Anthropometry and strength parameterization of lower limb disabled individuals pertinent to agricultural applications

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Abstract: Limited anthropometric and strength data availability pertinent to lower limb disabled individuals (DI) restricts agricultural and allied sector application developments. In such pursuit, anthropometric and strength data pertinent to lower limb disabled individuals (DI) from the state of West Bengal (India) was acquired and analyzed. A total of 44 body dimensions and 8 strength parameters of such forty individuals were collected in sitting posture. Mean body weight and height of selected subjects were 52±13 kg (Mean±standard deviation) and 779±39 mm, respectively. Anthropometric parametrization identified twenty-nine body dimensions and four strength parameters to significantly correlate to other body dimensions (Pearson's correlation [r]: ±0.3–0.52, p<0.01). Overall, thirty-three body dimensions were found deterministic for estimating 44 body dimensions through simple (SLR) and multilinear regression (MLR) analysis (Determination coefficient [R^2]: 0.37–0.72), thereby minimizing the need for ergonomic efforts for data acquisition. Body dimension magnitudes of DI were significantly (p<0.01) lower than the abled individuals (AI) and had a higher variability possibly due to the extent of disability (2%–27%). Inclusion of disabled individuals' anthropometry could help develop suitable equipment and workplace for them in small scale systems for livelihood, especially in developing countries. A general hand reach workplace envelope for agricultural tractor and self-propelled machinery was attempted in the study and force limitations for control levers were also determined. The hand reach envelope developed for lower limb disabled individuals identified the region to be enclosed within 372–499 mm horizontal and 212–499 mm vertical from seat reference point (SRP).

Keywords: anthropometry, lower limb disability, workplace, agricultural machinery, hand reach envelope

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1 Introduction

Human body impairment structurally or functionally restricts from participating in physical activities. According to the world report on disability (World Health Organization and The World Bank, 2018), 785 million (15.6% of the total world population) are disabled and that in India are 26.8 million (Census of India, 2011). In Indian context, an increase of 5 million with such individuals was observed in last decade (1400 individuals per day). Among such disabled individuals (DI), 69% belong to rural areas of India of which 20% have movement disability. Such disability in rural India is majorly due to farm/non-farm accidents, congenital deformity, disease consequence, limited health care facilities and economic and nutritional challenges. Limited accessibility of such individuals to agricultural equipment or workplaces forces them to be dependent for daily activities and livelihood.

Human anthropometry varies with the region, nature of work, agro-climatic conditions, socio-economic conditions and physical condition (Gite and Yadav, 1989; Yadav et al.,

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1997, 2000, 2018; Lin et al., 2004; Dewangan et al., 2010a; Dewangan et al., 2010b; Agrawal et al., 2010). Mismatch between human capabilities and their machine requirements causes musculoskeletal discomfort that may induce health problems such as neck pain, eye pain, back strain, headache, fatigue, wrist, hand, elbow and shoulder illness, carpal tunnel syndrome and strenuous disorder (Dewangan et al., 2010a; Dewangan et al., 2010b; Deros et al., 2011; Vyavahare and Kallurkar, 2012; Dawal et al., 2015; Adnan and Dawal, 2019). Equipment or workplace design being the tradeoff between the human physiological needs and the design considerations of pertinent equipment or workplace requires anthropometric dimensions and strength data to be more efficient and productive also for the DI (Agrawal et al., 2010; Adnan and Dawal, 2019). Most anthropometric studies are focused on abled individuals (AI) (Tunay and Melemez, 2008; Darliana et al., 2016) thereby limiting the designs, safety and workplace environment for lower limb DI. Addressing such limitations is critical to provide equal opportunities and involvements in major activities as the AI (Paquet and Feathers, 2004). Sufficient ergonomic and anthropometric databases have been developed in the western countries (NASA, 1978a, 1978b; Syed, 1993; Kumar et al., 2016) and therefore encourages such attention also in the developing countries.

Researchers have been considering anthropometric dimensions of lower limb disabled population majorly for the wheelchair and other assistive aid designs. However, considering the fact that DI in rural areas is directly or indirectly involved in agricultural activities, such anthropometric considerations for agricultural equipment or workplace design is still very limited and unavailable to the target stakeholders. Existing agricultural machinery systems, tractors, farm implements, related workstations in agri-food-processing industries, etc. are designed for the abled agricultural workers. In a tractor, gear shift levers, hydraulic controls, hand brake, differential lock, power take off engaging disengaging levers require high hand push and pull forces and steering wheel requires high hand torque strengths (Dupis, 1959; Dewangan et al., 2010b; which is the most frequently used control (Mital and Kumar, 1998; Dewangan et al., 2010b; Mehta et al., 2011). Development of suitable workstation considering the anthropometric body dimensions and strength parameters of DI and modifications of standing workstation to sitting workstation (Kumari, 2018), and also the provision of working along with their wheelchair can create opportunities for DI in these industries.

This study was therefore conducted with an aim to develop anthropometry database of lower limb disabled agricultural workers in the state of West Bengal, India so as to add value and improve efficiency of existing systems in perspective of also the DI. Specific study objectives are (1) parametric assessment of anthropometric body dimensions and strength of DI in comparison to the AI and (2) inclusion of such anthropometric consideration towards a case-specific equipment/workstation design of an agricultural machinery system and allied sectors.

2 Materials and methods

2.1 Human subjects

Lower limb DI were listed from the grass-root government agencies (municipality and local medical center) in the Kharagpur region in the state of West Bengal, India. This included amputations due to accidents and diseases, spinal cord injuries, poliomyelitis and cardio-pulmonary conditions. The victims of farm accidents who stayed away from the field due to unavailability of assisting aids and fear of further injuries were also included as the participants. It was made sure that the participants are sufficiently efficient with their upper body, mental and visual health to perform relevant agricultural activities and are interested to participate. Participants in 18–45 years of age group were selected as most agricultural workers belong to this age group.

2.2 Anthropometric data

Forty-four anthropometric measurements of DI in sitting posture were collected in the ergonomics laboratory, IIT Kharagpur, West Bengal using an Integrated Composite Anthropometer (ICA) developed by IIT Kharagpur (Figure

1a). Standard terminologies given in anthropometric source book (NASA, 1978a, 1978b) and anthropometric and strength data book (Gite et al., 2009) were considered for the measurements. ISO 7250 (1996) (Basic human body measurements for technological design) was also given due attention. Static measurements such as height, eye height, acromial height, elbow rest height, popliteal height, knee height, inside grip diameter, outside grip diameter, middle finger palm grip diameter; functional dimensions such as vertical grip reach, shoulder grip length, thumb tip reach and forearm hand length and circumferential dimension i.e. waist circumference were collected. Eight strength parameters; hand grip (left and right), push (left and right), pull (left and right), hand grip torque and torque strengths (both hands) were also measured using the strength measurement set-up developed at Central Institute of Agricultural Engineering, Bhopal, India (Figure 1b) (Mehta et al., 2007, 2011).

