based on the previous studies Grainger et al. (2017) and Barone and Curcio (2004), who have also assessed subjective discomfort while riding scooter/bicycle under laboratory conditions. During this duration (5 min), the experimenter captured images (as shown in **Appendix D1 and D2)** from the top and side-view. Later, these images were processed using Matlab (as mentioned in subsection 4.2.2.2), and coordinates of the red markers on body-landmarks were noted in the MS Access Form (as shown in **Appendix F1 and F2**).

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 (as shown in **Appendix G1 and G2).** This questionnaire had three subsections, including (1) General information; (2) Discomfort rating scale; and (3) Comfort rating scale. Since, no instrument can directly measure the postural discomfort/comfort (based on joints angles) (De Looze et al., 2003; Mansfield et al., 2020; Vink and Hallbeck, 2012), the study used a subjective method (perceived discomfort/comfort rating scale). Some researchers used both discomfort and comfort scales to check the alternative forms of reliability (De Looze et al., 2003; Helander and Zhang, 1997; Kee and Lee, 2012; Mansfield et al., 2020; Vink and Hallbeck, 2012). Similarly, complying with the existing literature, in the present study, we used two different scales, one for discomfort and others for comfort. Alternative form of reliability was also evaluated to check the degree of consistency among subject's perceived discomfort and comfort ratings (explained in subsection 4.2.3.4). The discomfort ratings (as shown in **Appendix H**) 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. The subject were asked to perceive and report discomfort/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). 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 (see **Appendix- G1**) 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 (see **Appendix- G2**) was measured based on the SAE (2000) which was included to establish 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.

Computing weighted comfort joint angle:

The weighted comfort joint angle can express the combined impact of the joint angles obtained for the CRP 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 cannot be the same among subjects, the comfort rating-weighted joint angle can be used to normalize the joint angles of the subjects. Hence, the mean and standard deviations (or tolerance) of weighted comfort joint angles were estimated using equation (4) and (5), respectively. These equations were adopted from previous studies (Chou and Hsiao, 2005; Deng et al., 2015).

$$\theta_{wj} = \frac{\sum_{n=1}^{120} \theta_{jn}\, w_{jn}}{\sum_{n=1}^{120} w_{jn}} \qquad (4)$$

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

$$\Delta\theta_{wj} = \frac{\left|\theta_{wj} - (\theta_{nwj})_{max}\right| + \left|\theta_{wj} - (\theta_{nwj})_{min}\right|}{2} \qquad (5)$$

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 the weighted comfort joint angle of the total subjects.

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

Sample size:

In this experiment, the two-stage cluster sampling 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, 120 subjects (from the main experiment) were randomly clustered into three percentile bandwidth groups. The percentile bandwidths for clustering the groups were chosen as below $P_{30\%}$, $P_{30\%}$ to $P_{70\%}$, and above $P_{70\%}$ (Kong et al. 2005). In each cluster, 3 subjects was formed and randomly chosen during the cluster 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).

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, the 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), a 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 incurring, which in turn might cause biased results. Therefore, Taguchi L9 orthogonal array that allowed to reduce 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 4.1.

Table 4. 1: Descriptive of the subjects (n=120) - Comfortable riding positions (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	91	4	26	79	105	85	91	96
MR_2	26	5	23	15	38	18	25	37
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 handlebar/grips; L represents the distance between the G'-points on the right and left handlebar/grips; O represents the distance between the F-points on the right and left footrest.

Among the ten variables of riding position, the variability was minimal among the three variable viz. L, T, and O. Hence, the mean dimension of these variables considered to be an optimum and fixed parameter in the Taguchi DOE. Since MR_1 and H dimensions were strongly correlated with the R_1 dimension (as shown in **Appendix I**), only R_1 was considered instead of MR_1 and H. Similarly, MR_2 was strongly correlated 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 a 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 (bicycle) lies between within one standard deviation (i.e., mean ± 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 a new group of subjects in the confirmation test. Based on the explanation above, the L9 (partial) orthogonal array of Taguchi DOE considered for the present experiment. Thus, the L9 orthogonal array (nine test conditions) was generated using Minitab 17 (as shown in Table 4.2).

Table 4. 2: Test Conditions for Taguchi DOE (control variables and levels) (Unit: cm)

Test Condition	R_1	R_2	R_3	R_4	L^*	T^*	O^*
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			

*L, T, O were fixed parameters for all test conditions

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 the physical/ cognitive state of a person (Rowe et al., 1998 and 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 an automatic blood pressure monitor (Model: OMR223, Make: Omron). The mean HR of the subjects measured in the nine subsequent days were shown in **Appendix J**. The HR were in-line with the inter heart rate recommendations by Tan et al., (2011) for healthily subjects.

Following HR measurement, the subjects were asked to sit on the test-rig for 5 minutes, which was adjusted to the test conditions, respectively. During this period, subjects were asked to feel discomfort/comfort (if any) in body joints/parts. After 5 minutes, subjects were asked to rate the overall body discomfort/comfort using the same questionnaire mentioned in section 4.2.3.1 (perceived discomfort/comfort evaluation). The mean rating scores of the three groups from the nine test conditions were analysed. The observations have been presented in the results and discussion section 4.3.2.

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 (6) was used to determine the S/N ratio of overall discomfort ratings from nine test conditions. Similarly, “Lager is better” equation (7) was used to estimate the S/N of overall comfort ratings.

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

$$\frac{S}{N}ratio = -10log\left(\frac{\sum_{i=1}^{n}\frac{1}{y^2}}{n}\right) \tag{7}$$

4.2.3.3 Reliability evaluation of joint angles and riding position measurements

Manual (using goniometer and laser pointer based measuring setup) and image (using digital image processing - DIP) 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 (joint angles and riding position) from these two measurement methods (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 measurements, images of the rider and test-rig were captured with red makers, which was affixed by an observer on the landmarks mentioned in section 4.2.2.1. Later, these images were processed in the DIP to ensure the image-based measurements.

The alternative-form of reliability (correlation coefficients) between manual and image-based measurements were found from 0.92 to 0.98, significant (p < 0.05). Likewise, for (joint) angular measurement, the correlation coefficients were found from 0.94 to 0.99, significant (p

< 0.05). Several previous investigations (Heale and Twycross, 2015; Mohajan, 2017; Mukaka, 2012) approved that the measurements could be considered consistent and reliable for alternate-form reliability (correlation coefficients) values higher than 0.90. Therefore, the image-based measurements would be trustworthy for the further survey.

4.2.3.4 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 the 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 4.2.3.2).

Early research by Mukaka, (2012) and De Looze et al., (2003) stated that the correlation coefficient between -0.7 to -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 discomfort/comfort rating showed a strong negative correlation. Hence, the perceived responses to comfort could be considered reliable for further analysis.

4.3 Results and Discussion

One hundred twenty 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).

4.3.1 Experiment for estimating comfortable riding posture/ Main experiment

The postural variables were measured/ estimated, as stated in the earlier subsection (4.2.2.2). Tables 4.3 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. 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

Table 4.4 summarizes the frequency distribution of the comfort rating among 120 subjects during the main experiment (Refer 4.2.3.1), whereas the frequency distribution of discomfort rating was presented in **Appendix H.** It could be observed from Table 4.4 that most of the subjects rated beyond a comfort score of 5 (marginal comfort) after their main experiment.

Table 4. 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 4.5 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 4.5 are critical for evaluating the riding posture as one of the research questions was related to exploring the comfortable riding posture (CRP) (joint angle) for the motorcyclists.

Table 4. 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		
					5^{th}	50^{th}	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

To visualize the weighted comfort joint angles ($\theta_{wj} \pm \Delta\theta_{wj}$) presented in Table 4.5, the digital manikin/ human model (DHM) was created (using CATIA V5 software) with a CRP by incorporating these angles (Figure 4.7). This presentation of weighted comfort joint angles in manikin would help the readers to apprehend the primary objective of the present study, i.e., the suggested angles for comfortable motorcycle riding.

This study is first of its kind to present a summary of comfort angles for motorcycles. The values of weighted comfort joint angles from the present study were further compared (in tabular format) with the data obtained in other earlier studies, which followed similar joint angle measurement procedures (Table 4.6). Other studies considered for this purpose included a) Indian sport motorcycle riders (Jeyakumar and Gandhinathan, 2014); b) Nigerian motorbike riders (Imaekhai 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). While comparing, seven angular variables (θ_{W2} - θ_{W8}) were taken into consideration from the aforesaid literature. Neck angle (θ_{W1}) was excluded for the comparison in Table 4.6 and Figure 4.8 since the neck angle measurement adopted in the present study was different from earlier studies.

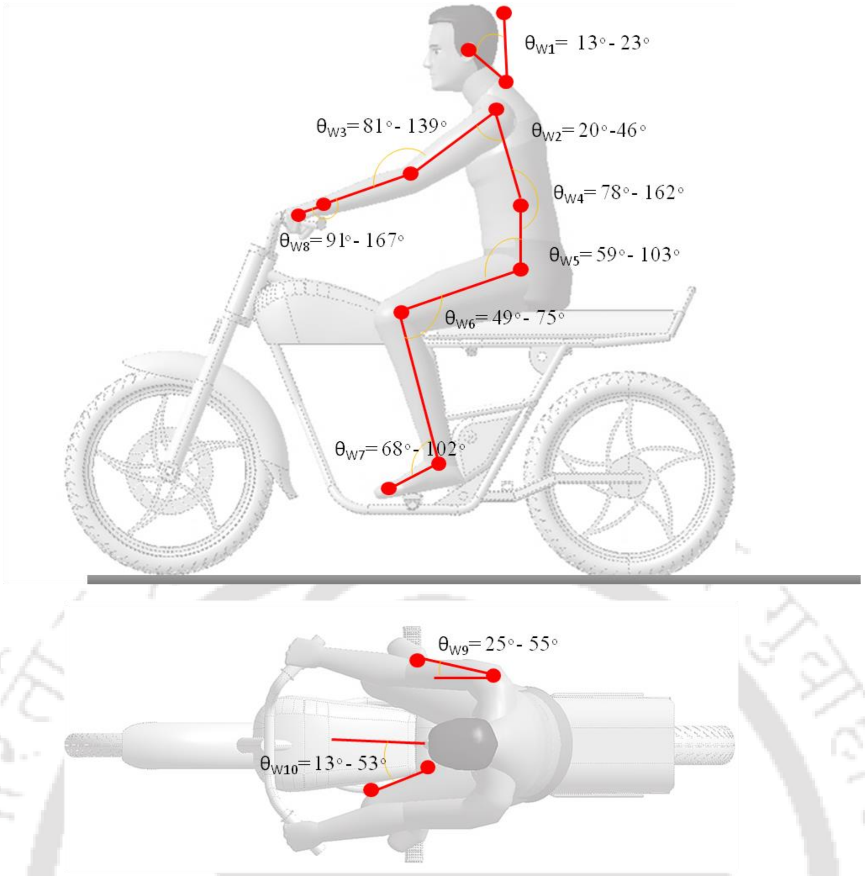

Figure 4. 7 : $\boldsymbol{\theta_{wj}} \pm \Delta\boldsymbol{\theta_{wj}}$ Comfort riding posture (CRP) (joint angles) (Unit: °) in a motorcycle design

In most of the previous studies, only riding postures at the static conditions in the Sagittal plane (θ_{W1} - θ_{W8}) were studied. However, in the present research, researchers have considered the transverse plane to record the abduction/ adduction angles of the hip and shoulder joints (θ_{W9} and θ_{W10}). 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 the figure 8. Whereas, other studies do not consider 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 Figure 8.

Table 4. 6: Tabular comparison of comfort joint angles (Unit: ◦) of the riding posture for the present study with previous studies

	Population/ Sample Size/ Type of two-wheeler	Shoulder	Elbow	Lower back	Hip	Knee	Ankle	Wrist
Present 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

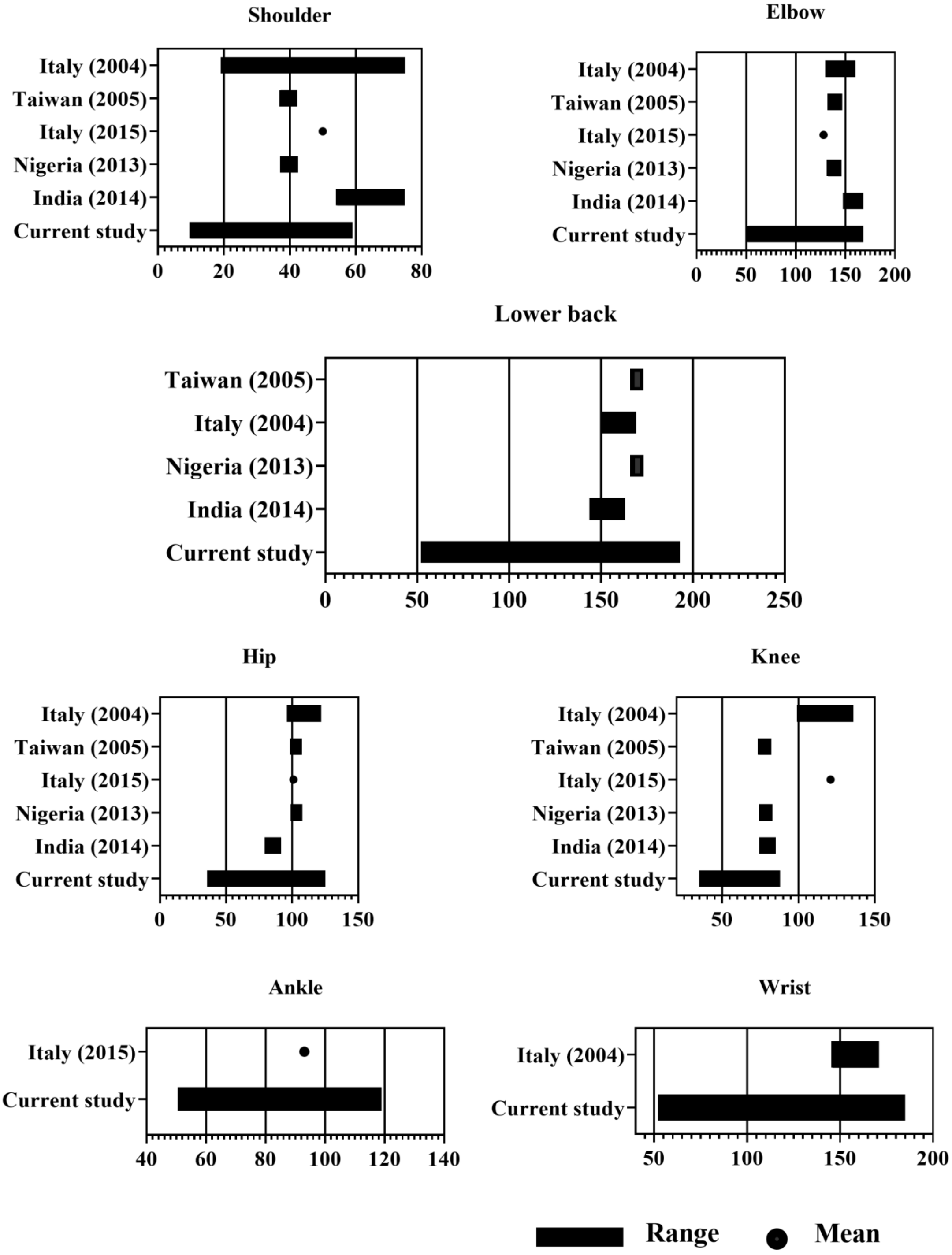

Figure 4. 8 : Demonstration of graphical comparative analysis of the CRP across different countries. Note: *x*-axis unit: ◦. The bar graph represents the minimum and maximum comfort joint angles ranges. Dot plot represents the mean of comfort joint angles

The observed range of comfortable shoulder angle (from 10°- 59°) in the present study corroborates with range obtained by Barone and Curcio, (2004) (Italian scooter study). Lawrence (2013) and Chou and Hsiao (2005) got a narrow range from 37° to 42° and 38° - 43° with the mean values (40°) much higher than the present study (33°). Moreover, the observation from the present study was different from the suggestion of Barone and Lo Iacono, (2015) and Jeyakumar and Gandhinathan (2014), who collected measurements in 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. The comfortable range of elbow angle obtained in the present study was 52° – 168° with a mean value much lower than the suggested angle by Barone and Lo Iacono (2015) and Jeyakumar and Gandhinathan, (2014). But it coincided with the observations made by Barone and Curcio, (2004), Lawrence, (2013) and Chou and Hsiao, (2005). Concerning the lower back angle, the present study obtained range (53°- 193°) cover the suggested range of Jeyakumar and Gandhinathan, (2014). Barone and Lo Iacono (2004) found a lower-back angle ranging from 150° to 169°, with a mean value slightly higher than the present study. It was somewhat different from the suggestions recommended by Lawrence (2013) and Chou and Hsiao, (2005). For the hip angle, the present study range (37°- 125°) was in agreement with the range observed by Jeyakumar and Gandhinathan, (2014). Barone and Lo Iacono, (2015), Lawrence, (2013), Chou and Hsiao, (2005) and Barone and Curcio, (2004) observed a narrow range of hip angle with a mean value much higher than the present study. Regarding the comfortable knee angle, ranges suggested by Jeyakumar and Gandhinathan, (2014), Lawrence (2013) and Chou and Hsiao, (2005) were found slightly narrower with its mean value relatively higher than the present study. Barone and Curcio (2004) recommend the range (99°- 136°), which does not comply with the present study. Moreover, most of the subjects in the present study perceived better comfort in the inclined backward sitting position (see **Appendix K** for the measurement method of inclined forward/backward sitting position).

The empirical evidence from the comparison (Table 4.6) depicts that the majority of the early studies ignored considering minor segments (body parts) like ankle and wrist joint angles. However, Barone and Curcio (2004) and Barone and Lo Iacono (2015), during their measurements, only considered ankle and wrist joint angle, respectively. The range of comfortable ankle angle in the present study was slightly lower than the suggestions by Barone and Curcio (2015), whereas the range of the comfortable wrist angle the present study is covered the range reported by Barone and Lo Iacono (2004).

