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Identification of Preferred Choice of Materials for Constituent Parts of Prototype Through Modal Analyses and Response Spectrum Study of Multi Body Dynamic Assembly Model of Humanoid Robot

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With respect to the Anthropometric or humanoid robots, need exists to identify correct materials for various parts constituting the final assembly during prototype development phase. Accordingly, the current work is undertaken with the objective of identifying the preferable materials from the available choices by carrying out structural analyses of Multi Body Dynamic models of various components forming parts of final humanoid assembly model. Modal and Response spectrum analyses using suitable tool, are done for this, for two different choices of material. Modal analysis is done to provide valuable insights into the behaviour of various parts of humanoid model during their virtual functioning while Response spectrum analyses are aimed to suggest on preferable combination of materials commonly used during development of humanoid. Accordingly, at the end of the work, it is demonstrated that we are able to achieve considerable reduction in resulting linear Force Reaction, by selecting Carbon Fiber as constituent material for almost all the parts, excluding 'Lower Leg'. For other parts, the benefits achieved range from 46.97% (minimum) to 98.49% (maximum). Similarly, considerable amount of reduction in resulting linear Normal stress is achieved, by selecting Carbon Fiber as constituent material for almost all the parts except 'Head' and 'Neck', though the benefit is 3.52% only for 'Lower Leg'. For other parts, the benefits achieved range from 35.06% (minimum) to 93.76% (maximum). We are able to achieve considerable amount of reduction in resulting linear Normal Elastic Strain, by selecting Carbon Fiber as constituent material for almost all the parts, except 'Head', though the benefit attained is only 15.67% for 'Neck'. For other parts, the benefit achieved ranges from 45.01% (minimum) to 90.95 % (maximum). With respect to the Total deformation, it is observed that we can attain considerable amount of reduction in resulting Total Deformation, by selecting Carbon Fiber as constituent material for the 'Shoulder Line', 'Upper Arm' and 'Lower Arm', with benefit achieved ranging from 0.69% (minimum) to 2.13 % (maximum) though the Total deformation values are increased for other parts, with the revision in constituent material.

Keywords: Body mass index, Force reaction, Multi body dynamic model, Modal analysis, Response spectrum study

1. Introduction

Multi Body Dynamic (MBD) models are widely used now-a-days as part of realising the prototypes of Mannequins like PETMAN[1] (Protection Ensemble Test Mannequin), which is an Anthropometric robot or Humanoid Robot. Said Humanoid MBD model assembly is comprised of various sub system models representing different human body parts, which when assembled together mimics the human activity. Thus, need exist to carry out Modal Analysis to assess whether the constituent parts of MBD model assembly interact with each other in harmony, so that end objective is met. Again to make the prototype hardware of humanoid robot to achieve superior structural properties, feasibility of using combination of materials for various parts needs to be studied.

Accordingly, in the current work, Modal Analyses and Response spectrum studies are carried out on various sub-models forming part of humanoid MBD assembly model. First one is to provide valuable insights into the response of various parts of humanoid during their functioning and the latter one is to focus on suggestions on possible combination of materials to achieve superior structural properties during prototype development of humanoid, considering various aspects.

2. Methodology

2.1 Brief

As part of current work, first a comparative study is made with respect to the body Mass Index values of typical human subject and two versions of pre-existing Multi Body Dynamic Humanoid model available at "mathworks.com[2]", considered to be made of two different materials suggested in prior-art. This is done by importing the respective step files into the GUI environment of Ansys R19.2 Work Bench[3]. Aim of the study is to identify preferred material choice for the prototype to represent the human subject to more extent. Then various part models constituting said Humanoid model assembly are individually subjected to Modal analysis using suitable tool, again for two different material choice. From this, the values of Natural frequencies of the parts are obtained. This is mainly to provide valuable insights into the behaviour of various parts of humanoid model during their virtual functioning—by assessing whether the fundamental Natural frequencies of adjacent body part models lie well away from each other so that the condition of resonance is avoided during their intended operation while realizing the hardware model of designed Robot CAD model of Figure 1.

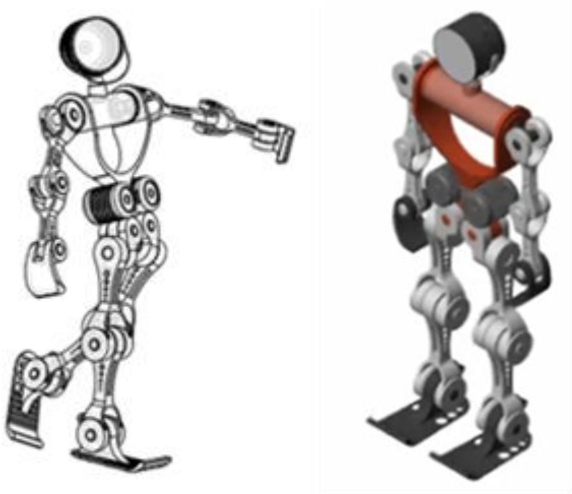

Figure 1: Walking Humanoid Robot Model of Mathworks.com[2]

Response spectrum analysis is also carried out and Response spectra are obtained to study the structural response of constituent parts of said Humanoid assembly model to suggest on possible combination of materials for various parts during the development of humanoid prototype, as mentioned earlier. In both of these activities, two different materials *viz.*, the structural Steel and Carbon Fiber (as suggested as alternatively preferred material for humanoid robot applications, in established work[4]**,** are considered.