Table 1 Instruments used for anthropometric body dimensions and strength parameters measurement

Anthropometric and strength parameters	Instruments
Anthropometric body dimensions (static and functional)	Integrated composite anthropometer (ICA) (Sensitivity: 1 mm)
Body weight	Weighing scale (Capacity: 120 kg, accuracy: 0.1 kg)
Hand and foot dimensions	Vernier calliper (least count: 0.1 mm)
Circumferential body dimensions	Measuring tape (accuracy: 1 mm)
Grip diameter	Wooden cone
Strength parameters	Strength measurement setup

(a) Vertical grip reach (b) Torque strength (both hands)

Figure 1 Anthropometric and strength measurements

During the measurements, participants were seated on the horizontal seating platform of the ICA with thighs and wrists in horizontal position and asked to stretch their body to the maximum possible limit, look straight forward and free their shoulders. Trained technical staffs in the field of ergonomics were employed for such body dimensions measurement and due attention to safety and comfort during the study. Initially two replicate measurements were conducted per parameter and if their difference exceeded the acceptable limit then a third replicate measurement was conducted to exclude the recording error. The role of percentile in ergonomic design problems is to provide a basis for judging the proportion of a group of individuals that exceeds or falls within some possible design limit. Therefore, in addition to mean, the 5th and 95th percentile values of body dimensions were calculated to assess various possible design limits of DI to potentially operate farm machinery and related workspace layouts.

2.3 Statistical analysis

Collected data was statistically analyzed in the Microsoft Excel (2016) and IBM SPSS (Statistical Package for Social Science) version 20.0 software (IBM Corporation., Armonk, N.Y., USA). Mean (m), standard deviation (s), 5th percentile (m - $1.645\times s$) and 95th percentile (m + $1.645\times s$) of anthropometric and strength parameters were calculated and inter-correlations were analyzed through Pearson's linear correlation. Correlogram of body dimensions and strength parameters was developed using RStudio (RStudio, Boston, USA). Simple linear regression (SLR) and multilinear regression (MLR) equations were also developed to estimate some possible body dimensions as functions of other body dimensions (Dewangan et al., 2010a). Student's t-test was then conducted to compare anthropometric dimensions and strength parameters of DI with those of AI. Thirteen body dimensions of DI from different countries i.e. America (Paquet and Feathers, 2004), Mexico (Lucero-Duarte et al., 2012), Malaysia (Adnan and Dawal, 2019), Iran and Poland (Davoudian et al., 2017) were analyzed and compared with dimensions of Indian DI through t-tests. Principal component analysis (PCA) was also conducted (MATLAB 2015, MathWorks, MA, USA) and common factors were rotated through varimax method to extract important body dimensions by maximizing their squared loadings and minimizing absolute values of other factors (Dewangan et al., 2010a).

3 Results

Raw 44 anthropometric and 8 strength parameters were obtained and mean weight and height of selected subjects were 52 (±13) kg and 779 (±39) mm, respectively (Table 2).

Table 2 Anthropometric and strength parameters of lower limb DI

Sr.	Parameters	Mean	SD	CV	5th percentile	95th percentile
Anthropometric body dimensions						
1	Weight (W)	52	13	25.74	30	75
2	Height (H)	779	39	5.06	714	844
3	Eye height (EH)	670	29	4.32	622	718
4	Vertical grip reach (VGR)	1126	27	2.38	1082	1170
5	Acromial height (AH)	541	26	4.78	499	584
6	Popliteal height (PH)	402	45	11.27	327	476
7	Knee height (KH)	495	64	12.94	390	600
8	Thigh clearance height (TCH)	118	48	40.95	38	197
9	Elbow rest height (ERH)	181	19	10.66	149	212
10	Abdominal depth (AD)	230	34	14.85	174	287
11	Buttock knee length (BKL)	541	60	11.08	442	639
12	Buttock popliteal length (BPL)	421	32	7.71	367	474
13	Hip breadth (HB)	311	34	10.87	255	366
14	Elbow-elbow breadth (EEB)	419	37	8.72	359	479
15	Knee-knee breadth (KKB)	163	30	18.55	113	213
16	Waist back length (WBL)	450	20	4.44	417	483
17	Scapula to waist back length (SWBL)	636	76	12.01	510	762
18	Wall to acromion distance (WAD)	77	14	18.18	54	100
19	Bi-acromial breadth (BAB)	364	52	14.26	279	449

20	Bi-deltoid breadth (BDB)	401	29	7.26	353	449
21	Chest breadth (CB)	274	24	8.90	234	314
22	Interscye breadth (ISB)	328	35	10.65	271	385
23	Waist breadth (WB)	270	42	15.49	201	338
24	Waist circumference (WC)	711	33	4.62	657	765
25	Thump tip reach (TTR)	662	80	12.04	531	794
26	Shoulder grip length (SGL)	475	18	3.79	445	505
27	Elbow grip length (EGL)	366	19	5.24	334	398
28	Forearm hand length (FHL)	417	23	5.52	379	455
29	Coronoid fossa to hand length (CHL)	356	19	5.20	326	386
30	Hand length (HL)	189	8	3.98	177	202
31	Palm length (PL)	118	31	26.53	66	169
32	Grip diameter (inside) (GDI)	53	2	3.09	50	56
33	Grip Diameter(outside) (GDO)	89	4	4.30	83	96
34	Middle finger palm grip diameter (MFGD)	43	5	11.63	35	51
35	Maximum grip length (MGL)	126	17	13.49	98	154
36	Hand breadth across thumb (HBAT)	97	7	7.23	85	108
37	Hand breadth (HB)	76	5	7.00	67	85
38	Hand thickness at metacarpal-III (HTM)	28	5	17.50	20	36
39	Span (S)	1652	32	1.93	1599	1705
40	Head length (HEL)	203	10	5.05	187	220
41	Head breadth (HEB)	159	14	8.74	136	182
42	Foot length (FL)	225	17	7.56	197	253
43	Instep length (IL)	173	13	7.51	152	194
44	Foot breadth (balls of foot) (FB)	87	11	12.43	69	105
Strength parameters						
45	Hand grip strength right (HGSR)	304	141.70	46.61	70.90	537.10
46	Hand grip strength left (HGSL)	253.8	99.78	39.31	89.67	417.93
47	Push strength left hand (PSL)	62.2	19.74	43.06	18.20	106.60
48	Push strength right hand (PSR)	62.4	26.86	31.75	29.72	94.68
49	Pull strength left hand (PUSL)	66	22.54	27.63	34.48	91.92
50	Pull strength right hand (PUSR)	63.2	17.44	34.16	28.91	103.09
51	Torque strength both hands (TSB)	137	18.49	13.50	106.56	167.44
52	Hand grip torque (HGT)	16.8	6.61	39.40	5.91	27.69

Note: All body dimensins are in mm, weight in kg and strength parameters in N.

Twenty-nine anthropometric dimensions had significant correlations with other body dimensions (Figure 2). Pertinent coefficients (r) were greater than 0.30 at 5% significance and greater than 0.41 at 1% significance. Highest correlation was observed between knee to knee breadth and elbow rest height (0.52) followed by shoulder grip length and waist breadth (0.51). Head breadth had highest number of correlations (4 nos.) i.e. eye height (0.43), acromial height (0.36), knee height (-0.36) and corronoid fossa to hand length (-0.38). Similarly, among strength parameters pull strength of left hand had highest correlation with the pull strength of right hand (0.41) followed by the correlation between torque strength of two hands with push strength of right hand (Figure 3). Hand grip torque highly correlated with the hand grip strength of left hand (0.35) followed by hand grip strength of right hand (0.34) and left hand push strength (0.34).