4.3.2 Experiment for estimating optimal riding position (using Taguchi methods)

The estimated S/N has been presented in Table 4.7 with mean discomfort/comforts rating scores of the 3 groups (< $P_{30\%}$ - short, $P_{30\%}$ to $P_{70\%}$ - medium, < $P_{70\%}$ - taller).

Table 4. 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: Group tall – stature above 175cm; Medium group - stature from 174cm to165cm; Short group - stature below 165cm. [a]Rating consisted of a 5-point scale. [b]Rating consisted of the 10-point scale

All groups reported a maximum level of comfort rating and the minimum level of discomfort rating for the 4th test condition (R1 → 48cm, R2 → 65cm, R3 → 34cm, R4 → 17cm) when compared with other test conditions. Based on these ratings, the calculated S/N ratio of the 4th test condition was found to be optimal. Perhaps, the reason for higher compatibility with the 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 a lower leg length of the 50th percentile of Indian motorcyclist (is 44cm) (Refer chapter 3, Table 3.1) (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 of 5th percentile of Indian motorcyclist's acromion grip length (is 55cm). 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 a higher level of discomfort. For example, R_3 and R_4 (horizontal distance between the F-point and G-point) 71cm was even more than 95th percentile value of acromion grip length (is 70cm) of Indian motorcyclist (Refer chapter 3, Table 3.1) (Arunachalam et al., 2020).

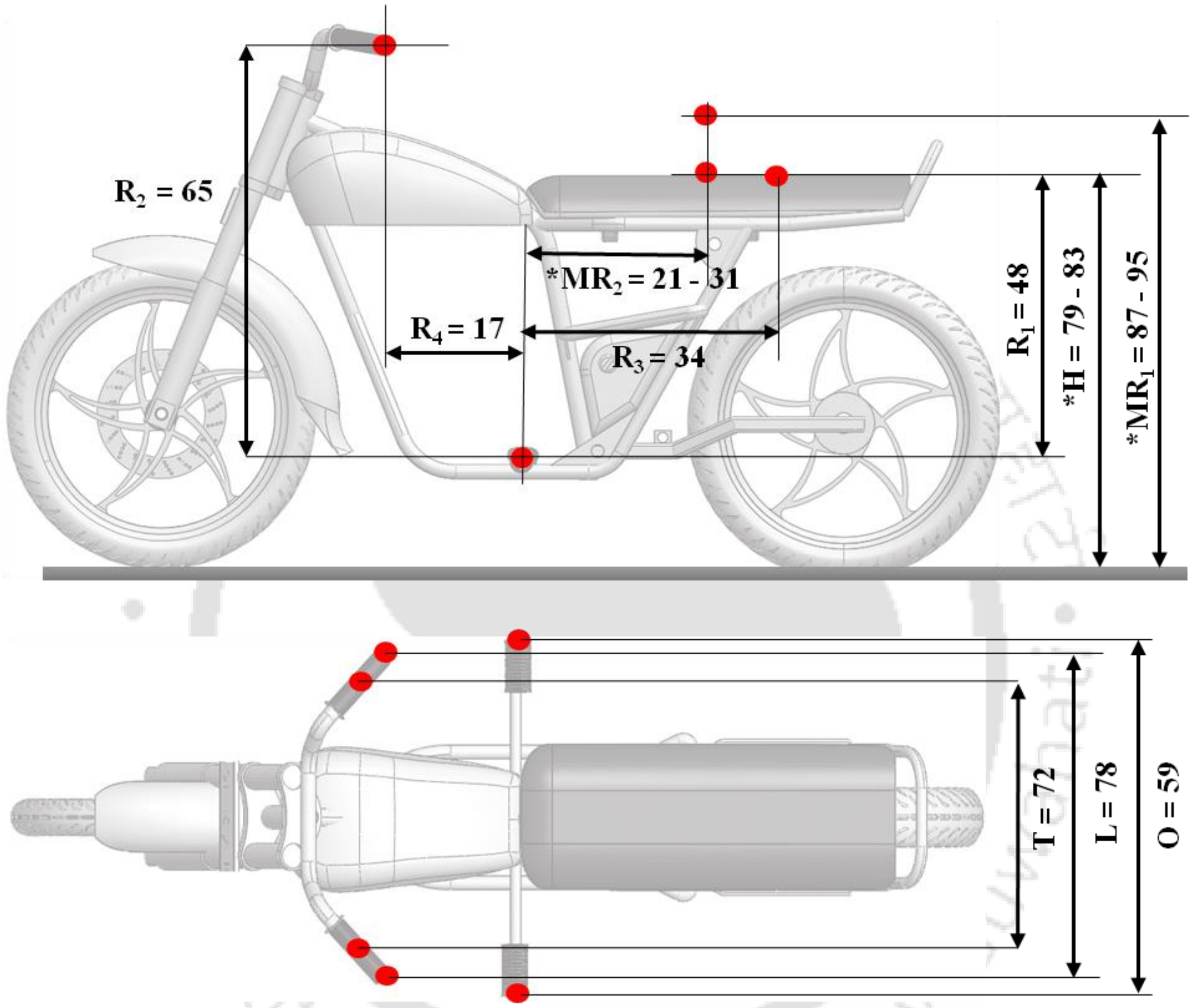

Figure 4. 9: Suggested optimum riding position in a motorcycle design (unit: cm). Note: The recommendations for H, MR_1, and MR_2 shall be represented as mean ± SD (Shamasundara and Ogale, 1999). H ~ 81 ± 2cm, MR_1 ~ 91 ± 4cm and MR_2 ~ 26 ± 5cm)

Figure 4.9 demonstrates the motorcycle model for the optimal riding positions obtained from this study. The recommended value of R_1 = 48cm was in the range of 42 to 58cm and 30 to 59cm, proposed by Kolekar and Rajhans, (2011) and JASO T003:2009, respectively. Similarly, for R_2, the present study suggested 65cm, falls in the range of 50 to 70 cm and 32 to 90cm proposed by Kolekar and Rajhans, (2011) and JASO T003:2009, respectively. The recommended value of R_3 = 34cm in the present study falls into the recommended range (20 to 53cm), suggested by JASO T003:2009. However, it was relatively different from the dimensions proposed by Kolekar and Rajhans, (2011). Our study proposes R_4 = 17cm, 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 91cm (with SD: 4cm) in the present experiment. According to the early study of Shamasundara and Ogale, (1999) on preference posture of 1410 Indian motorcyclist, the MR_1 was found in the range between 53 and 65cm. Contrarily, our research found a range from 69 to 89cm. Also, MR_2 of the present research (range from 21 to 31cm) differed from the study range (from17 to 40cm) observed by Shamasundara and 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/grip width (distance between the G'-points on the right and left-handle grips) reported by Shamasundara and Ogale (1999) from 54 to 76cm was found almost matches to our present research (72 to 82cm).

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

4.3.2.1 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: $R_1 \rightarrow 48$ cm, $R_2 \rightarrow 65$ cm, $R_3 \rightarrow 34$ cm, $R_4 \rightarrow 17$ cm, $L \rightarrow 78$ cm, $T \rightarrow 72$ cm, and $O \rightarrow 59$ 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 71 (8) 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 minutes rest at a supine position (on the table) 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 minutes. During these 5 minutes, a road riding simulation video was played on the white screen using a projector. Afterward, the subjects were asked to rate their discomfort/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 4.8 and 4.9 show 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 to 4 (intolerable complaints to poor comfort) in the neck, shoulder, elbow, wrist, low back, hip, knee ankle were mentioned by 10%, 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.

Table 4. 8: Discomfort rating of the subjects (n=30) – Distribution of frequency count and its percentage

Discomfort ratings[a]	Joints																	
	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

Table 4. 9: 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

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 15535:2012, 2012). Since a decreasing trend of female motorcyclists has been evident in the present Indian scenario (Government of India, 2018), the present 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 (which environmental factors like road/vibration, etc.), this was a laboratory study. However, we anticipate further this longitudinal work in dynamic situations (riding on a flat road).

4.4 Conclusion

The study experimentally acquired comfort joint angles using the image processing technique. Also, 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 results revealed θ_{W1}: 18°, θ_{W2}: 33°, θ_{W3}: 110°, θ_{W4}:120°, θ_{W5}: 81°, θ_{W6}: 62° θ_{W7}: 85°, θ_{W8}: 129°, θ_{W9}: 40°, θ_{W10}: 33° as mean postural comfort joint angles (CRP) and R_1: 48 cm, R_2: 65 cm, R_3: 34 cm, R_4: 17 cm as best/optimal riding positions. Subsequently, the confirmation test supports the findings of the optimal riding position. This was the first attempt to find the comfortable riding posture (CRP) and optimum riding position for a particular class/type of motorcycles. The result can further be utilized in improving the motorcycle design for comfortable riding experience. The comparison results concluded that most of the CRP 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).

Chapter-5: Association between comfortable riding posture/position and anthropometric and range of motion among motorcyclists

Abstract:

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

5.1 Introduction

India has the largest motorcycle market as compare to other Asian countries such as China, Indonesia, and Vietnam (SIAM, 2018). These markets supposed to be derived from a user's satisfaction. In fact, a recent survey of Sai Praveen and Ray (2015) stated that motorcycle users are giving importance to riding comfort while buying a motorcycle in India. But, several research articles reported about riding discomfort experienced by Indian motorcyclists (Anoop and Binoosh, 2019; Dutta et al., 2014; Mohan and Raghuathan, 2017; Ramasamy et al., 2017;

Velagapudi et al., 2010). Thus, the enhancement of riding comfort has been the topic of interest for a few years since a rider feels more discomfort/pain than a person along for the ride.

In general, there have been three types of research topics in the motorcycle design: (1) studies of motorcycle's seat design and its assessment – Velagapudi and Ray, (2017) developed a subjective seating comfort assessment techniques; Balasubramanian and Jagannath, (2014) developed an objective seating discomfort/comfort assessment method; Mathurkar, (2016) developed a new seat for better riding comfort. (2) Studies of anthropometric collections in India, which are essential for motorcycle design - anthropometric database of (motorcyclist/car/truck) driver population of India (Kulkarni et al., 2011; Shamasundara and Ogale, 1999) and anthropometric data-set of a motorcyclist from particular city (Pune) of India (Amrutkar and Rajhans, 2011). (3) studies of motorcycle design and its assessment via posture - Arunachalam et al. (2019) published an article, which was a review of 124 research articles published in India and aboard. This review article highlights the research gaps and bottlenecks in the motorcyclist posture research topics, which were aforementioned. On the whole, the literature review revealed that investigation have not been done to understand the connection between human and motorcycle design attributes.

Although motorcycle industry follows Japanese standards (JASO T003:2009, 2009; JASO T005:2009, 2009; JASO T102-84, 1975) for motorcycle design, the ergonomic evaluation has been conducted through Digital Human Modelling (DHM) tools in the early conceptualization stage of the motorcycle design process (Cucinotta et al., 2019). This DHM tool requires the target user's anthropometrics, ROM measurements, and CRP to perform a virtual ergonomics analysis of a newly designed motorcycle. Also, some of the laboratory experiments were conducted to check the riding comfort in the motorcycle industry (Praveen and Ray, 2018). However, the association between the rider's physical attributes (anthropometrics and ROM measurements) and motorcycle attributes (CRP/RP) have not been overlooked by motorcycle industry and researchers in India.

Although research investigations established the association between the comfortable posture of drivers (car/tractor/truck) and seat position and body dimension (anthropometric) (Fatollahzadeh, 2006; Park et al., 2019, 2000; Porter and Gyi, 1998), this similar investigation still misses owing to the sacristy of literature in the motorcycle's ergonomics. Also, the relationship between the ROM and CRP has not been explored and missed to understand the importance of ROM in the user-centered design process of the motorcycle (Apostolico et al., 2014; Cucinotta et al., 2019). Indeed, ergonomist/designer/researchers well-known with research trends in the industry have point toward that new research investigation should make immediate use of rider's physical attributes in the motorcycle design process at future.

Based on the literature survey, the research question has been formulated as:

RQ6: Which are the principal factors (from a larger set of variables) that explaining/ representing most of the variance of CRP and RP?

RQ7: How are the association of anthropometric, and range of motion variables with CRP and RP?

Based on the research question, the authors constructed a hypothesis which has been broken into two working hypotheses. These were:

Hypothesis: CRP and RP might significantly association with anthropometrics and ROM variables

Working Hypotheses 1:

Null Hypothesis 1 (H_1): The CRP is not significantly associated with the anthropometric and ROM variables of the motorcyclists.
Alternative Hypothesis 1a (H_{1a}): The CRP is significantly associated with the anthropometric and ROM variables of the motorcyclists.

Working hypotheses 2:

Null hypothesis 2 (H_2): The RP is not significantly associated with the anthropometric and ROM variables of the motorcyclists.
Alternative hypothesis 2 (H_{2a}): The RP is significantly associated with the anthropometric and ROM variables of the motorcyclists.

5.2 Methods and materials

Subjects, experimental procedure and experimental setup -details – Refer Chapter 4, subsection 4.2

5.3 Data analysis

CRP and RP were observed (Refer chapter 4, Section 4.2.3.1) for the data analysis. The descriptive analysis of CRP and RP were presented in Table 4.5 and Table 4.1, respectively. Since there were more extensive set of intra-correlation (see **Appendix L, Table 1 and 2**) among the CRP (θ_j) and RP variables (R_i, MR_i, etc.). We have used principal component analysis (PCA) on CRP/RP to reduce them into smaller subset of PCs. Also, this analysis helps to answer the first research question of the present research i.e. what principle factors contain most of the information in representing CRP and RP?

PCA is typically recognized for dimensional reduction of a more enormous set of variables into a smaller subset (Tavana et al., 2016). This dimensional reduction method was applied on ten joint angles (θw_1 - θw_{10}) and riding position (R_1, R_2, R_3, R_4, MR_1, MR_2, L, T, O, H) variables to find the most influential components (contributing to maximum variance) from the original variables. This factor analysis was performed under the following consideration: (1) Eigenvalues greater than 1, (2) Extraction method as varimax rotation and (3) Factor loading coefficient greater than 0.4. Before performing the PCA on the CRP and RP variables, the data were checked for the following assumptions: (1) Intra-correlation between all the variables using Pearson's correlation coefficient; (2) The adequacy of sample size (evaluated using Kaiser-Meyer-Olkin (KMO) and Bartlett's sphericity values) and; (3) Identifying outliers (using box and whisker plot for each variable).

Stepwise Multiple Linear Regression (SMLR) analysis was used to establish a regression model between the PCs of CRP/RP and the PCs of anthropometrics and ROM (from chapter 3, see Table 5.1). Unlike other Multiple Linear Regression (MLR) methods, SMLR selects the predictor variables based on statistical threshold-criteria. In every step, independent variables have been involved for adding to obtain the best fitting regression model. If the added independent variable fails to provide the best regression model, then that independent variables removed. Until the efficient regression model arrives, the process of adding/ removing of independent variables continued. Before performing regression analysis, the SMLR assumptions were examined, in the following order: (1) Multivariate Normality test (Shapiro-Wilk test); (2) Multi-collinearity among the CRP/RP variables (see **Appendix L – Table 1 and**

2 for Pearson correlation coefficient); and (3) Homoscedasticity (Bartlett's method). The statistical analyses were performed at a chosen confidence level set to 0.05 and 0.01. All statistical analyses were performed using SPSS 23.0 software.

Table 5. 1: Summary of Principal components obtained for anthropometrics and ROM

Rider's physical attributes	Principal Components (PC) - Names	Variables
Anthropometry	*Body length indicator*	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
	Volume indicator	Weight, BMI, Elbow-Elbow breadth, Hip breadth, sitting, Thigh circumference, Calf circumference, Upper arm circumference,
	Body fat indicators	Triceps skinfold, Subscapular skinfold, Supraspinal skinfold, Medial calf skinfold
	Sitting height indicator	Cervical height sitting, Shoulder height itting, Elbow height, Sitting, knee height
	Body bilateral length indicators	Femur breadth, humerus breadth, foot-breadth
ROM	*Motion at Sagittal plane*	Neck Flexion, Neck Extension, Wrist Flexion, Wrist Extension, Knee Extension, Elbow Flexion, Shoulder Extension
	Motion at Transverse plane	Hip Abduction, Shoulder abduction, Shoulder Abbuction
	Upperlimb Motions at Sagittal plane	Shoulder Flexion, Shoulder Extension
	lower limb Motions at the Sagittal plane	Hip Flexion, Hip Extension, Ankle Doris exion
	lower limb Motion at Transverse plane	Hip Abduction, Ankle Plantarflexion
	Spine Motion at Sagittal plane	Lumbar Flexion, Lumbar Extension
	Knee-elbow Motion at Sagittal plane	Knee Flexion, Knee Extension, Elbow xtension

Note: This table summarize the result of chapter 3, which established the Indian rider's physical attributes/characteristics (5 anthropometric PCs and 7 ROM PCs).

The results from the PCA of CRP and RP (present chapter) and the PCs of ROM and anthropometric (from chapter 3) were used to answer the research questions (RQ6 and RQ7) and test the hypothesis (H_{1a} and H_{2a}). While testing the hypothesis, the PCs of CRP and RP (as dependent variables) were predicted by PCs of anthropometrics and ROM variables (as independent variables, Table 5.1) using SMLR.