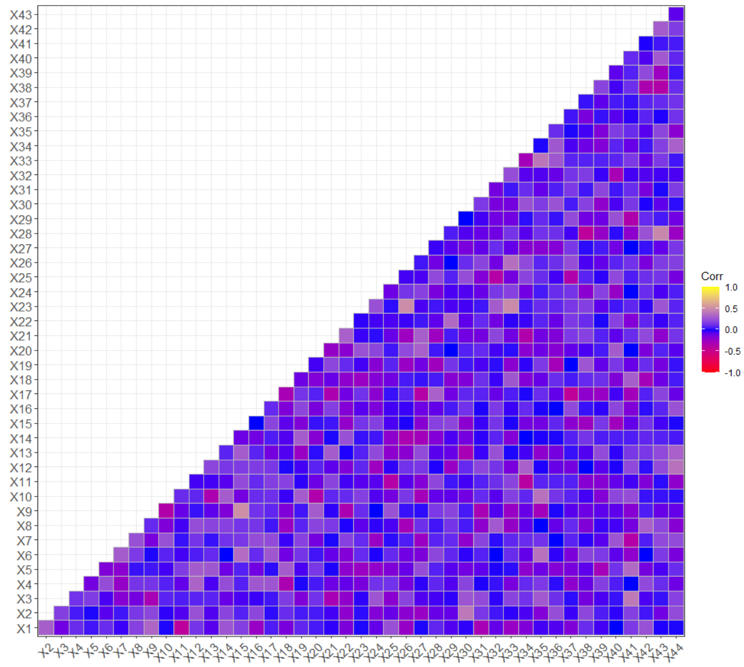


Figure 2 Pearson's linear correlation between anthropometric body dimensions (coded in Table 2)

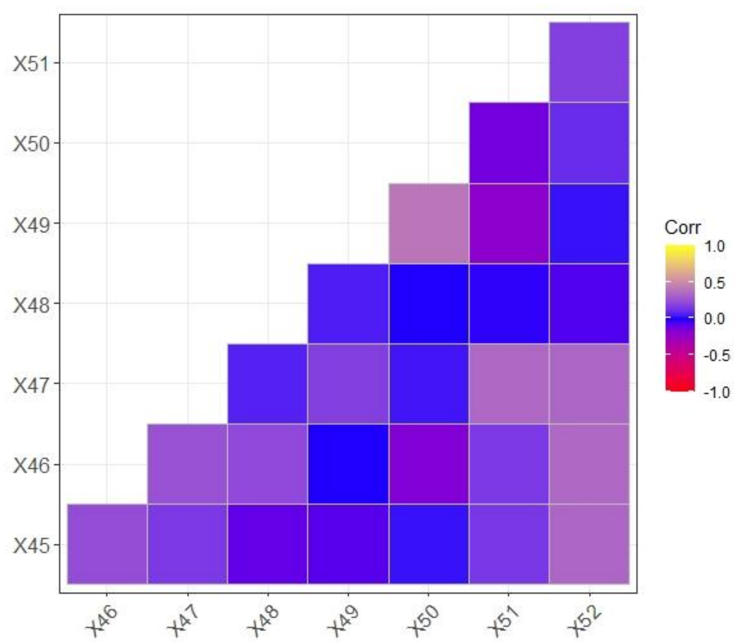


Figure 3 Pearson's linear correlation between strength parameters (coded in Table 2)

Anthropometric data collection is a time consuming, labor intensive and expensive task that restricts researchers and ergonomists from complete parametric assessments (Dewangan et al., 2010a; Dewangan et al., 2010b; Wang and Chao, 2010). Therefore, best fit SLR and MLR were developed after stepwise regression analysis, that indicated possibility of estimating eleven body dimensions (Table 3). Overall, 32 parameters could estimate all the 44 dimensions and all critical strength parameters with SLRs.

Table 3 Best fit linear equations for estimating body dimensions and strength parameters

Body dimensions	Equation	F value
Thigh clearance height	$0.96X_{42} - 479.19$	4.54*
Elbow rest height	$0.37X_{15} + 257.79$	11.01**
Abdominal depth	$0.70X_{35} + 289.48$	6.07**
Buttock popliteal length	$1.45X_{44} - 20.43$	7.80**
Elbow grip length	$0.27X_{20} + 240.21$	6.02**
Forearm hand length	$0.86X_{43} + 267.80$	11.84**
Coronoid fossa to hand length	$0.26X_{22} + 267.80$	5.97**
Hand length	$0.09X_{2} + 98.70$	6.64**
Grip diameter (inside)	$0.03X_{23} + 56.60$	6.29**
Instep length	$0.27X_{28} - 15.38$	8.62**
Foot breadth (balls of foot)	$0.71X_{34} + 56.32$	4.47*
Eye height	$0.97X_{41} - 0.44X_{21} + 464.94$	7.65**
Vertical grip reach	$0.31X_{12} - 0.16X_{7} + 1030.11$	5.22**
Acromial height	$0.71X_{41} - 0.36X_{39} + 910.86$	7.06**
Knee knee breadth	$0.87X_{9} + 0.25X_{6} - 172.01$	11.44**
Wall to acromion distance	$2.71X_{33} - 0.32X_{23} + 176.22$	7.51**
Waist breadth	$0.16X_{26} - 0.65X_{18} - 373.11$	11.56**
Shoulder grip length	$1.57X_{23} - 17.24X_{32} + 1079.90$	8.56**
Grip Diameter(outside)	$0.05X_{23} + 0.08X_{35} + 62.65$	14.78**
Maximum grip length	$0.13X_{6} + 1.34X_{33} - 78.42$	7.34**
Head breadth	$0.19X_{3} - 0.07X_{17} + 28.97$	8.36**
Inter scye breadth	$0.85X_{29} - 0.97X_{9} - 0.44X_{3} + 447.46$	8.42**
Popliteal height	$1.18X_{35} + 0.79X_{15} + 4.38X_{38} - 18.74$	9.12**
	Strength parameters	
Hand grip strength right	$7.33X_{52} + 180.93$	5.04*
Hand grip strength left	$5.22X_{53} + 166.03$	5.19*
Push strength right hand	$0.51X_{51} + 7.22$	5.30*
Pull strength right hand	$0.32X_{48} + 42.20$	7.72**
Pull strength left hand	$0.53X_{49} + 32.47$	7.72**
Torque strength both hands	$0.24X_{47} + 121.97$	5.30*
Hand grip torque	$0.02X_{46} + 10.96$	5.18*

Note: Subscripted numbers represent the body dimensions' (coded in Table 2).

Comparison of anthropometric dimensions and strength parameters of lower limb DI with those of AI (Table 4) identified 33 body dimensions and all strength parameters to be significantly different (p<0.01 and 0.05). Most of the body dimensions such as elbow rest height, elbow-elbow breadth, shoulder grip length, eye height, wall to acromion distance had higher percentage difference (Figure 4). Popliteal, knee, and thigh clearance heights were higher for DI by 0.24%, 3.03% and 5.61%, respectively.

Fifth percentile weight of DI was 27% lower than the AI whereas 95th percentile weight of them was 13% higher. Fifth percentile values of height, eye height, vertical grip reach, acromial height, popliteal height, knee height, thigh clearance height, elbow rest height of DI were found lower than the AI by 9%, 5%, 2%, 2%, 11%, 12%, 124%, 11%, respectively whereas 95th percentile of abdominal depth, hip breadth, elbow-elbow breadth, knee-knee breadth, waist back length, scapula to waist back length, bi-acromial breadth, bi-deltoid breadth, chest breadth, interscye breadth, waist breadth was found higher by 12%, 3%, 12%, 3%, 28%, 15%, 15%, 3%, 1%, 17%, 15%, respectively.

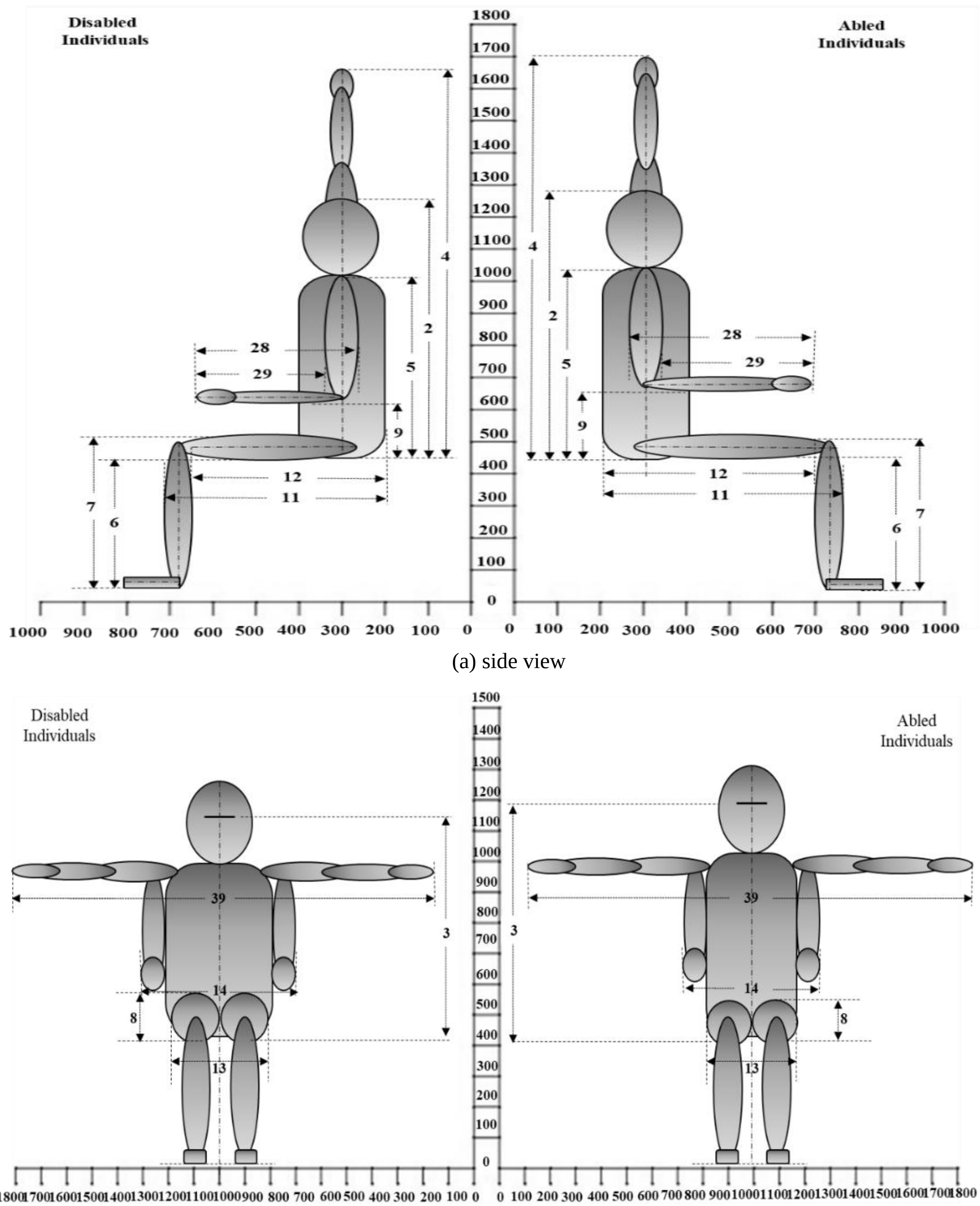
Body dimensions such as elbow rest height, knee-knee breadth, waist breadth, palm length and strength parameters such as hand grip strength, push strength and pull strength of DI had higher variability than the AI (Figure 5).

Table 4 Body dimension and strength parameter comparisons between DI and AI

		DI				AI				
Sr.	**Parameters**	**Mean**	**SD**	**5^{th} percentile**	**95^{th} percentile**	**Mean**	**SD**	**5^{th} percentile**	**95^{th} percentile**	**Significance**
1	Weight	52	13	30	75	51.4	7.9	38	64	-
2	Height	779	39	714	844	842	38	779	905	**
3	Eye height	670	29	622	718	731	44	659	803	**
4	Vertical grip reach	1126	27	1082	1170	1192	51	1108	1276	**
5	Acromial height	541	26	499	584	561	31	510	612	**
6	Popliteal height	402	45	327	476	401	22	365	437	-
7	Knee height	495	64	390	600	480	26	437	523	-
8	Thigh clearance height	118	48	38	197	111	15	86	136	-
9	Elbow rest height	181	19	149	212	215	30	166	264	**
10	Abdominal depth	230	34	174	287	210	24	171	249	**
11	Buttock knee length	541	60	442	639	539	33	485	593	-
12	Buttock popliteal length	421	32	367	474	414	32	361	467	**
13	Hip breadth	311	34	255	366	316	23	278	354	-
14	Elbow-elbow breadth	419	37	359	479	345	46	269	421	**
15	Knee-knee breadth	163	30	113	213	177	17	149	205	*
16	Waist back length	450	20	417	483	414	33	360	468	**
17	Scapula to waist back length	636	76	510	762	508	84	370	646	**
18	Wall to acromion distance	77	14	54	100	100	14	77	123	**
19	Bi-acromial breadth	364	52	279	449	325	32	272	378	**
20	Bi-deltoid breadth	401	29	353	449	392	26	349	435	-
21	Chest breadth	274	24	234	314	273	21	238	308	-
22	Interscye breadth	328	35	271	385	286	19	255	317	**
23	Waist breadth	270	42	201	338	253	20	220	286	*
24	Waist circumference	711	33	657	765	751	69	637	865	**
25	Thumb tip reach	662	80	531	794	770	41	703	837	**
26	Shoulder grip length	475	18	3.79	445	729	38	666	792	**
27	Elbow grip length	366	19	334	398	325	22	289	361	**
28	Forearm length	417	23	379	455	443	25	402	484	**
29	Coronoid fossa to hand length	356	19	326	386	379	27	335	423	**
30	Hand length	189	8	177	202	76	9	161	191	**
31	Palm length	118	31	66	169	100	5	92	108	**
32	Grip diameter (inside)	53	2	50	56	44	6	34	54	**
33	Grip diameter (outside)	89	4	83	96	81	5	73	89	**
34	Middle finger palm grip length	43	5	35	51	28	4	21	35	**
35	Maximum grip length	126	17	98	154	133	15	108	158	-
36	Hand breadth across thumb	97	7	85	108	92	6	82	102	**
37	Hand breadth	76	5	67	85	77	5	69	85	**
38	Hand thickness at metacarpal-III	28	5	20	36	26	2	23	29	**
39	Span	1652	32	1599	1705	1682	77	1555	1809	**
40	Head length	203	10	187	220	186	11	168	204	**
41	Head breadth	159	14	136	182	153	13	132	174	-
42	Foot length	225	17	197	253	249	14	226	272	**
43	Instep length	173	13	152	194	181	14	158	204	**
44	Foot breadth (balls of foot)	87	11	69	105	92	7	80	104	*
	Strength parameters									
45	Hand grip strength right	304	141	70	537	360	92	208	511	*
46	Hand grip strength left	253	99	89	417	340	93	187	492	**
47	Push strength left	62	19	29	94	74	17	46	101	**