5.4 Results and Discussion

5.4.1 Dimensional reduction technique analysis using principal component analysis (PCA)

5.4.1.1 Principal component analysis (PCA) of comfortable riding posture (CRP)

The PCA yielded 3 PCs from the 10 CRP (joint angles) variables. The potential PCs were recognized graphically using the scree plot (see Figure 5.1). This plot implied effective PCs (PC1-PC3) that have Eigenvalues greater than 1. The KMO measure of sampling adequacy was obtained as 0.71 (ranged between 0.70 and 0.79). It can be interpreted as a "middling" sample size for the research (Cerny and Kaiser, 1977). Bartlett's test was also found to be significant at $p < 0.001$, which indicates adequate sample size (Kuo et al., 2019). The intra-correlation coefficients between all the postural (joint angles) variables presented in **Appendix L, Table 1**.

Following varimax orthogonal rotation, three PCs accounted for 62.97% of the total variance in the original variables (see Table 5.2). PC 1 includes 3 variables (see Table 5.3), and accounts 37.12% of the total variance (Eigenvalue = 3.7). These factors were labeled as "*Comfort hip joint angles*" because these joints movements take place in the hip joint regions (i.e. Hip flexion/extension, hip adduction/abduction and Lower back joint angle). Since the lower back joint is connected with hip joint (tailbone), we considered it in the *"hip joint angle*". PC 2 was comprised of four variables and labeled as the "*Comfort joint angles of upper limbs*" since its accommodated joint angle related to upper part/limbs of the human body. It accounted for 15.13% of the total variance (Eigenvalue = 1.5). PC 3 consisted of three variables (10.17% of the total variance; Eigenvalue = 1.07) and labeled as "*Comfort joint angles of lower limbs*" (the joint angles of lower limbs).

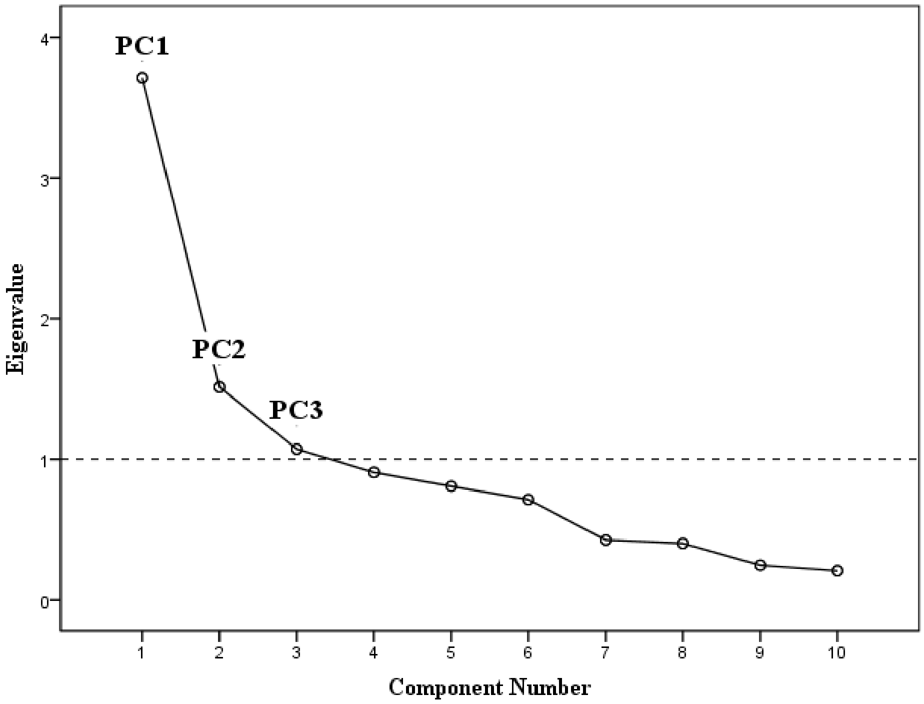

Figure 5. 1: Scree plot of CRP

Table 5. 2: Total variance explained for CRP

Principal Component (PC)	Initial Eigenvalues			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	3.713	37.128	37.128	2.212	22.125	22.125
2	1.513	15.130	52.259	2.190	21.897	44.022
3	1.071	10.715	62.973	1.895	18.951	62.973
4	.906	9.059	72.033			
5	.808	8.080	80.113			
6	.712	7.122	87.234			
7	.425	4.252	91.487			
8	.400	4.003	95.490			
9	.245	2.451	97.941			
10	.206	2.059	100.000			

Table 5. 3: Results of factor analysis for comfortable riding posture joint angles

	Principal Component (PC)		
	1	2	3
θ_{W1}		.820	
θ_{W2}		.750	
θ_{W3}		.686	.591
θ_{W4}	.650	.418	
θ_{W5}	.790		
θ_{W6}			.773
θ_{W7}			.432
θ_{W8}		.444	
θ_{W9}			.731
θ_{W10}	.816		

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

The PCA results interpret that the CRP could be classified into 3 major principal components, which will effectively represent all the 10 CRP variables (joint angles). The first component represents the joint angles of hip and lower back. The second component represents the joint angles of upper limbs like neck, shoulder, arms and hand/wrist. Whereas, the third component represents the joint angles of lower limbs like knee, foot. Moreover, these three principal components may represent/express 62% of the originals variance.

In line with our results, the study by Vergara and Page (2002) on automotive male drivers also revealed that the hip-related joints expresses most of the joint angles variables. Also, JASO T003:2009 recommend that the hip joint angles can be considered as the key measurements while designing motorcycles.

5.4.1.2 Principal component analysis (PCA) of comfortable riding position (RP)

Four PCs were yielded from the 10 RP variables. The potential PCs (PC1-PC4) were recognized graphically using the scree plot (see Figure 5.2). This plot implied that the effective PCs were having an eigenvalues larger than 1. The KMO measure of sampling adequacy was obtained as 0.64 (ranged between 0.60 and 0.69). It can be interpret as a “mediocre” sample size for the research (Cerny and Kaiser, 1977). Bartlett’s test was also found to be significant at p < 0.001, which indicate that the sample size was adequate (Kuo et al., 2019). The intra-correlation coefficients among the RP variables were presented in **Appendix L, Table 2**.

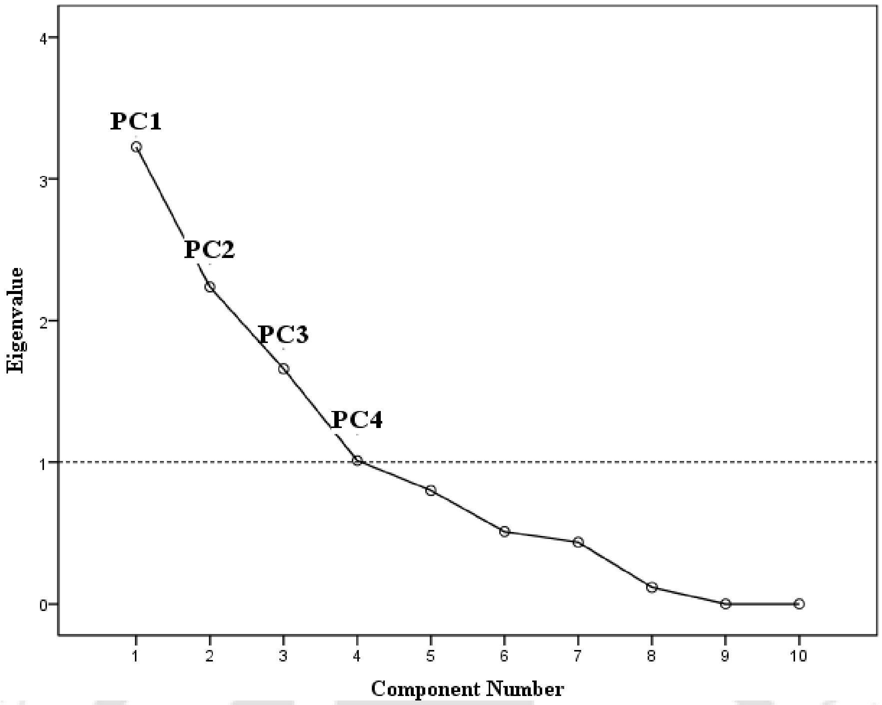

Figure 5. 2: Scree plot of RP

Following varimax orthogonal rotation, four PCs of the joint angles accounted for 81.5% of the total variance in the original variables (see Table 5.4). PC 1 includes 4 variables (see Table 5.5) and accounts 32.26% of the total variance (Eigenvalues = 3.2). These factors were labelled as "*Vertical dimensions at Sagittal plane*" because it accommodates the variables related to Z-axis (i.e. R_1, R_2, MR_1 and H). PC 2 was comprised of two variables and labelled as the "*Dimensions at Transverse plane*" since it accommodated variables related to top plane. It accounted for 22.37% of the variance (Eigenvalues = 2.2). PC 3 consisted of three variables (16.59 % of the variance; Eigenvalues = 1.6) and labelled as "*Horizontal dimensions at Sagittal plane*" because it accommodates variables related to X-axis (i.e. MR_2, R_3, and R_4). PC 4 consisted of one variable (10.12% of the variance; Eigenvalues = 1.01) and labelled as "*Footrest dimensions at Transverse plane*" (the footrest dimension in the transverse plane).

The PCA results interpreted that the RP could be classified into 4 major principal components, which will efficiently represent all the 10 riding position variables. The first PC1 represents the vertical dimensions at Sagittal plane like R_1, R_2, MR_1 and H. The second PC2 represents dimensions at Transverse plane like L, T. The PC3 component represents the horizontal dimensions at Sagittal plane like MR_2, R_3, R_4. Whereas, PC4 represents the footrest dimension. Moreover, these four principal components may represent the 10 originals variables (more than 81% of the variance were explained). In line with our results, the JASO T003:2009 recommend that the vertical dimensions were key dimensions of motorcycles. Whereas, some of motor vehicle standards (J1100, 2009) were also suggested that the vertical dimensions were key dimensions of vehicle design.

Table 5. 4: Total variance explained for riding positions variables

Principal Component (PC)	Initial Eigenvalues			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	3.226	32.260	32.260	2.736	27.358	27.358
2	2.237	22.374	54.634	2.281	22.811	50.169
3	1.659	16.591	71.225	2.093	20.933	71.103
4	1.012	10.124	81.349	1.025	10.247	81.349
5	.801	8.013	89.362			
6	.511	5.105	94.467			
7	.436	4.357	98.824			
8	.118	1.176	100.000			
9	4.016E-7	4.016E-6	100.000			
10	5.019E-8	5.019E-7	100.000			

Table 5. 5: Results of factor analysis for riding position variables

	Principal Component (PC)			
	1	2	3	4
R_1	.960			
R_2	.440			
R_3			.895	
R_4		-.538	-.558	
MR_1	.801			
MR_2			.940	
H	.960			
G		.977		
D		.977		
F				.988

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

5.4.2 Factors associated with a comfortable riding posture (CRP)

The present section describes the association of the CRP PCs with anthropometrics and ROM. Also, it includes the prediction models of 3 PCs CRP (comfort hip joint angles, comfort joint angles of upper limbs and comfort joint angles of lower limbs) based on 5 anthropometrics PCs and 7 ROM PCs.

Table 5. 6: Comfortable riding posture (joint angles) regression models

F	R	R^2	Regression Model		
			Explanatory variables[†]	β	*p*
Comfort hip joint angles F(4, 115) = 8.482	0.47	0.228	Motion at Sagittal plane**	0.335	<0.01
			Motion at Transverse plane**	-0.213	
			Lower limb Motion at Transverse plane**	-0.193	
			Upper limb Motions at Sagittal plane**	0.182	
Comfort joint angles of upper limbs F(4, 115) = 8.932	0.48	0.237	Dimensions at Transverse plane	-0.358	<0.01
			Horizontal dimensions at Sagittal plane	-0.273	
			Sitting height indicator*	0.235	
			Motion at Sagittal plane**	0.183	
Comfort joint angles of Lower limbs F(2, 117) = 12.586	0.42	0.177	Body length indicator*	-0.292	<0.01
			Spine Motion at Sagittal plane**	0.226	

[†] refer table 5.1
*Anthropometry PCs
** ROM PCs

Table 5.6 shows the Stepwise Multiple Linear Regression (SMLR) analysis. The predicted model explained 22.8% of variance the variables related *comfort hip joint angles*. A high significant SMLR analysis was found (F (4,115) = 8.482, $p < 0.01$), with an R^2 of 0.228. The multiple correlations (R) between *comfort hip joint angles* and the five predictors (PCs of ROM and anthropometrics) were moderate (0.47). Motion at Sagittal plane (β =0.335, p < 0.01), motion at Transverse plane (β = -0.213, p < 0.01), lower limb Motion at Transverse plane (β = -0.193, p < 0.01), and Upper-limb Motions at Sagittal plane (β =0.182, p < 0.01) were associated with higher *comfort hip joint angles*. In other words, the slender subject who is usually having greater ROM than the obese subject are likely to sit in the erect posture rather than the collapsed/slumped posture (Chakrabarti, 1997). The *comfort hip joint angles* are significantly linked/ associated with most of the ROM which are performed at Sagittal/Transverse plane.

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

While analysing *comfort joint angles of lower limbs*, a high significant SMLR analysis was found (F (2,117) = 12.58, $p < 0.01$), with an R^2 of 0.177. The predicted model explained 17.7% of the *comfort joint angles of lower limbs*. The multiple correlations (R) between *comfort joint angles of lower limbs* and the two predictors (PCs of ROM and Anthropometrics) were moderate (0.42). Body length indicator ($\beta = -0.292$, $p < 0.01$) and Spine Motion at Sagittal plane ($\beta = 0.226$, $p < 0.01$) were associated with higher *comfort joint angles of lower limbs*. Needless to say, shorter subjects were stretching their knee/foot to reach the footrest while perceiving a comfortable riding posture. This make the subject to move forward from original sitting position and increases the flexion of spine for reaching the handlebar. In line with these results, a study by Porter and Gyi, (1998) found that the shorter drivers prefer outstretched arms while driving.

Although the independent variables (PCs of anthropometric and ROM) were moderately predicted the PCs of CRP (joint angles), the regression models were highly significant ($p<0.01$). In support with our results, the study by Grainger et al., (2017) on bicycle riders also adopted the similar procedure and revealed that the comfortable (bicycle) riding postures were moderately predicted by the anthropometrics of riders. Altogether, It’s evident from the regression analysis that the CRP were associated (zero-order correlation, see **Appendix M)** and predicted by anthropometrics and ROM of riders at a highly significant level of $p<0.01$. Thus, ***Null Hypothesis 1*** (H_1) has been rejected, and ***Alternative Hypothesis 1a*** (H_{1a}) has been established.

5.4.3 Factors associated with comfortable riding position (RP)

This section describes the association of RP with the PCs of anthropometrics and ROM. Also, it includes the prediction models of 4 PCs RP (Vertical dimensions at Sagittal plane, Dimensions at Transverse plane, Horizontal dimensions at Sagittal plane, and Footrest dimensions at Transverse plane) based on 5 anthropometrics PCs and 7 ROM PCs.

Table 5. 7: Comfortable riding position (RP) regression models

F	R	R^2	Regression Model		
			Explanatory variables[†]	β	*p*
Vertical dimensions at Sagittal plane F(2, 117) = 8.581	0.35	0.128	Motion at Sagittal plane** Body fat indicators*	-0.272 -0.224	<0.01
Dimensions at Transverse plane F(2, 117) = 41.16	0.64	0.413	Body bilateral length indicator* Upperlimb Motions at Sagittal plane**	-0.520 0.256	<0.01
Horizontal dimensions at Sagittal plane F(2, 117) = 7.85	0.344	0.118	Body length indicator* Comfort angles of upper limbs	0.233 -0.239	<0.01
Footrest dimensions at Transverse plane F(2, 117) = 5.71	0.298	0.089	Motion at Transverse plane** Lower limb motion at Transverse plane**	0.214 0.208	<0.01

[†] refer table 5.1
*Anthropometry variables
** ROM variables

Table 5.7 show the SMLR analysis, the predict model explained 12.8% variances of the *Vertical dimensions at Sagittal plane*. A high significant SMLR analysis was found (F (2,117) = 8.581, $p < 0.01$), with an R^2 of 0.128. The multiple correlations (R) between *vertical dimensions at Sagittal plane* and the two predictors (PCs of ROM and Anthropometrics) were moderate (0.35). Motion at Sagittal plane ($\beta = 0.272$, $p < 0.01$), and body fat indicators ($\beta = -0.224$, $p < 0.01$) were associated with higher dimensions at Sagittal plane. It can be inferred that the overweighed subjects preferred to keep their riding position dimensions (R_1, R_2, MR_1 and H) lower, which may help them to keep lesser flexion movements of joints at Sagittal plane.

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

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

For the *footrest dimensions at Transverse plane*, a high significant SMLR analysis was found (F (2,117) = 5.71, $p < 0.01$), with an R^2 of 0.089. This predicted model explained 29.8% of the *footrest dimensions at Transverse plane*. The multiple correlations (R) between *footrest dimensions at Transverse plane* and the two predictors (PCs of Motion at Transverse plane and

Lower limb motion at Transverse plane) were moderate (0.298). Motion at Transverse plane (β =0.214, $p < 0.01$), and lower limb motion at Transverse plane (β =0.208, $p < 0.01$) were associated with higher *footrest dimensions at Transverse plane*. Though explanatory variables moderately predicted the comfortable riding position (RP), the regression models were highly significant (p<0.01). In line with our results, the study by Park et al., (2000) on passenger car driver revealed that association were moderate/low between the seating dimensions and anthropometrics of drivers. Overall, It's evident from the SMLR analysis that the RP were associated (zero-order correlation, see **Appendix N)** and predicted by ROM and anthropometrics of riders at a highly significant level of p<0.01. Thus, ***Null Hypothesis 2*** (H_2) has been rejected, and ***Alternative Hypothesis 2a*** (H_{2a}) has been established that RP significantly correlation with anthropometric and ROM variables of the motorcyclist.