48	Push strength right hand	62	26	18	106	77	17	49	104	**
49	Pull strength left hand	66	22	28	103	88	19	56	119	**
50	Pull strength right hand	63	17	34	91	92	19	60	123	-
51	Torque strength both hands	137	18	106	167	287	71	170	403	**
52	Hand grip torque	16	6	5	27	33	14	9	56	**

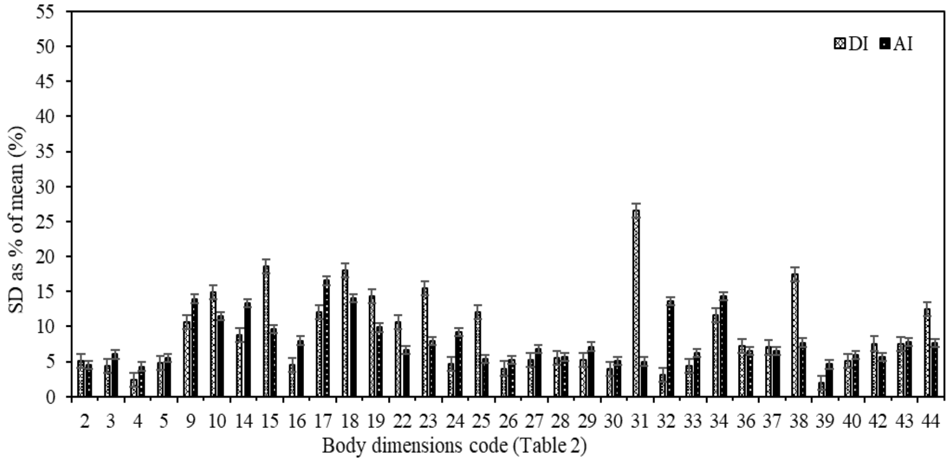
Note: *- Significant at 5%, **- Significant at 1%.



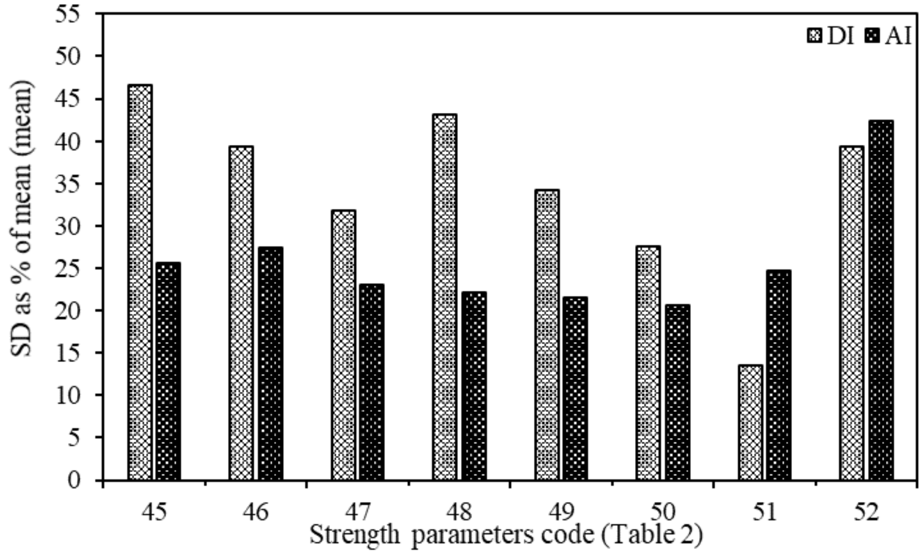
(b) front view

Figure 4 Visualisation of difference between DI and AI body dimensions

Note: Numbers represents body dimensions coded in Table 2



(a) Anthropometric body dimensions



(b) Strength parameters

Figure 5 Comparison of variability of the body dimensions and strength parameters between DI and AI

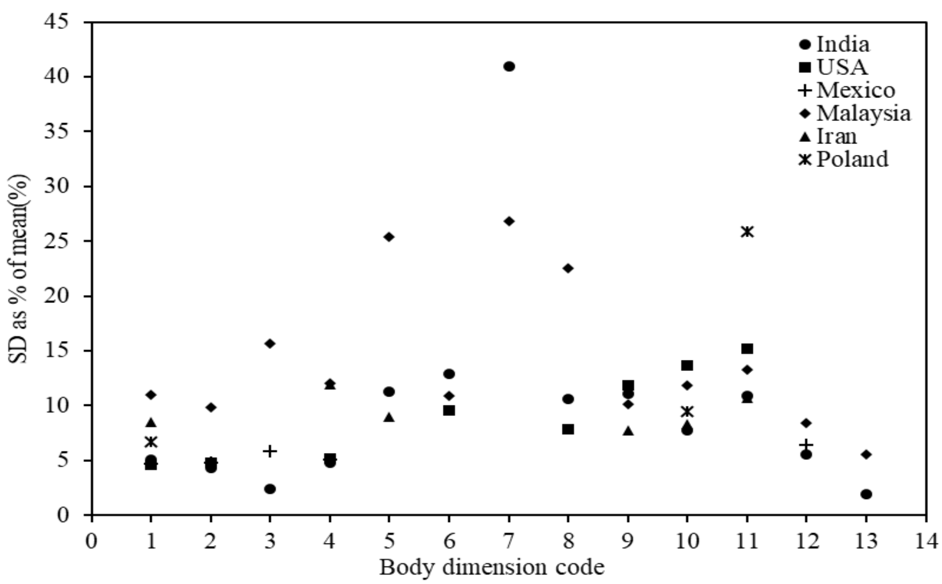


Figure 6 Variability of DI body dimensions from different countries

All body dimensions of the selected Indian DI were significantly lower in magnitude than such individuals in America and Mexico (Table 5). Additionally, vertical grip reach, elbow rest height, forearm hand length and span of individuals from Malaysia, popliteal height, buttock knee length and buttock popliteal height of individuals from Iran and sitting height and buttock popliteal height of individuals from Poland were significantly different than the individuals selected in this study. Body dimension variabilities were higher among Malaysian DI except their knee height (-2.1%), thigh clearance height (-14.1%) and buttock knee length (-0.93%) compared to the selected Indian individuals. Such variability was also higher in case of DI from Poland and Iran, except the popliteal height (-2.3%) and buttock knee length (-3.38%) of Iranian individuals (Figure 6).

Table 5 Body dimensions and strength parameters of Indian DI relative to other countries

Parameters	India[a]	USA[b]	Mexico[c]	Malaysia[d]	Iran[e]	Poland[f]
	Mean (±SD)					
Height	779(±39)	1309(±60)**	1282(±60)**	790(±87)	784(±67)	864(±58)**
Eye height	670(±29)	1196(±57)**	1182(±57)**	689(±68)	-	-
Vertical grip reach	1126(±27)	-	1640(±95)**	1210(±190)**		-
Acromial height	541(±26)	1042(±54)**	1026(±52)**	533(±64)	526(±63)	-
Popliteal height	402(±45)	-	-	444(±113)*	436(±39)**	-
Knee height	495(±64)	628(±60)**	-	515(±56)	-	-
Thigh clearance height	118(±48)	-	-	123(±33)	-	-
Elbow rest height	181(±19)	741(±58)**	-	200(±45)**	-	-
Buttock knee length	541(±60)	623(±74)**	-	512(±52)	584(±45)**	-
Buttock popliteal length	421(±32)	518(±71)**	-	429(±51)	481(±40)**	548(±52)**
Hip breadth	311(±34)	270(±41)**	-	316(±42)	363(±39)**	329(±85)
Forearm hand length	417(±23)	-	799(51)**	809(±68)**	-	-
Span	1652(±32)	-	-	1700(±95)**	-	-

Note: [a]Current study; [b]Paquet and Feathers, 2004; [c]Luvero-Duarte et al., 2012; [d]Adnan and Dawal, 2019; [e,f]Davoudian Talab et al., 2017. *5% significance, **1% significance.

Factors that explained data variations were identified through varimax rotation of the Eigen vectors using Kaiser Criteria (Kaiser, 1960) in the PCA. Optimum components were screened as per Kaiser's Criteria, scree test, proportion of variance accounted, and interpretability. The PCA was conducted in four groups; body dimensions measured in vertical direction, body dimensions measured in horizontal direction, hand dimensions, and strength parameters. Total 18 factors for 44 dimensions and three factors for eight strength parameters were found optimum for minimum errors (Tables 6-9).

First factor analysis conducted for body dimensions measured in vertical direction extracted 4 dominant factors contributing 68.79% of cumulative variance identifying factor 1 (20.77%) and factor 2 (17.58%) of highest contributions. Variables of higher loading contribute more towards the factors (Johnson and Wichern, 2002). Popliteal height was observed with highest loading (0.76) in factor 1 followed by acromial height (0.60) which identified factor 1 as height. Similarly, vertical grip reach (0.79) and knee height (0.71) were observed with higher loading than others identifying factor 2 as reach. PCA Bi-plot (Figure 7a) also identified popliteal height as most influential for PC-1 (factor 1) and knee height for PC-2 (factor 2).

PCA of body dimensions measured in horizontal direction extracted 7 important factors explaining cumulative variance of 73.01%. Factor 1 was contributed the most (14.87%) followed by factor 2 (12.28%) and factor 3 (11.62%). Abdominal depth (0.88) followed by elbow-elbow breadth (0.57) and bi-acromial breadth (0.51) had highest loadings and identified factor 1 as breadth. Similarly, factor 2 was mostly influenced by waist circumference (0.78) followed by waist breadth (0.74) that identified waist as factor 2. Bi-plot (Figure 7b) identified abdominal depth to mostly influence PC-1.

PCA of hand dimensions extracted 7 important factors contributing towards the cumulative variance of 71.22%. Factor 1 contributed the most (14.33%) followed by factor

2 (12.71%). Middle finger palm grip diameter contributed the most (0.55) to factor 1 followed by thumb tip reach (0.53) and hand length (0.52) that identified hand as the factor 1. Factor 2 was mostly influenced by the grip diameter (outside) with load of 0.74. Bi-plot (Figure 7c) identified middle finger palm grip diameter to be most influential for PC-1 and grip diameter (outside) for PC-2.

PCA for strength extracted 3 influential factors contributing to cumulative variance of 59.13%. Factor 1 was the largest contributor (25.32%) followed by factor 2 (19.15%). Hand grip torque contributed the most (0.76) to factor 1 followed by push strength of right hand (0.65). Factor 2 was mostly influenced by pull strength of right hand (0.83) followed by pull strength of left hand (0.81). Bi-plot (Figure 7d) identified hand grip torque and pull strength right hand to be most influential for PC-1 and -2, respectively.

Table 6 Coefficients for factor loading matrix after varimax rotation for body dimensions in vertical direction

Body dimensions	Factor 1	Factor 2	Factor 3	Factor 4
Height	0.24	0.09	0.07	0.76
Eye height	0.18	0.28	0.84	0.15
Vertical grip reach	0.12	0.79	0.05	0.15
Acromial height	0.60	0.11	0.12	0.18
Popliteal height	0.76	0.05	0.06	0.15
Knee height	0.46	0.71	0.02	0.29
Thigh clearance height	0.26	0.13	0.15	0.67
Elbow rest height	0.13	0.35	0.75	0.29
Eigen value	1.66	1.41	1.26	1.17
% of Variance	20.77	17.58	15.85	14.58
Cumulative %	20.77	38.36	54.21	68.79

Note: *All values are absolute.

Table 7 Coefficients for factor loading matrix after varimax rotation for body dimensions in horizontal direction

Body dimensions	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7
Abdominal depth	0.88	0.10	0.03	0.04	0.05	0.10	0.09
Buttock knee length	0.09	0.12	0.02	0.05	0.15	0.82	0.06
Buttock popliteal length	0.13	0.13	0.26	0.15	0.79	0.07	0.09
Hip breadth	0.41	0.21	0.28	0.23	0.65	0.14	0.10
Elbow-elbow breadth	0.57	0.02	0.36	0.05	0.38	0.17	0.28
Knee-knee breadth	0.23	0.28	0.08	0.18	0.35	0.62	0.02
Waist back length	0.06	0.12	0.13	0.05	0.12	0.05	0.85
Scapula to waist back length	0.11	0.07	0.12	0.87	0.06	0.23	0.02
Wall to acromion distance	0.09	0.37	0.41	0.59	0.03	0.18	0.29
Bi-acromial breadth	0.51	0.10	0.17	0.19	0.14	0.19	0.40
Bi-deltoid breadth	0.41	0.39	0.26	0.29	0.04	0.31	0.03
Chest breadth	0.04	0.07	0.59	0.37	0.04	0.25	0.48
Interscye breadth	0.12	0.09	0.82	0.03	0.12	0.11	0.17
Waist breadth	0.19	0.74	0.10	0.19	0.10	0.03	0.01
Waist circumference	0.12	0.78	0.07	0.23	0.10	0.05	0.14
Eigen value	2.23	1.84	1.74	1.66	1.25	1.22	1.01
Variance explained	14.87	12.28	11.62	11.08	8.31	8.11	6.73
Cumulative variation (%)	14.87	27.16	38.77	49.85	58.17	66.28	73.01

Note: *All values are absolute.