5.5 Conclusion

It can be established from the results of PCA that out 10 CRP (joint angles), only 3 variables (joint angles of hip and lowers back) and out of 10 riding position only 4 variables (R1, R2, MR1, H) were identified as the principal components explaining most variance in CRP and RP. This is the first attempt to establish the link between the CRP/RP and ROM and anthropometrics. It can be concluded that the ROM and anthropometrics of riders were significantly associated with their CRP and RP. Also, CRP and RP can be predicted using rider ROM and anthropometry. It can be concluded that the ROM and anthropometrics of riders are equally important in motorcycle design process. Therefore, it is suggested to establish a wide anthropometric and ROM database of Indian motorcycle users.

Chapter – 6: Discussion, recommendations and implication of the research

Abstract:

Observations and results of the investigations from "chapter-2" to "chapter-5" have been briefly explained in the present chapter with key findings of the present thesis. This explanation includes how research questions have been answered and how hypotheses have been tested. The present chapter provides recommendation for improving the degree of motorcyclist's comfort based on the experimental results. According to this recommendation, engineers/ designers should consider the targeted population's anthropometric as well as ROM measurements during design and development of motorcycles for user satisfaction and better market acceptance. These suggestions and findings would be helpful for the designer to decide on the design (frame size) of standard motorcycles. This chapter also lists the novelties of present research in terms of methodology, knowledge-base, and industry. This chapter ends with limitations, future scopes, and an overall conclusion of the present thesis work.

6.1 Discussion

In the present thesis, the association of anthropometric and range of motion ROM with the comfortable riding posture (CRP) and comfortable riding position (RP) have been described by establishing the roles of these riders' attributes. Previous studies were unable to establish the effect of rider's physical attributes in the context of CRP and optimal riding positions. However, few two-wheeler (bicycle) studies (Grainger et al., 2017; Hsiao et al., 2015) established the relationship between the (cyclist) riders' physical attributes (anthropometry), CRP and seating/ saddle positions. The present thesis shows the method to increase the degree of comfort using riders' physical attributes via anthropometrics as well as ROM measurements. The present chapter explains the key findings or outcomes of the whole research described in different chapters.

6.1.1 Key findings of the present thesis

The salient findings of the present thesis obtained from the experimental studies described in different chapters are listed below.

- Eighteen (18) key dimensions were measured from each of the 23 motorcycles (standard motorcycles of different make and models which are popularly available in India) using the new (in-house fabricated) instruments. This measurement helped to find the dimensional difference across the standard motorcycles under study. It was intended to understand the standard or traditional dimensions, which are practiced for three interface parts (handlebar, seat, and footrest) in a motorcycle. It was found that 12 out of 18 key dimensions had a marginal deviation from the mean value. For instance, standard deviation (SD) of seat dimensions (i.e. front width (SS), narrowest width (SXL), distance between the front width and narrowest width (S2S)) were found between 1.3 cm and 2cm. The fuel tank's dimensions (i.e. tank length, minimum and maximum fuel tank breadths) varied with a SD ranging from 3.1cm to 5.3cm. The SD of footrest dimensions (i.e. distance between the footrests (F)) SD were also found as 2cm. Although there were some variations of the dimensions across the motorcycles but the SD values were very less or marginal for most of the cases. Moreover, the measured dimensions were in line with the existing Japanese standards, namely JASO T003:2009, 2009, and JASO T102-84, 1975. Dimensional data regarding the 3 interface points (handlebar, seat and footrest) gathered from the 23 standard motorcycles helped to develop the test-rig or static-simulator for studying the comfort/discomfort posture of the motorcyclists.

- In the present research, 29 anthropometric dimensions, and 20 ROM measurements were taken from 120 male adult (aged 19–44 years) Indian motorcycle riders following standard measurement protocol. Conducting PCA analysis, a total of 14 out of 29 anthropometric variables (i.e., crotch height, stature, buttock extension, sitting shoulder height, sitting cervical height, lower-leg length, knee height, elbow–hand length, shoulder–elbow length, buttock–popliteal length, buttock–knee-length, acromion grip length, hand length, and ball-of-foot length) and six out of 20 ROM variables (i.e., wrist extension, wrist flexion, elbow flexion, knee extension, shoulder extension, and shoulder abduction) were identified as the key variables defining the physical characteristics of Indian male motorcyclists.

- Although higher dimensional differences were evident while comparing with general Indian population data, the anthropometry of Indian drivers was more or less similar to Indian motorcyclists (present study). Overall, the results showed that there was profound difference in most of the anthropometric dimensions between the non-Indian and Indian motorcyclist populations. While the ROM data from the present study were compared with general Indian population data, prominent variations were noticed. 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. It is evident from the present study that the existing anthropometry and ROM databases of Indian general population are either inadequate in terms of relevant information or not representative of the whole Indian motorcycle rider population. As there is no other anthropometric and ROM database for the Indian motorcyclist population, the physical measurements acquired in present research could be used for the ergonomic design of motorcycles for Indian users unless a larger database is generated.

- Following the experiment on static motorcycle test-rig, CRP and RP was identified based on the perceived discomfort/comfort of the joint angles. The mean comfort joint angles (CRP) for the ten joints were observed as Neck (θ_{W1}) 18°, Shoulder (θ_{W2}) 33°, Elbow (θ_{W3}) 110°, Lower back (θ_{W4}) 120°, hip (θ_{W5}) 81°, Knee (θ_{W6}) 62°, Ankle (θ_{W7}) 85°, Wrist (θ_{W8}) 129°, Shoulder abduction/adduction (θ_{W9}) 40°, and Hip abduction/adduction (θ_{W10}) 33°. Similarly, dimensions of rider-motorcycle interface points (handlebar, seat and footrest) were measured by adjusting different adjustable features of the motorcycle test-rig to identify the comfortable riding position (RP). Finally, the optimal riding position was defined based on the ten (10) dimensional variables which included the vertical distance between the F-point and D-point (R_1) 48 cm, the vertical distance between the F-point and G'-point (R_2) 65 cm, the horizontal distance between the F-point and D-point (R_3) 34 cm, the horizontal distance between the F-point and G'-point (R_4) 17 cm, the distance between the G'-points on the right and left handlebar/grips (G) 78 cm, the distance between the G-points on the right and left handlebar/grips (T) 72 cm and the distance between the F-points on the right and left footrest (O) 59 cm, D -point from the ground (H) 81 cm, the vertical distance between the H-point and the ground (MR_1) 91 cm and horizontal distance between the H-point and the F-point (MR_2) 26 cm.

- PCA analysis revealed that comfort hip joint angles, comfort joint angles of upper limbs, and comfort joint angles of lower limbs are the principal components that explain the most variance in CRP (joint angles). Similarly, following PCA analysis of RP variables, principal components like vertical dimensions at sagittal plane, dimensions at transverse plane, horizontal dimensions at sagittal plane, and footrest dimensions at transverse plane were able to explain the most variance in the RP. Considering the principal components of anthropometrics and ROM as independent variable, and CRP as dependent variable, stepwise multiple linear regression (SMLR) analysis was conducted. Significant association of CRP were found with the anthropometric and ROM variables of the motorcyclists. Likewise, SMLR analysis showed significant association of RP with the physical characteristics (anthropometry and ROM) of the motorcyclists.

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6.2 Fulfillment of the objectives

Obj 1. *To study the dimensional variations in three interface parts/points (handlebar/ grip, seat, and footrest) in existing motorcycles*

Eighteen (18) key dimensions of various interface parts/ points (i.e. handlebar/ grip, seat, and footrest) of the 23 standards motorcycles were measured using a new instrument and simple method. These measurements helped to investigate the dimensional variation across the existing motorcycles make and models popularly available in Indian market. Thus, **objective-1 of the research was fulfilled**. Detail description of the measurement procedure and the gathered data on dimensional variation is disclosed in the chapter 2.

Obj 2. *To study the most influential anthropometric and ROM variables that define the physical characteristics of Indian male motorcyclists*

An anthropometric and ROM measurement survey was conducted with Indian male motorcyclist (n=120) using a standard method and anthropometry instruments. Data pertaining to twenty-nine (29) anthropometric and twenty (20) ROM measurements were measured from the volunteers. Principal Component Analysis (PCA) was conducted on the collected data to identify the most influential anthropometric and ROM variables which characterize the physical attributes of Indian male motorcyclists. Thus, **research objective- 2 was fulfilled**. This was described thoroughly in the chapter 3 of the thesis.

Obj 3. *To identify the optimum riding position in terms of interface point's (handlebar/ grip, seat, and footrest) dimensions of a motorcycle*

Obj 4. *To define the motorcyclist's comfortable riding posture (CRP) in terms of comfort joint angles*

To experimentally find the CRP, and optimum riding position, a riding simulator (Test-rig) based study was conducted in the laboratory condition. Rider's CRP and optimum riding position were measured using an image processing technique and Taguchi's DOE method, respectively. Detail methodology and the findings of the experiments have been described in chapter- 4. Thus, this empirical study helps to **fulfil the research objectives 3 and 4**. This was elaborately explained in the chapter 4 of the thesis.

Obj 5. *To determine the principal factors (from a larger set) contain most of the information in explaining/ representing comfortable rider posture (CRP) and comfortable riding position (RP).*

Obj 6. *To study the relationship of anthropometry and range of motion variables with the comfort table rider posture, as well as with comfortable riding position.*

Principal Component Analyses (PCA) were conducted as the dimensional reduction technique to identify the small set of comfort joint angle variables which can explain the most of the variance of comfortable riding posture (CRP) and a small set of dimensions which can explain the most of the variance of comfortable riding position (RP). Further, using stepwise multiple regression analysis, relationships were established between rider's physical attributes (anthropometrics and ROM) and CRP and RP. Thus, **research objective 5 and 6 were fulfilled**. This has been described in the chapter 5.

6.3 Testing of hypothesis

Working Hypotheses 1:

Null Hypothesis 1 (H_1): The comfortable riding posture (CRP) is not significantly associated with the anthropometric and ROM variables of the motorcyclists.

***Alternative Hypothesis 1a (H_{1a}): The CRP is significantly associated with the anthropometric and ROM variables of the motorcyclists*.** In order to test the hypothesis 1 (i.e. H_{1a}), anthropometric and ROM data were gathered from Indian motorcyclists (Ref: Table 3.1 and 3.2, chapter 3). The comfortable postures (based on the comfortable joint angles) of riders were measured from the experimental studies (Ref: Table 4.5, chapter 4). Using PCA, principal components of anthropometry, ROM (Ref: Table 3.6 and 3.8, chapter 3), and CRP (Ref: Table 5.2, chapter 5) were identified. The principal components of anthropometric and ROM were considered as independent variables, and CRP were considered as dependent variable, in the stepwise multiple linear regression analysis, during hypothesis (H_{1a}) testing. Results of these analyses (Ref: Table 5.6, chapter 5) revealed that the CRP was significantly ($p<0.01$) associated with the anthropometric and ROM variables of the motorcyclists. **Thus, the alternative hypothesis 1a (H_{1a}) was accepted and the null hypothesis 1 (H_1) was rejected.**

In specific, ROM variables, such as the motion at the sagittal plane (i.e., neck extension, neck flexion, wrist extension, wrist flexion, elbow flexion, knee extension, and shoulder extension), Motion at Transverse plane (i.e., hip abbuction, shoulder abduction, shoulder adduction), Lower limb Motion at Transverse plane (i.e. hip abduction, ankle plantarflexion), Upper limb Motions at Sagittal plane (i.e., shoulder flexion, shoulder extension), Spine Motion at Sagittal plane (i.e. lumbar flexion, lumbar extension) and anthropometric variables, such as sitting height indicators (i.e., sitting shoulder height, knee height, sitting cervical height, and sitting elbow height), body length indicators (i.e., 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) were significantly associated with CRP. Thus, this finding was in favor of accepting the ***hypothesis 1a*** (H_{1a})

Working hypotheses 2:

Null hypothesis 2 (H_2): The comfortable riding position (RP) is not significantly associated with the anthropometric and ROM variables of the motorcyclists.

***Alternative hypothesis 2 (H_{2a}): The RP is significantly associated with the anthropometric and ROM variables of the motorcyclists**.* To test the hypothesis 2 (i.e. H_{2a}), anthropometric and ROM data were collected from Indian motorcyclists (Ref: Table 3.1 and 3.2, chapter 3). Data on the RP was gathered from the experimental studies (Ref: Table 4.1, chapter 4). Using PCA, principal components of anthropometric, ROM (Ref: Table 3.6 and 3.8, chapter 3) and RP (Ref: Table 5.5, chapter 5) were identified. The principal components of anthropometrics and ROM as independent and RP were considered as dependent variables in the SMLR, during hypothesis (H_{2a}) testing. The analysis results (Ref: Table 5.7, chapter 5) revealed that the RP were significantly ($p<0.01$) associated with the anthropometric and ROM variables of the motorcyclists. Thus, **Thus, the alternative hypothesis 2a (H_{2a}) was accepted and rejects the null hypothesis 2 (H_2) was rejected.**

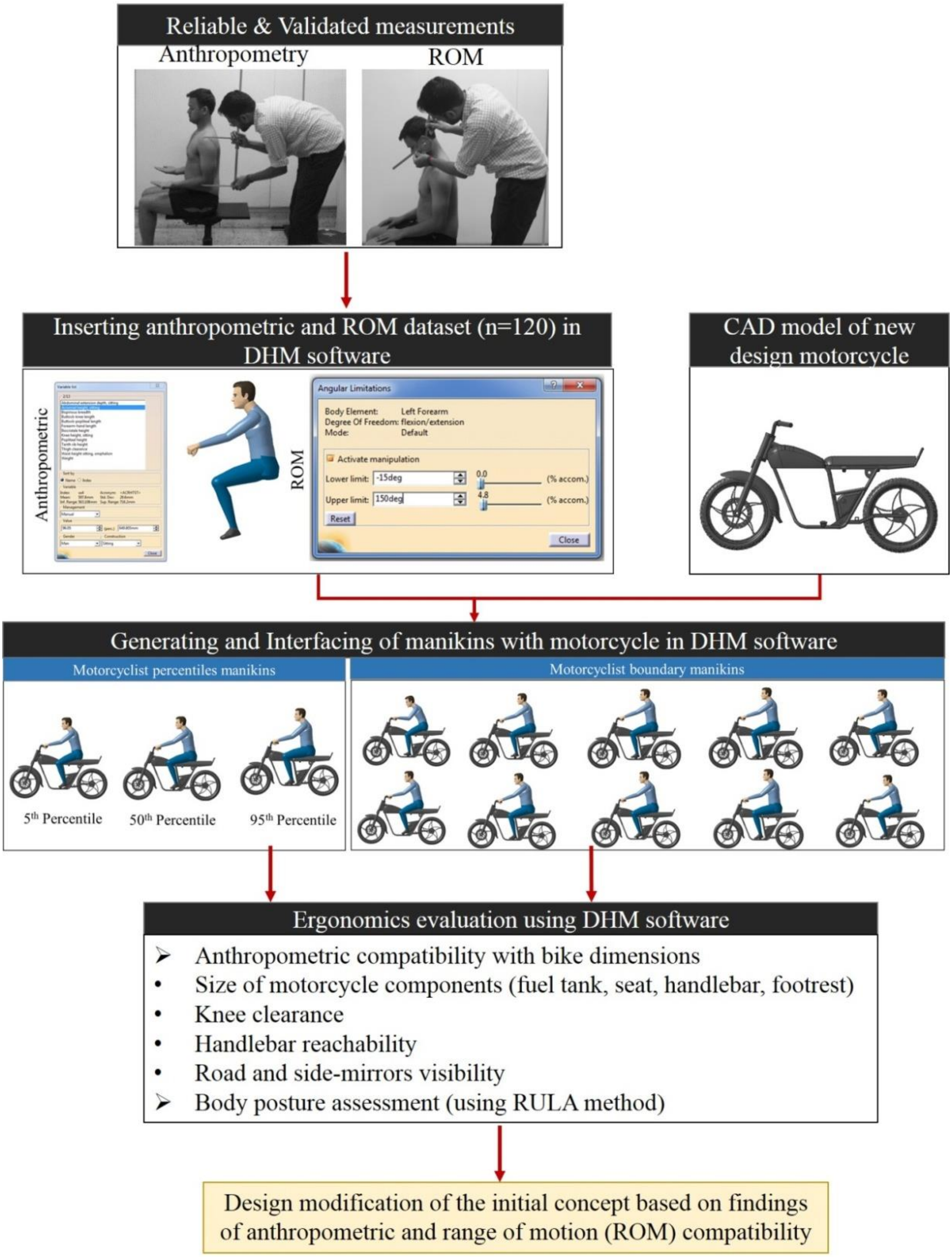
In particular, ROM variables like motion at sagittal plane (i.e., neck extension, neck flexion, wrist extension, wrist flexion, elbow flexion, knee extension, and shoulder extension), upperlimb motions at sagittal plane (i.e., shoulder flexion, shoulder extension), motion at transverse plane (i.e., hip abbuction, shoulder abduction, shoulder abduction), and lower limb motion at transverse plane (i.e., hip abduction, ankle plantarflexion) and anthropometric variables like body length indicators (i.e., 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), Body bilateral length indicator (i.e., femur breadth, humerus breadth, foot-breadth) and body fat indicators (i.e., triceps skinfold, subscapular skinfold, supraspinal skinfold, medial calf skinfold) were significantly associated with the comfortable riding position (RP). Thus, these findings are in favor of acceptance of alternative ***hypothesis 2a*** (H_{2a}).

Following the testing of hypotheses (as described in chapter-5), both the alternative hypotheses **H_{1a} and H_{2a} were accepted.** It's was also observed that riders' physical attributes anthropometry and ROM equally contributed in predicting of CRP and RP.

6.4 Implications of the findings of present research on motorcycle design from ergonomics perspective

- *Implications of developed dimensional dataset of the standard motorcycles:* Non-availability of the dimensional database (of different motorcycle models), which is essential for simulator design, is the main hindrance of developing the riding simulators. It is expected that the dimensional dataset of standard motorcycles generated from the present research would be useful for deciding the dimensions of the standard motorcycle simulator. The dimensional data regarding the interface points (handlebar, seat and footrest) of the standard motorcycle facilitated the present researcher to develop the test-rig/simulator and perform experiments in India.

- *Implications of anthropometrics and ROM measurements:* A generic project workflow maintains the following sequence: the project exploration stage → the project validation stage → design freeze → final data → production. A manikin (a CAD model of humans) is used in the validation and project exploration stages of the aforementioned workflow. In particular, percentile manikins (95th, 50th, and 5th percentiles) are used in the project exploration stage. Sometimes, boundary manikin approach (a multiple-percentile approach) is also used in the project validation stage (Caputo et al., 2019; Scataglini and Paul, 2019) to ensure the accommodation of anthropometric variations of the targeted user population. As there is no anthropometric and ROM database for Indian motorcyclists, the measurements obtained in this study would be utilized for development of percentile manikins as well as boundary manikins during the motorcycle design and development process. Moreover, it could be useful in the virtual environment (CAD) analysis, where, reach, vision, clearance, and inferences, and the comfort of the newly designed motorcycle could be performed in the stage of project validation. Thus, the new or modified design of motorcycle could be easily assessed in the stage of project validation. Virtual environment evaluation would be useful for the better user-compatibility of the riders (as shown in Figure 6.1). Further, the insights from the comparative analysis of anthropometric and ROM measurements would act as the roadmap for developing comprehensive anthropometric and ROM database of Indian motorcyclists.



Body Element: Left Forearm
Degree Of Freedom: flexion/extension
Mode: Default

Activate manipulation

Lower limit: -15deg 0.0 (% accom.)

Upper limit: 150deg 4.8 (% accom.)

- ➢ Anthropometric compatibility with bike dimensions
- • Size of motorcycle components (fuel tank, seat, handlebar, footrest)
- • Knee clearance
- • Handlebar reachability
- • Road and side-mirrors visibility
- ➢ Body posture assessment (using RULA method)

Design modification of the initial concept based on findings of anthropometric and range of motion (ROM) compatibility

Figure 6. 1: Application of the anthropometrics and ROM measurement in virtual ergonomics evaluation of newly design/ re-designed motorcycle

- *Implications of motorcyclist's comfort joint angles and optimum riding positions:* Due to various incompatibilities in terms of human factor issues, majority of the Indian motorcyclists remain unsatisfied with their motorcycle (Sai Praveen and Ray, 2015). The present research provides immediately accessible information regarding comfortable riding posture (CRP) and optimal riding position for better design of motorcycle in India. Moreover, it is anticipated that the motorcycle designers could adopt a similar methodology as followed in present research to address the discomfort among the motorcycle users. Due implementation of the present research findings would be helpful in improving user comfort. It will undoubtedly help to improve the design of motorcycle.

- As there is no clearly defined design process for Indian motorcycles in the DHM software (RAMSIS, CATIA, Jack and Santos), the inclusion of anthropometric, ROM, and comfort joint angle dataset in the DHM software would be benefit during the design and ergonomic evaluation of motorcycles. For instance, in the RAMSIS software, it could aid through the Marco-programmed database, which would consist of mean comfort joint angle values (Sabbah and Bubb, 2008). In case CATIA V5 software (Dassault Systèmes, France), the ".txt" file would be generated with all comfort joints angles percentiles values. Whereas, in the case of Jack and Santos software, these comfort joint angles would be manually fed during the comfort analysis of motorcycle. The mean comfort joint angle value of the present study is presented in Figure 6.2. The optimal riding position dimensions (see Figure 6.3) could be applied through the golden ratio during the motorcycle concept sketching (ideation/generation) and prototype (Chou and Hsiao, 2005).

Recommendations from the association study (chapter-5): The vital information for motorcycle design is comfortable riding position (RP) and CRP. These findings of the association study of CRP and RP with the rider's physical characteristics (anthropometry and ROM) can be applied to decide the dimensions of interface points (handlebar, seat and footrest) of motorcycle.

I. For example, while deciding the vertical dimensions of the motorcycle (i.e., R_1, R_2, MR_1, and H) in the design process, target population's *Body fat indicators* (i.e., Triceps skinfold, Subscapular skinfold, Supraspinal skinfold, Medial calf skinfold) and Motion at Sagittal plane (i.e., flexion/extension of the neck, wrist, knee, elbow, and shoulder) have to be considered.

II. Similarly, in other instants, dimensions at transverse plane (i.e., T: the distance between the G-points on the right and left handle grips and L: the distance between the G'-points on the right and left handle grips) have to be decided based on the target population's *Body bilateral length indicator* (i.e., femur breadth, humerus breadth, foot-breadth) and Upperlimb Motions at Sagittal plane (i.e., Shoulder Flexion, Shoulder Extension).

III. Dimensions at the transverse plane (i.e., T and L) and horizontal dimensions at the sagittal plane (i.e., MR_2, R_3, and R_4) are negatively affecting the comfort joint angles of upperlimb (i.e., comfort joint angles of the neck, shoulder, arms and hand/wrist). Thus, these riding position dimensions need to be wisely decided by the designer.

IV. Comfort joint angles of lower limbs (i.e., comfort joint angles of the knee, foot) is significantly associated with *Body length indicator* (i.e., Stature, crotch height, buttock extension, cervical height–sitting, shoulder-elbow length, knee height, lower leg length, shoulder-elbow length, elbow-hand length, buttock-knee length, buttock-Popliteal length, Acromion grip length, ball of foot length and hand length). As the body length indicators might be changed over decades (Pheasant, 1996), the designer must consider the most recent anthropometric database of the targeted population.

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

VI. A guideline for CRP and optimal riding position are presented in chapter 4. Although not all people will comfortable with whole range of postures as individuals. However, this will guide to develop a better motorcycle design in India.

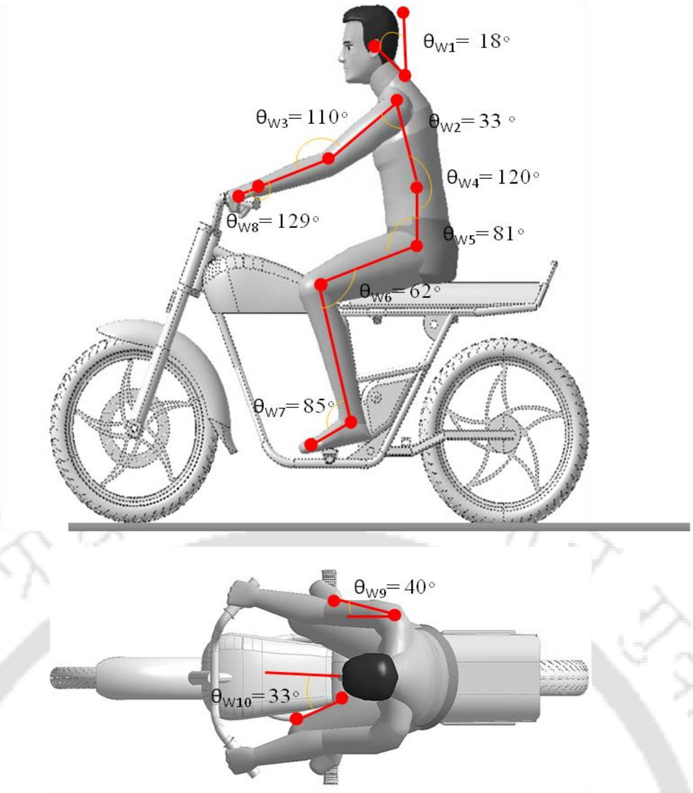


Figure 6. 2: Suggest mean comfort joint angles in a standard motorcycle design (unit: °)

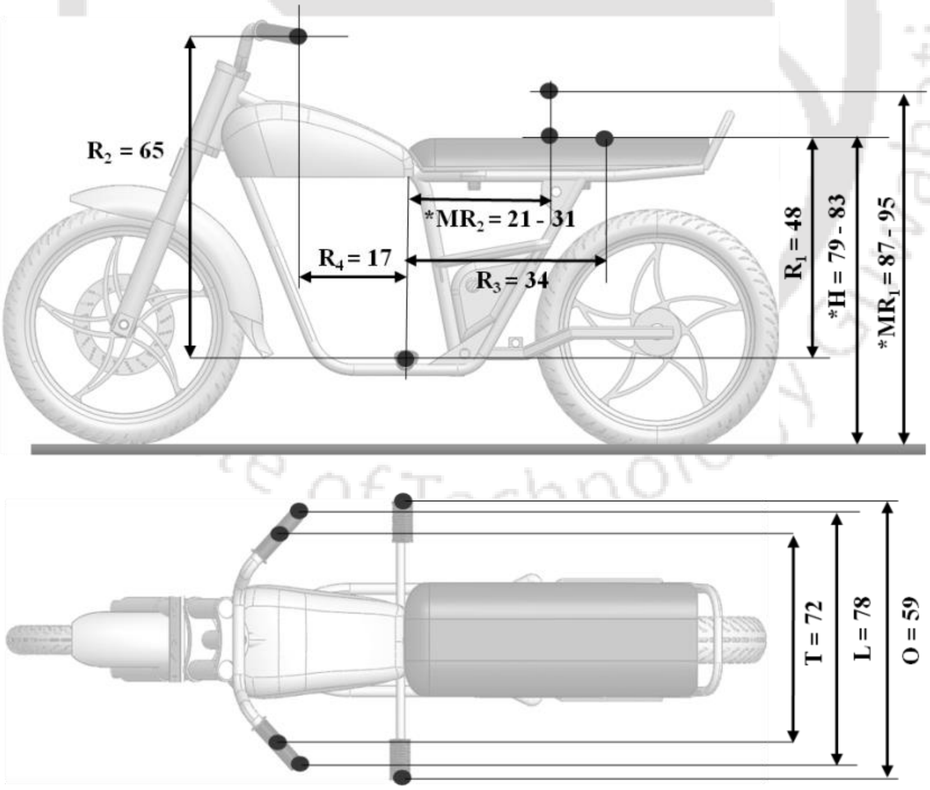


Figure 6. 3: Suggested optimum riding position in a standard motorcycle design (unit: cm).

6.5 Novelties (key contributions) of the present research

Findings of the research are the significant addition in the domain of both knowledgebase and design-development of motorcycles in Indian scenario. The novel contributions of the present research are listed below point-wise.

6.5.1 Contribution to knowledge-base

Reference dimensional database of standard motorcycles in India:

There are only a few simulators are available in South-Asia, especially in Malaysia (postura Montego) and India (Honda Smart trainer). The lack of information on motorcycle dimensions in research publications and articles may be a reason for a minimal number of locally manufactured and low-cost simulator development. The motorcycle dimensions are essential information to design a motorcycle simulator. In the present research, 18 key dimensions were measured from each of the 23 standard motorcycles popularly used in India. Collected dimensional data might be considered as a basic reference dimensional database of standard motorcycles in India. This database would be useful for the motorcycle designers/ engineers to design the motorcycle simulator or test-rig with allowable dimensional adjustability features for the rider-motorcycle interface points (handlebar, seat, and footrest) for better training or experimental facility development.

Development of anthropometrics and biomechanical (range of motion and comfort joint angle) reference dataset for Indian motorcyclists:

From literature review, it is evident that there is no anthropometric and biomechanical database of Indian motorcyclists till date. The physical measurements (anthropometry, ROM, and comfort joint angles) of present research could be used for the ergonomic design of motorcycles for Indian users, unless a larger database is generated. It the present research, 29 anthropometric dimensions, and 20 ROM measurements were taken from 120 male adult (aged 19–44 years) Indian motorcyclist following standard measurement procedure. These databases will help automobile designers to conceptualize the better ergonomic design of motorcycles. Besides, the ergonomists/ engineers could consider the postural comfort evaluation methodology as adopted in the present research, while analyzing the comfort experienced by the motorcyclists.

Establishing the association between comfortable riding posture and rider's physical attributes (anthropometry and ROM measurements):

From the literature survey, it is evident that the earlier researchers studied the relationship between comfortable posture (in terms of comfort joint angles) and anthropometry of the occupant (rider or driver) in two/ four wheeler context (Park et al., 2019, 2000; Porter and Gyi, 1998). It is also noticed that none of them attempted to establish the association between CRP and rider's anthropometric and ROM variables. Thus, the association study of motorcyclist's CRP with anthropometric and ROM characteristics, using stepwise multiple linear regression is some new addition in knowledge-base. Result of the present research also included the intra and inter correlations between CRP and rider's physical characteristics (anthropometry and ROM) by mentioning the strength and direction of the relationships.

Establishing the association between motorcycles attributes (comfortable riding position) and rider's physical attributes (anthropometry and ROM measurements):

Reported researches are available regarding association between anthropometry and riding/ driving position in case of bi-cycle and car (Fatollahzadeh, 2006; Park et al., 2019, 2000; Porter and Gyi, 1998) From the literature survey, it is evident that none of the earlier researchers attempted to establish the association between comfortable riding position (RP) and rider's anthropometric and ROM characteristics together. Thus, the present research is the first of its kind study to establish such association (using multiple linear regression) by considering both anthropometric and ROM of the rider in case of motorcycle. Result of the present research also included the intra and inter variable correlations between dimensions of RP and rider's physical characteristics (anthropometry and ROM) by mentioning the strength and direction of the relationships.

6.5.2 Contribution towards methodological perspective

Methodology adopted in the present research was robust in terms of the selection of appropriate tools and techniques backed by the reliability and validity through statistical analyses. Developed co-ordinate measurement instrument (laser-based and in-house fabricated) for measuring the dimensions of motorcycles was calibrated, and reliability of the measurements were checked (R^2=0.999). For measuring anthropometric dimensions, ROM and CRP (perceived comfort body joint angles), standard methodologies were adopted along with the assessment of reliability of the measurement process. Image processing technique was utilized for easy capturing of riding postures as well as riding positions. Moreover, principal component analysis was used to identify the key anthropometric dimensions, ROM variables, CRP and RP. The optimal riding position out of the nine test conditions (defined by the positions of the 3 interface points) was estimated using Taguchi Design of Experiments (DOE).

The methodologies adopted for data acquisition, representation, and statistical analysis for interpretation in the context of defining CRP and optimal riding position to ensure ergonomic design of motorcycle would be very useful for the motorcycle designers/ engineers. The present research methodology would act as guide-book to address the postural discomfort due anthropometric and ROM incompatibility of the targeted users with the design of the motorcycles. Indian motorcycle manufacturers should be encouraged to implement the design methodology adopted in this study. It will undoubtedly help in improving the ergonomics design of Indian motorcycle models.

6.5.3 Contribution to the motorcycle design process

Dimensional data of the standard motorcycles generated from the present research would be useful for deciding the dimensions of the standard motorcycle simulator or test-rig for the experimental and training purposes. It is expected that this data would act as a benchmarking dataset for the designers during their design modification or conceptualizing a new design of motorcycle. Developed anthropometric, ROM, and comfort joint angle data-sets would be used in the proactive ergonomic assessment (using DHM software) of the new motorcycle design as described in section 6.4. In addition, an optimum riding position, and thereby CRP could be ensured during the conceptual stage of the motorcycle design process. Findings of the association study of CRP and RP with the physical characteristics (anthropometry and ROM) of the rider can be utilized to decide the dimensions and positions of the handlebar, seat and footrest. Overall, all the findings of the present research have high potentials to support the designers/ engineers in the motorcycle design process.

6.5.4 Contribution to society

Various findings of the present research suggest plausible ways to improve the degree of postural comfort in terms of body joint angles of the riders. Design of a new motorcycle or redesigning of existing one based on the anthropometric and ROM data for defining optimal riding position and thereby CRP would certainly reduce muscular discomfort/ pain of the motorcyclists. Most of these findings are feasible and easy to implement by the designers/ engineers of the motorcycle manufacturing industry. Implementations of these findings would definitely address the identified problems of postural discomfort (body parts discomfort or pain) due to anthropometric and ROM incompatibilities with the dimensions of the motorcycle's interface points (handlebar, sea and footrest). It is envisaged that improvement in riding posture through ergonomic design of motorcycle would certainly reduce the discomfort of the riders and thereby minimize the possibility of motorcycle accident due to this factor (postural discomfort). Ergonomic design of the motorcycles would ensure the better health of motorcyclists and thus enhanced road safety.

6.6 Limitations and future scopes of the present research

- Limited source and time constraints forced to limit the sample size to 120, in agreement with the recommended sample size while conducting anthropometry studies (ISO 15535:2012, 2012). The number of female (8%) two-wheeler (motorcycle/scooter) users is very less than that of male counterpart (92%) (MRTH, 2018). Since the number of female riders are significantly low than male riders, the present study involved only males. However, the authors recommend inclusion of 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.

- Majority of the Indian riders are in the age range of 19–44 years (MRTH, 2018). Hence, this particular age range was selected for selecting the volunteers (riders) for the experiments/ data collection. However, the age range should be extended beyond 44 years to achieve a more realistic representation of Indian motorcyclists. State or zone-wise motorcyclist data in India are unavailable on regional transport office websites. Therefore, we assumed an equal percentage of male motorcyclists in six zones and thus an equal proportion of the strata. Due to limited data available in previously published databases and research papers, a comparative study of the mean difference was conducted rather than statistical tests. Future studies should be conducted with a larger sample size so that a highly reliable ROM and anthropometric database of Indian motorcyclists can be obtained. Such studies may also consider factors such as ethnicity and nutrition, which may influence the ROM and body dimensions of motorcyclists.

- The optimal riding position (defined by the dimensions of the 3 interface points) was estimated using Taguchi Design of Experiments (DOE). There was a critical limitation in the adopted method. Here, 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 condition, vibration, etc.), present study was laboratory based. The study objectives were achieved through experimentations on a static test-rig (experimental set-up), which was developed to provide a naturalistic riding posture to the subjects. Postural comfort/discomfort was evaluated during static riding posture. Thus, the perception of postural comfort/discomfort may differ to some extent in real dynamic road scenario whereas many other influencing factors come into play. Hence, experiment on dynamic (real road) riding conditions can be planned as longitudinal research in future.