Table 8 Coefficients for factor loading matrix after varimax rotation for the hand dimensions

Body dimensions	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7
Thump tip reach	0.53	0.47	0.04	0.34	0.07	0.33	0.23
Shoulder grip length	0.22	0.60	0.18	0.12	0.08	0.20	0.51
Elbow grip length	0.41	0.09	0.07	0.26	0.06	0.22	0.60
Forearm hand length	0.37	0.08	0.66	0.07	0.21	0.01	0.07
Coronoid fossa to hand length	0.22	0.01	0.12	0.44	0.16	0.48	0.50
Hand length	0.52	0.09	0.47	0.07	0.36	0.01	0.02
Palm length	0.03	0.32	0.49	0.13	0.46	0.11	0.10

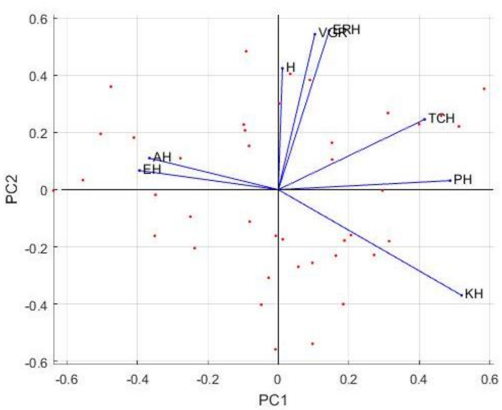
Body dimensions	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7
Grip diameter (inside)	0.51	0.26	0.14	0.03	0.42	0.46	0.07
Grip Diameter(outside)	0.04	0.74	0.35	0.47	0.07	0.07	0.09
Middle finger palm grip diameter	0.55	0.03	0.41	0.23	0.06	0.41	0.12
Maximum grip length	0.38	0.36	0.31	0.37	0.28	0.23	0.13
Hand breadth across thumb	0.46	0.40	0.05	0.07	0.23	0.34	0.15
Hand breadth	0.16	0.53	0.06	0.56	0.18	0.24	0.09
Hand thickness at metacarpal-III	0.32	0.04	0.52	0.45	0.42	0.21	0.06
Span	0.38	0.01	0.29	0.34	0.55	0.18	0.19
Eigenvalue	2.15	1.91	1.72	1.46	1.27	1.13	1.05
variance explained (%)	14.33	12.71	11.43	9.74	8.45	7.52	7.04
Cumulative variation (%)	14.33	27.04	38.47	48.21	56.66	64.18	71.22

Note: *All values are absolute.

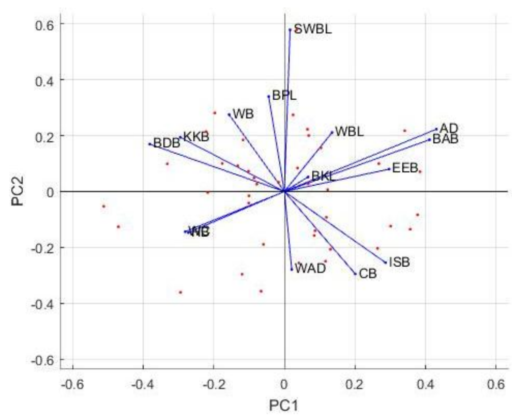
Table 9 Coefficients for factor loading matrix after varimax rotation for strength parameters

Strength parameters	Factor 1	Factor 2	Factor 3
Hand grip torque	0.76	0.13	0.04
Push strength right hand	0.65	0.16	0.26
Hand grip strength right	0.64	0.05	0.25
Hand grip strength left	0.54	0.16	0.53
Torque strength both hands	0.52	0.36	0.03
Pull strength right hand	0.02	0.83	0.17
Pull strength left hand	0.05	0.81	0.17
Push strength left hand	0.11	0.04	0.86
Eigen value	2.03	1.53	1.17
% of Variance	25.32	19.15	14.67
Cumulative %	25.316	44.46	59.13

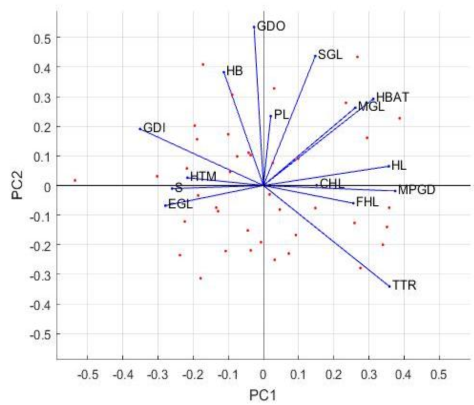
Note: *All values are absolute.



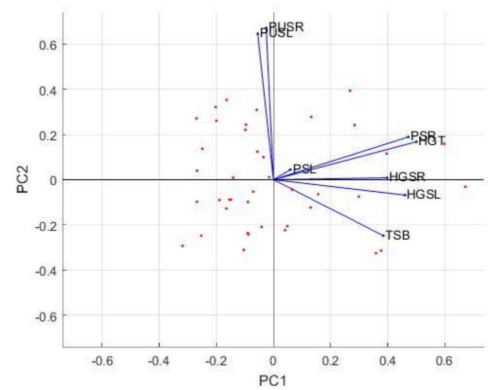
(a) body dimensions in vertical direction



(b) body dimensions in horizontal direction



(c) hand dimensions



(d) strength parameters

Figure 7 Biplots of principal component analysis

4 Discussion

Significant differences between DI and AI were majorly due to disorders in joint, ligament and neural-muscle system causing deformations and subject diversity (Goswami et al., 1987; Paquet and Feathers, 2004; Lane and Bauer, 1999; Davoudian et al., 2017). Body breadth dimensions; bi-acromial, bi-deltoid, chest, interscye, and waist were higher for DI possibly due to frequent wheelchair use that promotes over development of upper body, and more atrophied and weakened lower body (Dingley et al., 2015; Goswami et al., 1987). Height dimensions i.e. sitting height, eye height, vertical grip reach, acromial height, and elbow rest height were higher for AI suggesting their normal growth compared to the DI. Lower height dimensions of DI may be the result of growth reduction and abnormality due to medical condition, and deformed skeletal system, and back muscles looseness restricting them to be upright (Floyd et al., 1966; Goswami et al., 1987; Jarosz, 1996; Davoudian et al., 2017; Adnan and Dawal, 2019). Hand dimensions; thumb tip reach, shoulder grip length, maximum grip length, and spans were lower for DI similar to trends observed in other studies (Nowak, 1996; Bolstad et al., 2001; Barroso et al., 2005; Davoudian et al., 2017). Higher grip diameter (inside and outside), middle finger palm grip diameter, hand breadth across thumb suggests over dependency on the palm and grip to overcome restrictions of disability (Goswami et al., 1987).

Variability was higher for most body dimensions of DI than AI, reason being abnormal/disproportionate body growth, disease varieties, injuries, genetic, congenital conditions and low precision of measurement due to lack of ability to hold certain postures (Bradtmiller and Annis, 1997; Adnan and Dawal, 2019). Anthropometric body dimensions of DI from developed countries were larger than the DI from the developing countries for the reasons of different growth environment, heredity and genetic growth, socio-economic condition, cultural practices for independence, and lifestyles (Abeysekera and Shahnawaz, 1989; Steinfield et al., 2009; Dewangan et al., 2010a; Dewangan et al., 2010b).