- The present research attempted to find out the association between the riders' physical characteristics (anthropometry and ROM) and RP and CRP. This ergonomic study of postural comfort/discomfort on motorcycle design did not consider other mechanical aspects (i.e. aerodynamics, suspension system, and vehicle dynamics) which may influence the perception of comfort/discomfort. These mechanical aspects might be important for the comfortable design of motorcycle. Thus, the future scope of the research may include mechanical aspects of the motorcycle.

6.7 Conclusion

This was the first attempt to find the comfortable riding posture (CRP) and optimum riding position for a particular class/type of motorcycles. The result can be utilized further in improving the motorcycle design for a comfortable riding experience. The comparison results concluded that most of the CRP (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.

Present research has developed databases (anthropometry, ROM, CRP (comfort joint angles) of Indian motorcycle riders (19–44 years) for motorcycle riding posture. Moreover, optimum riding position based on 3 interface points (handlebar, seat and footrest) have been defined. The present research is the first-of-its-kind study to establish association (using stepwise multiple linear regression) of CRP and RP with the physical characteristics (anthropometric and ROM together) of the Indian riders. As there is no clearly defined comfort joint angles database to ensure CRP 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) available in the market. Present study dataset (anthropometric, ROM, and comfort joint angles) of Indian motorcycle riders would enable the DHM software to perform the virtual ergonomic evaluation of motorcycles during the design process.

The research methodology followed in the present research is perhaps first-of-its-kind in the direction of ergonomic design of standard motorcycles in terms of optimal riding position and thereby CRP in Indian context. This methodology used in the present thesis might be adopted straightforwardly by researchers, motorcycle designers, and automobile engineers in the two-wheeler manufacturing industry. The research method and material used in the present research could be replicated by other similar two-wheelers (like sport, cruiser, scooter, etc.) in order to explore the CRP and optimal riding positions. Electric-motorcycle companies/ start-ups having a vision in establishing new electric-standard motorcycle, may find these thesis work endeavour extremely beneficial for their design process. The present thesis work significantly contributes to the knowledge-base, motorcycle design methodology, and improvement of motorcycle rider’s posture to ensure comfortable riding experience in the context of ergonomic design and development of standard motorcycles in India.

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8 Appendix

Appendix A. Anatomical landmarks of anthropometric measurements

[1] Stature was measured as the vertical distance between the floor and the highest point of the head

[2] Crotch height was measured as the vertical distance between the floor and the distal part of the inferior ramus pubic bone

[3] Thigh circumference was measured as the maximal circumference of the thigh

[4] Buttock extension was measured as the maximal extended point of the buttocks

[5] Knee height was measured as the vertical distance between the floor and the highest point of the superior border of the patella

[6] Cervical height sitting was measured as the vertical distance between the horizontal sitting surface and cervical

[7] Shoulder-elbow length 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 was measured as the vertical distance between the acromion process and the horizontal sitting surface

[9] Elbow height, Sitting 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] Lower leg length was measured as the vertical distance between the horizontal sitting surface and footrest surface

[11] Buttock-knee length was measured as the horizontal distance between the knee-cap (foremost point) and the buttock (rearmost point)

[12] Acromion grip length was measured as the distance between the center of an object gripped in hand and the acromion process

[13] Ball of foot length was measured as the distance between the inner ballpoint and the posterior heel point

[14] The buttock-Popliteal length was measured as the horizontal distance between the knee hollow and the buttock (rearmost point)

[15] Hand length was measured as the vertical distance between the styloid processes and the middle fingertip

[16] Elbow-Hand Length was measured as the horizontal distance between the elbow (rearmost point) and the middle fingertip

[17] Upper arm circumference was measured as the maximal circumference of the upper arm

[18] Calf circumference was measured as the maximal circumference of calf

[19] Hip breadth, sitting was measured as the maximal portion of the hip

[20] Elbow to elbow breadth was measured as the maximal horizontal distance between the bilateral surfaces of the elbow area

[21] Humerus breadth was measured as the horizontal distance of the medial and lateral epicondyles of the humerus

[22] Foot breadth was measured as the maximal distance between the inner ballpoint and outer ballpoint

[23] Femur breadth was measured as the horizontal distance of the medial and lateral epicondyles of the femur

[24] Medial calf skinfold was measured (in mm) as the vertical skin fold on the largest circumference of the calf

[25] Supraspinal skinfold was measured (in mm) as the diagonal skin fold on the superior-iliac crest (topmost of hip bone)

[26] Subscapular skinfold was measured (in mm) as the diagonal skin fold on the scapula (lower end of the shoulder blade)

[27] Triceps skinfold was measured (in mm) as the vertical skinfold middle from the acromion to olecranon processes

[28] Weight 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, 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 and [b] Neck Extension 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 and [d] Lumbar Flexion 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 and [f] Wrist Flexion 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 and [h] Elbow Flexion 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 and [j] Knee Extension 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 and [l] Shoulder Flexion 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 and [p] Ankle dorsiflexion 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 and [o] Shoulder Adduction 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 and [r] Hip Adduction was 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 and [t] Hip Extension 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. Correlation coefficients between anthropometric and ROM measurements

Table C1: Correlation coefficients between anthropometric measurements

	S	BMI	CH	BE	CHS	SHS	EHS	KH	LLL	SEL	EHL	BKL	PL	AL
W	.323**	.840**	0.064	.182*	.318**	.311**	0.136	0.122	-0.065	.229*	.320**	.405**	.273**	0.151
S	-	-.238**	.639**	.690**	.715**	.661**	0.048	.593**	.616**	.806**	.801**	.787**	.707**	.628**
BMI		-	-.295**	-.212*	-0.08	-0.059	0.116	-.220*	-.416**	-.232*	-0.129	-0.035	-0.125	-.207*
CH			-	.451**	.498**	.447**	0.033	.385**	.454**	.543**	.517**	.577**	.606**	.276**
BE				-	.437**	.415**	-0.101	.484**	.516**	.663**	.656**	.650**	.576**	.609**
CHS					-	.845**	.515**	.399**	.377**	.561**	.554**	.559**	.533**	.355**
SHS						-	.663**	.443**	.425**	.596**	.537**	.488**	.512**	.407**
EHS							-	0.023	0.012	-.183*	-0.037	-0.132	-0.069	-0.078
KH								-	.856**	.552**	.485**	.543**	.515**	.423**
LLL									-	.530**	.469**	.492**	.505**	.457**
SEL										-	.736**	.769**	.742**	.598**
EHL											-	.810**	.753**	.643**
BKL												-	.919**	483**
PL													-	.450**
AL														-

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

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

Table C1: Correlation coefficients between anthropometric measurements (continuous)

BFL	HL	FB	EEB	HBS	TC	T	SS	SR	MC	CC	UC	FrB	HB	
.244**	.255**	-0.121	.807**	.721**	.617**	.354**	.549**	.590**	.431**	.718**	.759**	.518**	.340**	W
.575**	.661**	0.131	0.178	.241**	0.006	.236**	0.095	-0.011	0.092	0.053	0.035	.359**	0.172	S
-0.081	-0.114	-.205*	.722**	.606**	.638**	.219*	.502**	.606**	.383**	.702**	.761**	.328**	.251**	BMI
.403**	.483**	0.132	0.056	-0.018	-0.087	0.113	0.11	-0.031	-0.019	-0.123	-0.111	.193*	-0.024	CH
.427**	.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
.339**	.395**	-0.008	.221*	.218*	-0.02	.247**	0.087	0.021	0.119	0.034	0.078	.247**	0.015	CHS
.262**	.405**	-0.018	.251**	.206*	-0.069	.268**	0.053	0.011	0.17	0.068	0.04	.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
.356**	.340**	.357**	-0.015	0.086	-0.145	.222*	0.022	-0.032	0.019	-0.009	-.210*	.234**	-0.118	KH
.366**	.375**	.322**	-0.085	-0.057	-.253**	.194*	-0.045	-0.157	-0.024	-.191*	-.303**	0.134	-0.092	LLL
.500**	.630**	0.149	0.121	0.106	-0.096	.250**	0.017	-0.049	0.13	-0.077	-0.047	.244**	0.085	SEL
.532**	.741**	0.122	.187*	.256**	-0.004	.344**	0.147	0.128	.250**	0.023	0.064	.290**	0.124	EHL
.531**	.591**	.251**	.200*	.380**	0.065	.347**	0.17	0.139	.255**	0.102	0.062	.329**	-0.016	BKL
.481**	.525**	.325**	0.102	.203*	-0.088	.310**	0.106	0.005	.200*	-0.027	-0.07	.258**	-0.13	PL
.376**	.544**	0.002	0.066	0.111	-0.07	0.171	-0.018	-0.053	0.11	-0.062	-0.048	.204*	0.164	AL
-	.500**	0.17	.209*	0.158	0.098	0.166	0.071	0.033	0.01	0.016	0.007	.261**	0.178	BFL
	-	-0.089	.183*	0.092	0.065	.309**	0.116	0.086	0.152	-0.029	0.05	.327**	.274**	HL
		-	-0.154	0.076	-0.145	-0.02	-0.095	-.247**	-0.07	-0.122	-.281**	0.057	-.403**	FB
			-	.536**	.448**	.435**	.510**	.533**	.506**	.529**	.754**	.293**	.365**	EEB
				-	.606**	.242**	.481**	.512**	.353**	.557**	.553**	.538**	0.171	HBS
					-	-0.051	.392**	.439**	0.166	.491**	.554**	.441**	.241**	TC
						-	.367**	.460**	.631**	0.108	.411**	0.013	.218*	T
							-	.680**	.439**	.432**	.508**	.305**	0.128	SS
								-	.567**	.531**	.519**	.254**	.205*	SR
									-	.291**	.458**	0.116	.214*	MC
										-	.555**	.454**	.211*	CC
											-	.214*	.425**	UC

Table C2: Correlation coefficients between ROM measurements

	NF	NE	LF	LE	WF	WE	KF	KE
NE	.452**	-						
LF	.222*	-0.095	-					
LE	0.035	-.246**	.336**	-				
WF	-0.092	-0.051	0.074	-0.103	-			
WE	-0.121	-0.018	-.180*	-0.064	.262**	-		
KF	-.191*	-0.135	-0.034	-.211*	0.121	-0.006	-	
KE	0.16	0.002	0.062	.193*	-.211*	-.245**	-0.048	-
HF	-.329**	-0.143	-0.031	-0.098	0.068	.270**	.245**	-.413**
HE	-0.029	0.079	0.011	0.102	-0.174	0.032	.200*	-0.021
HAb	0.003	-0.043	-0.091	0.01	0.045	-0.015	.236**	0.049
HA	-.239**	-.338**	-0.103	0.002	-0.109	-0.042	0.036	0.09
EE	-0.096	-.180*	0.076	-0.052	-0.006	-0.138	0.128	0.114
EF	0.012	0.021	-0.067	-0.09	0.012	.263**	-0.03	-0.052
SF	-0.027	-0.075	0.124	0.158	0.105	0.045	-0.15	-0.162
SA	0.017	0	0.058	.220*	-.234*	-.319**	.180*	.320**
SAb	-.272**	-.231*	-0.018	0.002	0.058	-0.018	0.049	-0.081
SE	-.198*	0.03	-0.121	-.247**	.386**	.354**	0.131	-.371**
AP	-0.007	-0.161	0.022	0.11	0.024	-.246**	0.136	-0.023
AD	-0.024	-0.145	-0.072	-0.107	-0.002	0.011	0.091	0.105

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

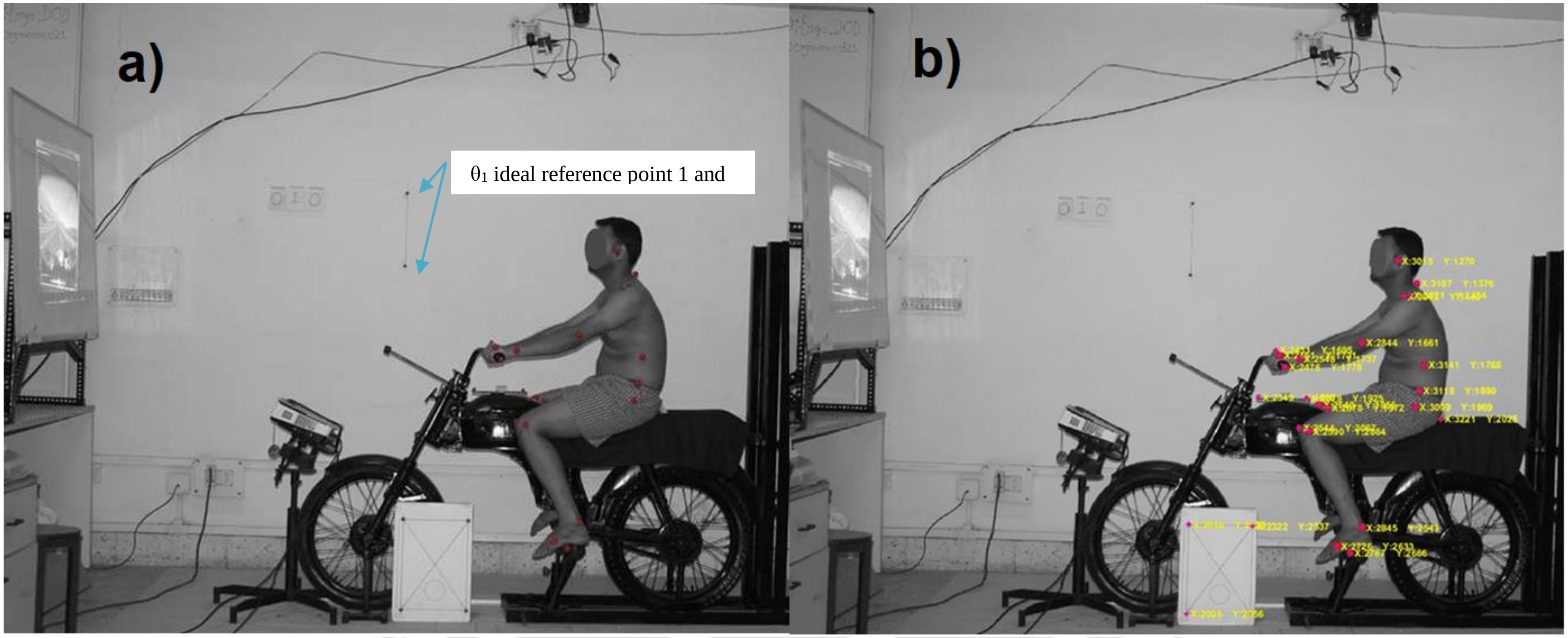
Table C2: Correlation coefficients between ROM measurements (continuous)

	HF	HE	HAb	HA	EE	EF	SF	SA	SAb	SE	AP
HE	0.142	-									
HAb	0.064	.230*	-								
HA	-0.12	-0.142	-0.093	-							
EE	-0.152	-0.11	-0.045	.219*	-						
EF	-0.058	-0.013	-0.038	-0.129	-0.13	-					
SF	0.024	-.218*	-0.028	-0.048	0.099	-0.135	-				
SA	-.210*	.236**	0.175	0.108	0.086	-.239**	-.338**	-			
SAb	0.006	0.017	-0.056	.187*	0.079	-.202*	.203*	-0.03	-		
SE	.243**	0.033	0.056	-0.105	-0.108	.240**	-0.016	-.264**	-.216*	-	
AP	-.230*	0.112	.195*	0.038	0.057	-0.1	0.012	0.174	.205*	-0.085	-
AD	0.036	.195*	.197*	0.106	-0.1	0.115	-.406**	.232*	0.037	0.044	.206*

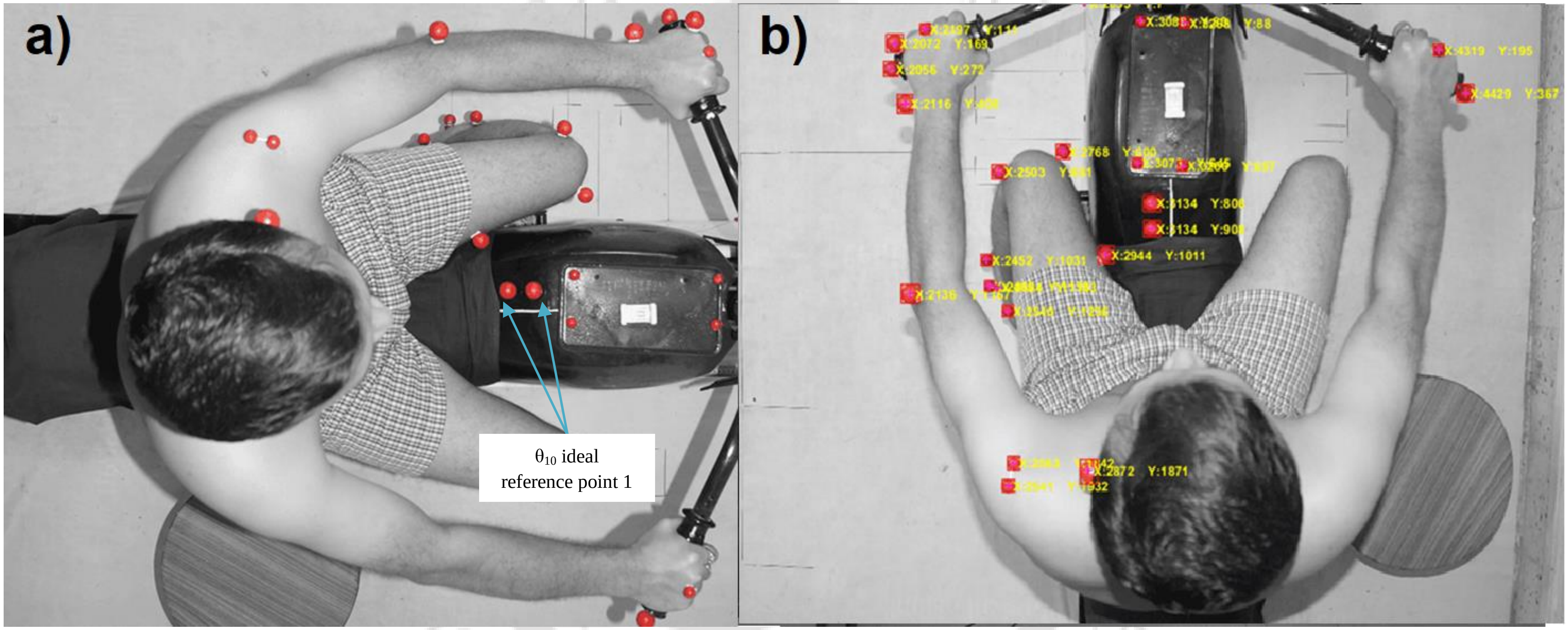
**Correlation is significant at the 0.01 level (2-tailed)

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

Appendix D1. A typical side view image of a subject with a) red markers; b) Identified landmark's coordinators using DIP



Appendix D2. A typical top view image of a subject with a) red markers; b landmark's coordinators using DIP



Appendix E. Image calibration system

The actual dimensions of the side and top view rectangular board are disclosed in Figure B1-S and B1-T. The red markers (Ø 12 mm) were placed in all the corners (ABCD and abcd points) of the rectangular boards. These red markers were considered as reference points in the process of image calibration. The 2-dimensional coordinators ((X_1 Z_1), (X_2 Z_2), (x_1 y_1), (x_2 y_2), and so on) from the images were used to estimate the pixel's DPI (Dot per Inch). Further, they were also used to compute the percentage of error deviation in angular (AEd%) and dimensional (Ed%) measurement between the actual (known size) and image measurement (coordinates) of the rectangular board.

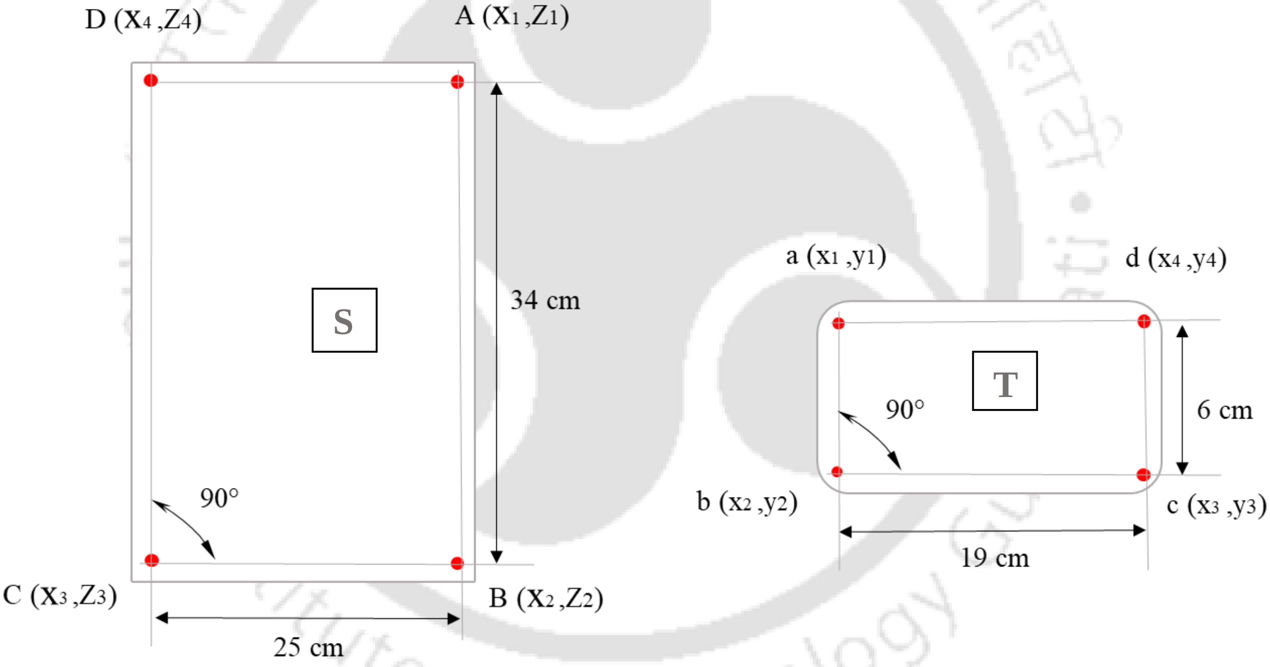


Figure B.1. Calibration system of the image with known size – (S) side-view calibration system and (T) top-view calibration system

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

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

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

Where,

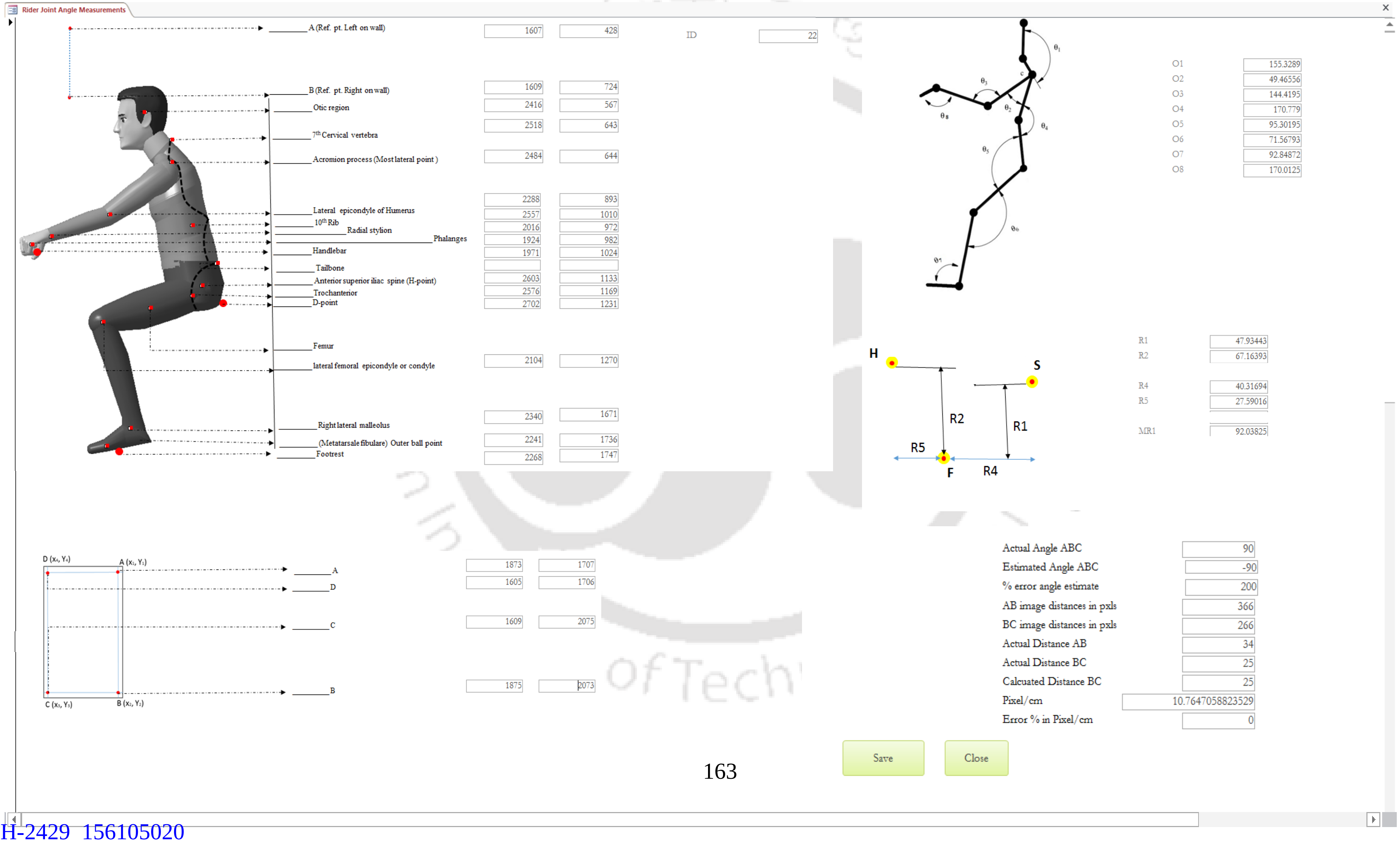
$$\text{Calculated BC} = \frac{(X_2 - X_3)_{\text{B to C pixels distance in the image}}}{\text{DPI of side view image}}$$

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

$$\text{AEd\%} = \begin{cases} \dfrac{(\measuredangle ABC = 90°) - (\text{Estimated } \measuredangle ABC)}{(\measuredangle ABC = 90°)} \text{X 100; if side view} \\ \dfrac{(\measuredangle abc = 90°) - (\text{Estimated } \measuredangle abc)}{(\measuredangle abc = 90°)} \text{X 100; if Top view} \end{cases} \qquad (a.3)$$

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

Appendix F1. A typical coordinators collection MS Access form for a subject's side view image



A (Ref. pt. Left on wall)	1607	428
B (Ref. pt. Right on wall)	1609	724
Otic region	2416	567
7th Cervical vertebra	2518	643
Acromion process (Most lateral point)	2484	644
Lateral epicondyle of Humerus	2288	893
10th Rib	2557	1010
Radial stylion	2016	972
Phalanges	1924	982
Handlebar	1971	1024
Tailbone		
Anterior superior iliac spine (H-point)	2603	1133
Trochanterior	2576	1169
D-point	2702	1231
Femur		
lateral femoral epicondyle or condyle	2104	1270
Right lateral malleolus	2340	1671
(Metatarsale fibulare) Outer ball point	2241	1736
Footrest	2268	1747

ID 22

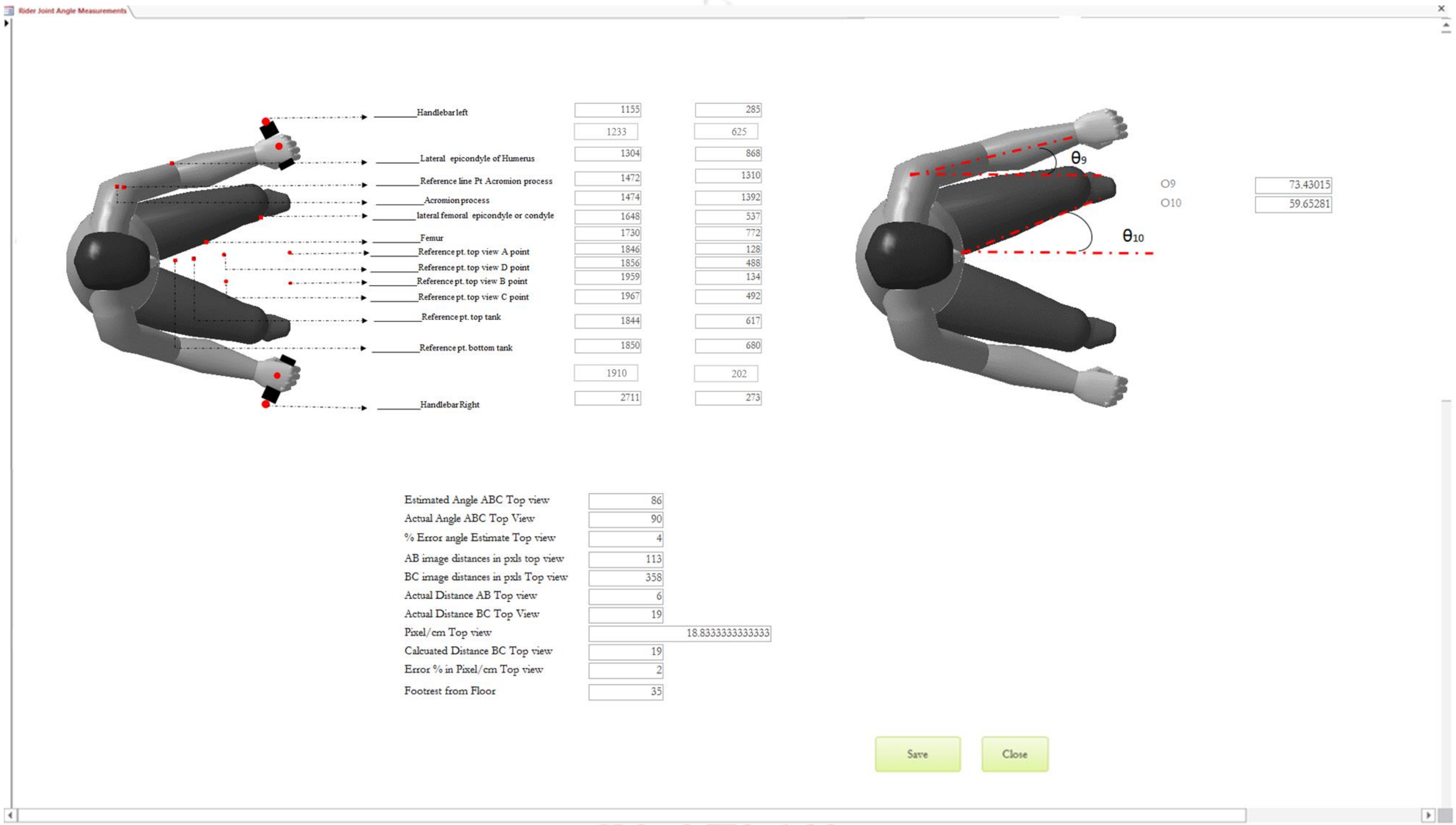
O1	155.3289
O2	49.46556
O3	144.4195
O4	170.779
O5	95.30195
O6	71.56793
O7	92.84872
O8	170.0125

R1	47.93443
R2	67.16393
R4	40.31694
R5	27.59016
MR1	92.03825

A	1873	1707
D	1605	1706
C	1609	2075
B	1875	2073

Actual Angle ABC	90
Estimated Angle ABC	-90
% error angle estimate	200
AB image distances in pxls	366
BC image distances in pxls	266
Actual Distance AB	34
Actual Distance BC	25
Calcuated Distance BC	25
Pixel/cm	10.7647058823529
Error % in Pixel/cm	0

Appendix F2. A typical coordinators collection MS Access form for a subject’s top view image

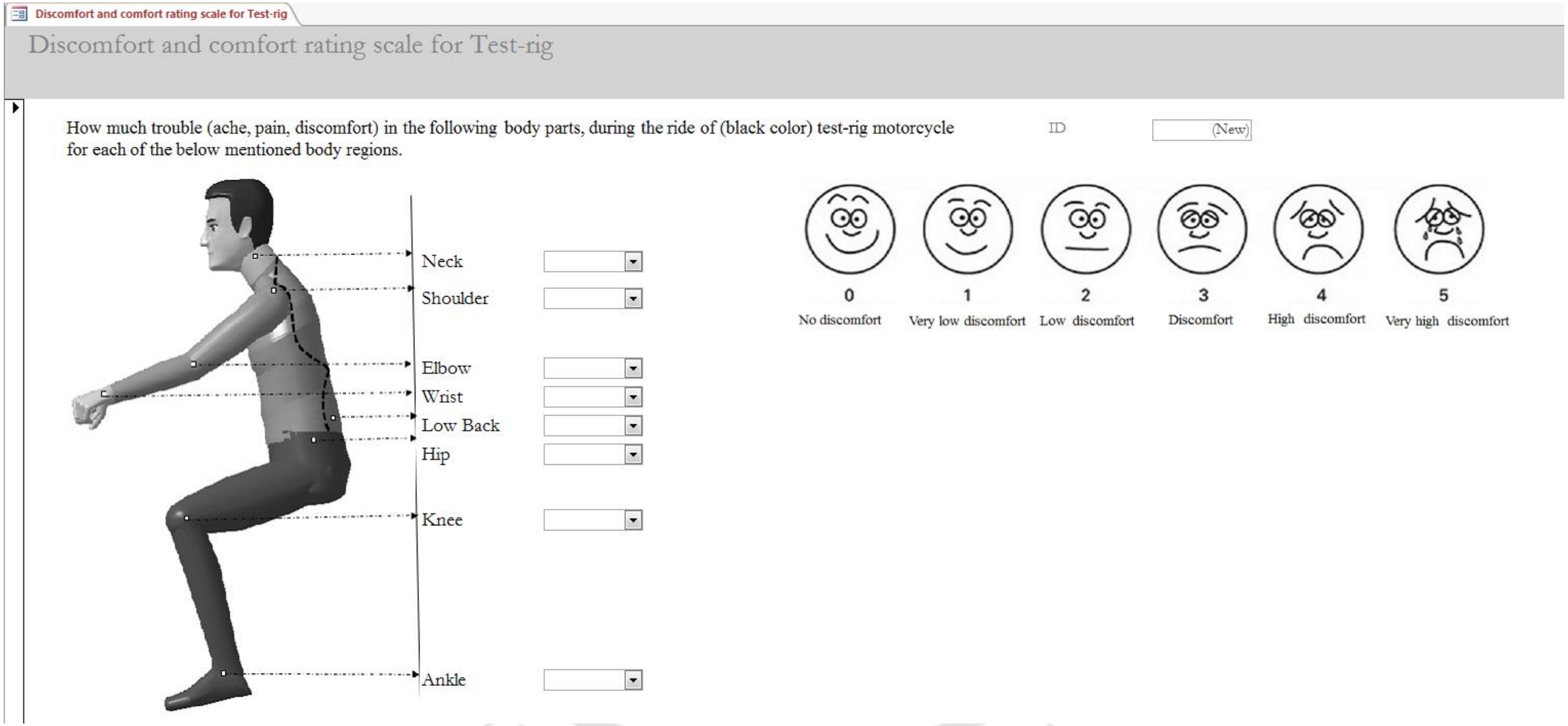


Handlebar left	1155	285
	1233	625
Lateral epicondyle of Humerus	1304	868
Reference line Pt Acromion process	1472	1310
Acromion process	1474	1392
lateral femoral epicondyle or condyle	1648	537
Femur	1730	772
Reference pt. top view A point	1846	128
Reference pt. top view D point	1856	488
Reference pt. top view B point	1959	134
Reference pt. top view C point	1967	492
Reference pt. top tank	1844	617
Reference pt. bottom tank	1850	680
	1910	202
Handlebar Right	2711	273

O9	73.43015
O10	59.65281

Estimated Angle ABC Top view	86
Actual Angle ABC Top View	90
% Error angle Estimate Top view	4
AB image distances in pxls top view	113
BC image distances in pxls Top view	358
Actual Distance AB Top view	6
Actual Distance BC Top View	19
Pixel/cm Top view	18.8333333333333
Calcuated Distance BC Top view	19
Error % in Pixel/cm Top view	2
Footrest from Floor	35

Appendix G1. Discomfort rating scales (MS Access form)



Discomfort and comfort rating scale for Test-rig

Discomfort and comfort rating scale for Test-rig

How much trouble (ache, pain, discomfort) in the following body parts, during the ride of (black color) test-rig motorcycle for each of the below mentioned body regions.