5 Agricultural machinery workplace design: case study

Design of occupational and non-occupational environments, tools, machines and equipment incorporating anthropometry requires reaches and hand forces of both, DI and AI for improved efficiency and productivity (Paquet and Feathers, 2004; Deros et al., 2011; Lucero-Duarte et al., 2012; Adnan and Dawal, 2019).

5.1 Agricultural tractor and self-propelled machinery

Tractor and self-propelled machinery such as power tiller, transplanter, reaper-binder, and mini combine harvesters are used only by AIs due to its design unsuitability to DIs of high step levels of ingress/egress, foot operated clutch and brakes, workplace and control non-considerations in tractor and self-propelled machinery. Unsuited workplace design and control placement requires higher operating forces that can overloading muscle-tendon-bone joints and lead to premature fatigue. This could be addressed by modifications for better visibility, safety and comfort (Gite and Singh, 1997; Mehta et al., 2007; Dewangan et al., 2010b; Khadatkar et al., 2017). As a future prospective, design of hydraulic or electrically actuated ingress/egress systems to shift DIs from ground to the operator’s seat and pertinent workplace and control lever modifications may facilitate tractor and self-propelled machinery operations.

An optimum hand reach envelope was developed with the anthropometry of DIs for workplace and controls designs in tractor and self-propelled machinery as described by Matthews and Knight (1971). Envelope was bounded by four points i.e. near low, near high, far low and far high (Figure 8). The operator’s hand can move horizontally within 372–499 mm from SRP and vertically within 212–499 mm from SRP.

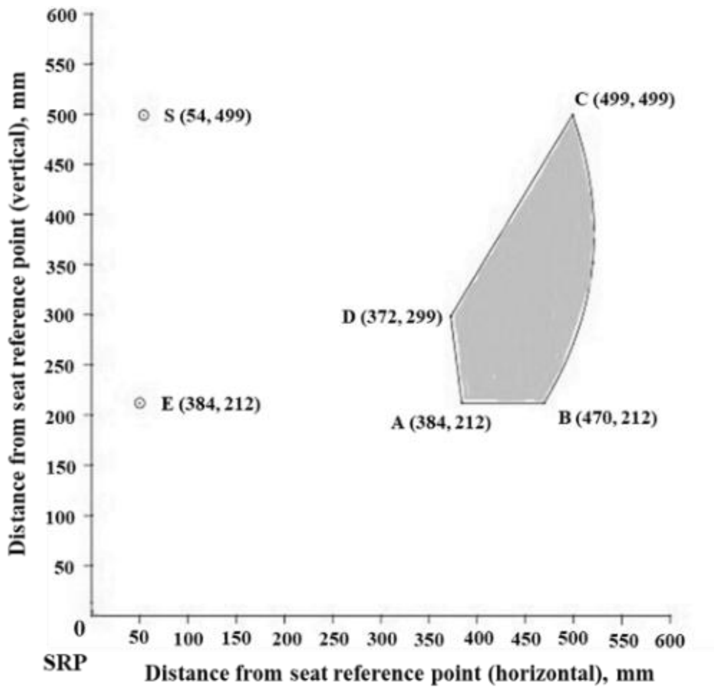


Figure 8 Optimum hand reach envelope for DI

Note: A: Near low point, B: Far low point, C: Far high point, D: Near high point, S: Shoulder pivot point, E: Elbow pivot point, SRP: Seat reference point.

Control lever designs consider 5th percentile strength parameters to suit even for a weakest individual and push forces are recommended for controls needing combinations of push and pull forces (Kumar, 1995; Dewangan et al., 2010b; Gite et al., 2019). Strength recommendation for gear shift lever and hydraulic controls is 29.7 N (5th percentile right hand push strength). Hand brake and accelerator require hand grip strength. Hence, the recommendation for a DI is 89.6 N (5th percentile of the left-hand grip strength). The limit for frequently used controls is 30% of the 5th percentile strength (Van Wely, 1970). Therefore, the recommendation for a DI to operate the steering wheel is 32.0 N as 5th percentile torque strength (both hands) is 106.5 N.

Self-propelled systems are operated by hand operated left and right clutches, gear shifting lever, brake, accelerator. Therefore, recommendation for left hand clutch is 89.6 N (5th percentile left hand grip strength) and for right hand clutch is 70.0 N (5th percentile right hand grip strength) and for other levers is 62.4 N (5th percentile right hand push strength).

5.2 Agro and food processing industries

Agro-processing and food processing industries converts agricultural produce to usable food, feed, fiber and fuel through different techno-economic activities (McNeill, 2005) which involves washing, cleaning, drying, grading, sorting, cleaning, waxing and packaging operations. All the above-mentioned operations involve different working postures like standing, sitting, sitting-standing combination, twisting, repetitive movements and also strenuous physical task resulting into musculoskeletal disorders and serious strain injuries (Mohd et al., 2017; Kumari, 2018).

Part of sitting workstation such as table height, table width, table depth, and curve at the surface of the table are the important parameters to be considered for the inclusion of the DI into agro-processing and food processing industries and to ensure their well-being and satisfaction during the daily activities. Uses of sitting height, eye height in design of workstation, workplace, reaches in adjusting barriers and controls determine the differences in the work place size, failing to meet the needs causes incompatibility and DI require more physical assistance (Pheasant, 2003). AI require greater workplaces and workspaces than the DI (Jarosz et al., 1996; Davoudian et al., 2017). Backrest and seat height should be designed according to popliteal height and acromial height of DI (Mououdi and Choobine, 2009; Pheasant, 2003; Davoudian et al., 2017). Hence, the recommended value for seat height is 325 mm (lower than the 5th percentile popliteal height, 327 mm) and backrest of the seat is 450 mm (lower than the 5th percentile sitting acromial height, 499 mm) to facilitate the shoulder free movement providing proper lumbar support to the workers. Shoulder grip length is used to determine reach to control levers, tools and control panels surrounding the worktable for easy accessibility and thumb tip reach (forward reach) is used for placement of barriers to avoid the risk of injury to the DI (Mououdi and Choobine, 2009; Davoudian et al., 2017). Hence, the recommended limit of control placement is 440 mm (lower than 5th percentile shoulder grip length, 445 mm) and limit of barrier placement is 800 mm (higher than 95th percentile thumb tip reach).

6 Conclusion

A total of 44 anthropometric body dimensions in sitting position and 8 strength parameters of lower limb DI were successfully collected and analyzed. Total 47 significant correlations between body dimensions (r: 0.31–0.52, $p<0.05$) and 5 significant correlations between strength parameters (r: 0.31–41, $p<0.05$) were observed from the analysis. Data suggested that thirty-two body dimensions can be used successfully for the estimation of 44 body dimensions through SLR and twelve MLR equations. Significant differences were also observed between the body dimensions and strength parameters of DI and AI ($p<0.05$) where those for DI were smaller/lower compared to AI (2%–11%) with higher variability (2%–46%). Body dimensions of Indian DI were observed significantly different than other countries' DI ($p<0.01$) with variability in the range of 2%–41%. A hand reach envelope was also derived for DI for tractor and self-propelled machine workplaces that offered horizontal movement of 372–499 mm and vertical movement of 212–499 mm from SRP. The developed database and equations could be useful to the researchers, ergonomists, and companies to develop/modify controls and workspaces in agricultural equipment and machinery for DI.

Conflict of interest

The authors declare no conflict of interest.

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