ID (New)

Neck

Shoulder

Elbow

Wrist

Low Back

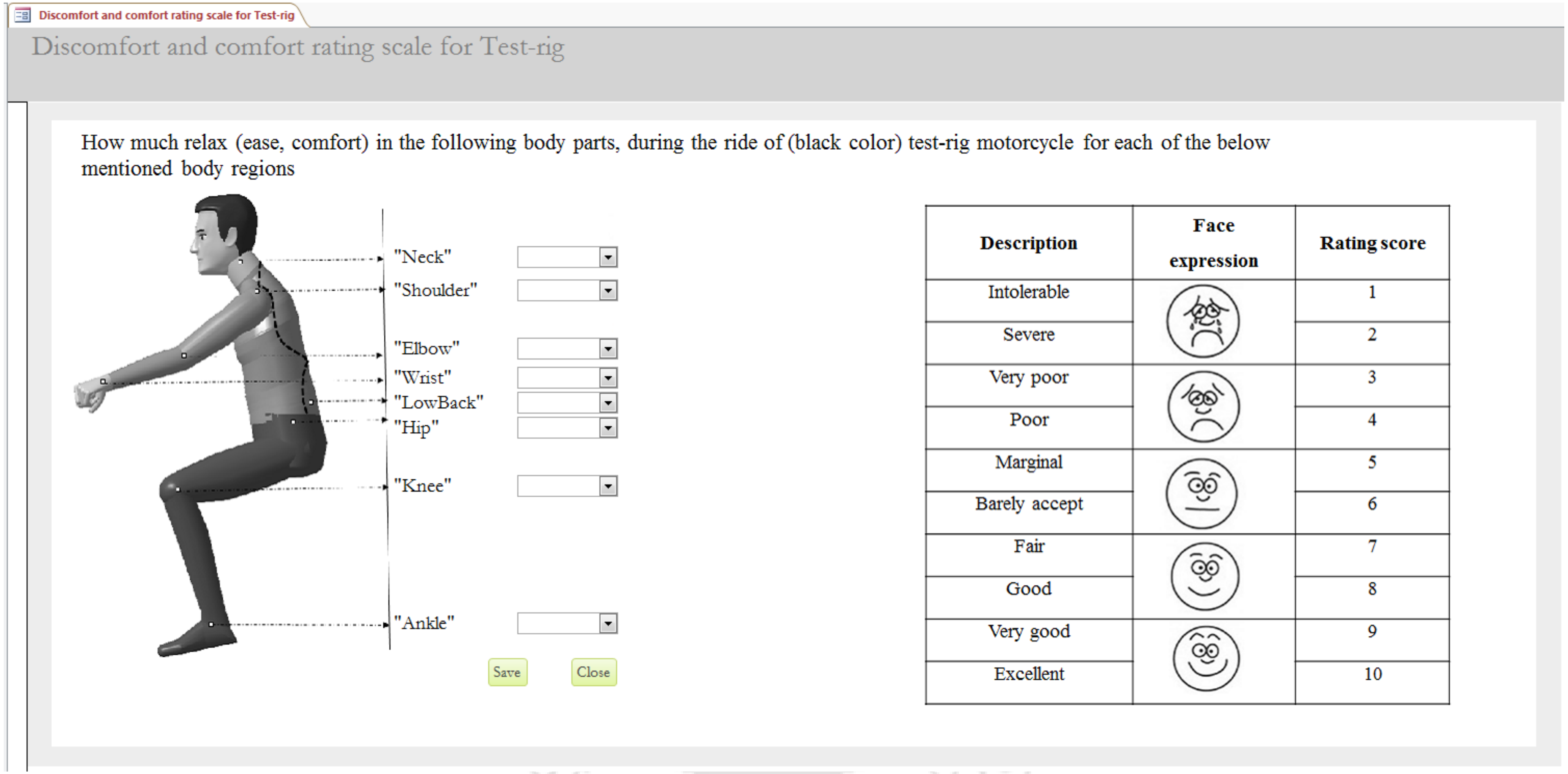
Hip

Knee

Ankle

0	1	2	3	4	5
No discomfort	Very low discomfort	Low discomfort	Discomfort	High discomfort	Very high discomfort

Appendix G2. Comfort rating scales (MS Access form)



Discomfort and comfort rating scale for Test-rig

How much relax (ease, comfort) in the following body parts, during the ride of (black color) test-rig motorcycle for each of the below mentioned body regions

Description	Face expression	Rating score
Intolerable		1
Severe		2
Very poor		3
Poor		4
Marginal		5
Barely accept		6
Fair		7
Good		8
Very good		9
Excellent		10

Appendix H. Discomfort rating of the subjects (n=120) - Frequency distribution

	Joints							
Discomfort ratings[b]	Neck	Shoulder	Elbow	Wrist	Low Back	Hip	Knee	Ankle
No discomfort (0)	29	39	49	50	25	50	71	54
Very low discomfort (1)	38	26	29	32	32	36	27	37
Low discomfort (2)	23	22	31	19	25	18	13	17
Discomfort (3)	17	23	4	12	21	11	5	9
High discomfort (4)	11	10	7	7	14	2	3	3
Very High discomfort (5)	2	0	0	0	3	3	1	0

[b] Rating consisted of 5-point scale

Appendix I. Spearman's correlation coefficient among riding position variables

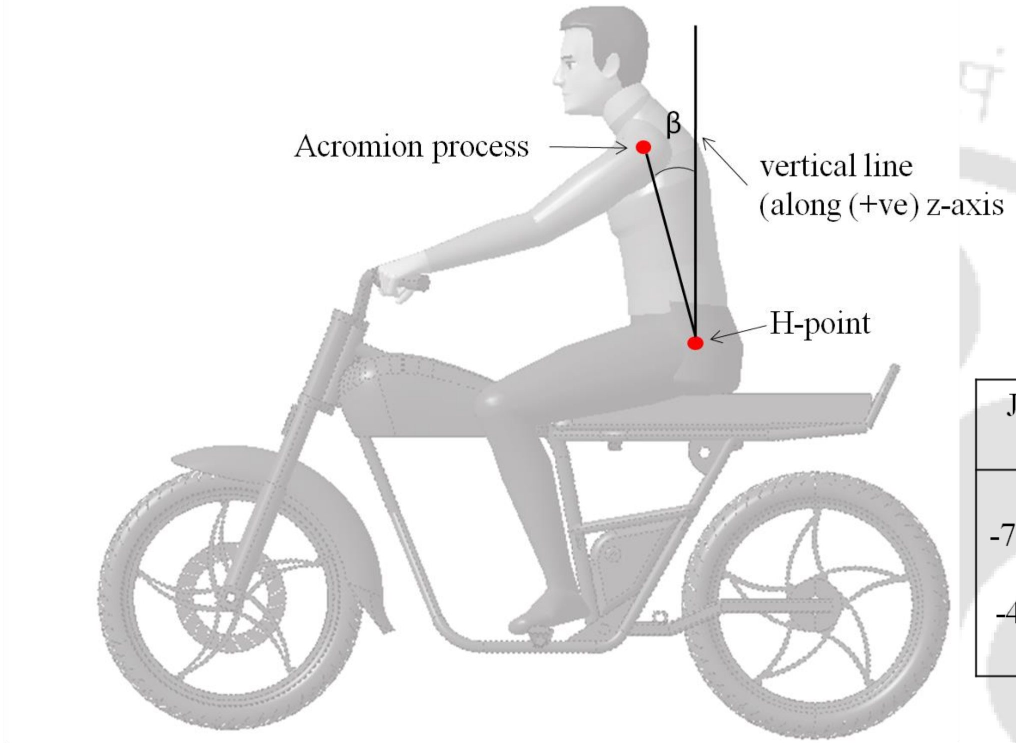
	R_1	R_2	R_3	R_4	MR_1	MR_2	H	L	T
R_2	0.328**	-							
R_3	0.167	0.181*	-						
R_4	0.021	-0.168	-0.468**	-					
MR_1	0.904**	0.276**	0.222*	-0.072	-				
MR_2	0.182*	0.265**	.810**	-0.371**	0.023	-			
H	0.95**	0.328**	0.167	0.021	0.850**	0.182*	-		
L	0.071	0.121	0.245**	-0.445**	0.217*	0.019	0.071	-	
T	0.071	0.121	0.245**	-0.445**	0.217*	0.019	0.071	0.950**	-
O	-0.083	-0.041	-0.024	0.1	0.018	-0.046	-0.083	0.009	0.009

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

Appendix J. Rest and pulse rate measurement

Groups Stature ranges		Group -tall Above 175 cm			Group – medium Between 174 cm - 165 cm			Group - Short below 165 cm		
Stature		186	182	178	174	170	167	162	159	156
Subjects		Subject 1	Subject 2	Subject 3	Subject 4	Subject 5	Subject 6	Subject 7	Subject 8	Subject 9
Test Conditions	1	77	83	93	90	65	66	60	78	66
	2	66	75	84	81	68	60	63	71	80
	3	68	70	81	73	75	66	56	65	66
	4	60	73	72	72	74	62	60	61	79
	5	65	75	63	72	62	63	72	77	73
	6	66	63	74	74	60	64	75	78	66
	7	65	72	72	78	73	77	61	62	65
	8	70	73	83	75	78	65	60	67	65
	9	65	79	84	76	72	64	72	56	72
Mean		67	74	78	77	70	65	64	68	70
SD		5	6	9	6	6	5	7	8	6

Appendix K. Design position angle (called as β)



JASO T006:2007 Suggestion	Current Study Observation
β shall be range between -7° to 10° for inclined backward and -45° to -7° for inclined forward	β angle of 120 subjects were found between the range of -5° to 14° (Mean: 8°; SD: 6).

Appendix L. Intra -Correlation between riding position and postural variables

Table L1. Intra -Correlation among postural variables

	θ_{W1}	θ_{W2}	θ_{W3}	θ_{W4}	θ_{W5}	θ_{W6}	θ_{W7}	θ_{W8}	θ_{W9}
θ_{W1}	-								
θ_{W2}	.446**	-							
θ_{W3}	.423**	.639**	-						
θ_{W4}	.353**	.357**	.391**	-					
θ_{W5}	.250**	.268**	0.148	.685**	-				
θ_{W6}	0.096	.246**	.406**	.375**	.304**	-			
θ_{W7}	.300**	.225*	.241**	.400**	.351**	.426**	-		
θ_{W8}	.344**	.209*	.267**	.398**	.235**	.225*	.234*	-	
θ_{W9}	0.092	.267**	.471**	.315**	.202*	.324**	.268**	.241**	-
θ_{W10}	0.124	0.05	-0.096	.344**	.481**	0.042	.287**	.203*	.381**

Table L2. Intra -Correlation among riding position variables

	R_1	R_2	R_3	R_4	MR_1	MR_2	H	L	T
R_2	0.328**	-							
R_3	0.167	0.181*	-						
R_4	0.021	-0.168	-0.468**	-					
MR_1	0.904**	0.276**	0.222*	-0.072	-				
MR_2	0.182*	0.265**	.810**	-0.371**	0.023	-			
H	0.95**	0.328**	0.167	0.021	0.850**	0.182*	-		
L	0.071	0.121	0.245**	-0.445**	0.217*	0.019	0.071	-	
T	0.071	0.121	0.245**	-0.445**	0.217*	0.019	0.071	0.950**	-
O	-0.083	-0.041	-0.024	0.1	0.018	-0.046	-0.083	0.009	0.009

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

Appendix M. Correlation of CRP with the PCs of anthropometrics and ROM

	Comfort Hip joint angles	Comfort angles of upper limbs	Comfort angles of lower limbs
Body length indicator	0.081	-0.063	-.362**
Volume indicator	-.281**	-0.014	0.075
Body fat indicators	-0.092	-0.055	-0.077
Sitting height indicator	-0.099	.193*	-0.174
Body bilateral length indicators	-0.094	.277**	-0.115
Motion at Sagittal plane	.335**	0.089	-0.07
Motion at Transverse plane	-.213*	0.15	-0.096
Upperlimb Motions at Sagittal plane	.182*	-.227*	0.058
lower limb Motions at the Sagittal plane	0.027	-0.068	-0.015
lower limb Motion at Transverse plane	-.193*	0.095	-0.042
Spine Motion at Sagittal plane	-0.139	0.004	.317**
Knee-elbow Motion at Sagittal plane	-0.142	-0.151	-0.165
Vertical dimensions at Sagittal plane	-.183*	0.11	0.165
Dimensions at Transverse plane	0.159	-.297**	0.037
Horizontal dimensions at Sagittal plane	0.014	-.254**	0.014
Footrest dimensions at Transverse plane	-0.139	0.076	0.01

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

Appendix N. Correlation between PCs of RP and ROM and Anthropometry

	Vertical dimensions at Sagittal plane	Dimensions at Transverse plane	Horizontal dimensions at Sagittal plane	Footrest dimensions at Transverse plane
Body length indicator	-0.042	-0.014	.248**	0.115
Volume indicator	0.15	0.007	0.082	0.036
Body fat indicators	-.233*	0.009	0.064	-0.049
Sitting height indicator	0.114	0.101	0.022	0.056
Body bilateral length indicators	0.047	-.594**	-0.067	0.002
Motion at Sagittal plane	-.279**	.204*	0.076	-0.074
Motion at Transverse plane	-0.141	-.297**	-0.089	.214*
Upperlimb Motions at Sagittal plane	0.102	.407**	-0.29**	0.016
lower limb Motions at the Sagittal plane	0.083	0.017	-0.062	-0.091
lower limb Motion at Transverse plane	0.086	-0.144	-0.039	.208*
Spine Motion at Sagittal plane	0.102	0.017	-0.093	0.05
Knee-elbow Motion at Sagittal plane	-0.095	-0.02	0.074	0.135
Comfort Hip joint angles	-.183*	0.159	0.014	-0.139
Comfort angles of upper limbs	0.11	-.297**	-.254**	0.076
Comfort angles of lower limbs	0.165	0.037	0.014	0.01

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

Appendix O. List of publications

Journal papers

1. **Arunachalam**, M., Mondal, C., Singh, G. and Karmakar, S., 2019. Motorcycle riding posture: a review. Measurement, 134, pp.390-399. **[SCIE/Scopus Indexed; Q1 Journal]**

2. **Arunachalam**, M., Singh, A.K. and Karmakar, S., 2020. Determination of the key anthropometric and range of motion measurements for the ergonomic design of motorcycles. Measurement, 159, p.107751. **[SCIE/Scopus Indexed; Q1 Journal]**

3. **Arunachalam**, M., Mondal, C. and Karmakar, S., 2020. Field Measurement of the Motorcycle's Key Dimensions Using Simple Method and in-House Fabricated Instrument. Instrumentation, Mesures, Métrologies, 19(4). **[Scopus Indexed; Q3 Journal]**

4. **Arunachalam**, M., Singh, A.K. and Karmakar, S., 2021. Perceived comfortable posture and optimum riding position of Indian male motorcyclists for the short-duration riding of standard motorcycles. International Journal of Industrial Ergonomics, 83, 103135. **[SCIE/Scopus Indexed; Q2 Journal]**

5. **Arunachalam**, M., Singh, A.K. and Karmakar, S., 2021. Exploring the association of riders' physical attributes with comfortable riding posture and optimal riding position. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering. *[In Press]*. https://doi.org/10.1177/09544070211012553. [**SCI/Scopus Indexed; Q2 Journal]**

Conferences proceedings

1. **Arunachalam, M**., and Karmakar, S., 2018. "Ergonomic Design and Evaluation of Innovative Main Stand of Motorcycle." In: Bagnara S., Tartaglia R., Albolino S., Alexander T., Fujita Y. (eds.) Proceedings of the 20th Congress of the International Ergonomics Association (IEA 2018). IEA 2018. Advances in Intelligent Systems and Computing, vol. 824, Pp.1099-1111 Springer, Cham. [ISBN 978-3-319-96070-8] **[Scopus Indexed]**

2. **Arunachalam, M**. and Karmakar, S., 2021. Classification of Motorcycles and Prediction of Indian Motorcyclist's Posture at the Conceptual Design Stage. In Emerging Trends in Mechanical Engineering (pp. 141-153). **Springer, Singapore**.

3. **Arunachalam M**, Mondal C, Karmakar.S, 2017. "Development of a laser-based 3D co-ordinate measuring device and its application in measuring key dimensions of motorcycles". In: Proceedings of International Ergonomics Conference, HWWE (15th ISE annual Conference), December 8-10, 2017, Aligarh Muslim University, India, pp.205-206. [ISBN: 978-93-5174-905-9].