The results are presented in the Results section and discussions are made.
Modal analyses of different part models constituting derived Humanoid Robot assembly model are carried out by importing the respective step files into the GUI environment of simulation software. From this, the Natural frequencies of the parts are obtained for study. This is mainly to check whether the values of fundamental Natural frequencies of adjacent body part models lie well away from each other so that the proneness to the condition of resonance is evaded during their functioning while realizing the hardware model of designed Robot CAD model.
Response spectra also have been obtained to study the structural response of said parts. In both of these activities, two different materials *viz.*, the structural Steel and Carbon Fiber (the one suggested as alternatively preferred material for humanoid robot applications, by Seward[4] *et. al.*) are considered. The results are presented and discussions are made.
As part of present work, exhaustive survey was carried out. Basically Anthropometry, refers to the study of the measurement of human body in terms of the dimensions of bone, muscle, and adipose (fat) tissue[5]. Thus, Anthropometric measurements[6] form the basis for formulation of Virtual human models, anthropometric robot models, and their hardware. Similarly, publications on robot models, their Anatomy[4] and mechanisms[5] also were studied.

A study with the aim of establishing a human anthropometric database with further investigation of anthropometric variability across ethnicity, age, and regions was taken up by Wibneh[7], *et. al.*_Pivotal Anthropometric data *viz.*, 'Stature' forming part of Anthropometric database established at the end of said study has been used in current work, while comparing different models.
A 3D Printed functional Robot for Human Pose Replication was disclosed by Kompally[8], *et.al*. Vide their work. At the end of the literature survey, it is observed that none of disclosed work is focused towards the identification of preferred material choice for various parts constituting the robot assembly, as done in the current work.

2.2 Comparative study on Body Mass Index (BMI) values of models with two different material choices

It is well known that "Body Mass Index (BMI)" is one of criteria widely used in the field of Anthropometry. BMI, expressed in kg/m^2, is the value of total body mass divided by the square of Stature (standing height). Wilbneh[7], *et. al.*, at the end of their exhaustive study, arrived at the BMI value of population of typical Army personnel as 23.00 kg/m^2, corresponding to the mean human body mass of 66.75 kg and mean Stature of 170.34 cm *i.e* 0.17034 m. While analysing the results of Modal Analysis & Response Spectra obtained for various part models constituting the Humanoid Robot model, considered to be made of two different materials, said criterion of 'BMI' is used as yardstick. For this, the BMI value of Humanoid Robot model is obtained. During this process, first the step files pertaining to various parts of MBD assembly are imported into the GUI environment of Ansys R19.2 Work Bench[3]. Typical part model viz., 'Head', imported into the GUI environment is shown in Figure 2.

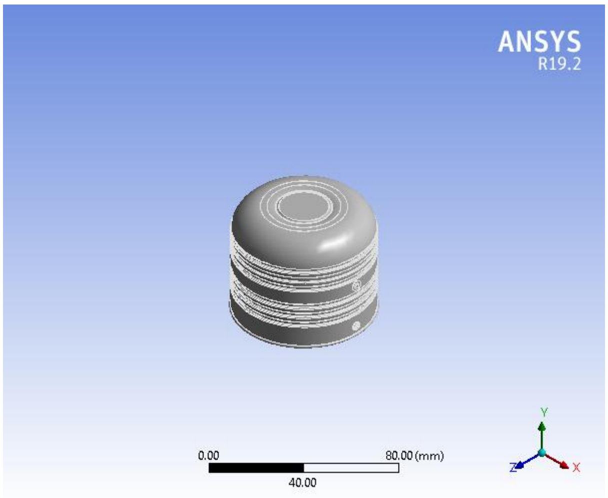

Figure 2: Model part 'Head' imported into Ansys WB[3]

Now the dimensions of the bounding boxes are obtained. Considering the default co-ordinate system and by giving due care for the overlapping of dimensions occurred during the assembly of MBD part models, value of net standing height of walking Robot model is obtained. The data is summarised and given in Table 1.

Table 1: Heights of different model parts forming Humanoid Robot

Model part	Height (mm)	Model part	Height (mm)	Model part	Height (mm)
Head	63.330	Lower Arm	101.600	Waist	42.640
Neck	71.755	Hand	61.466	Upper Leg	142.240
Shoulder line	49.530	Trunk	186.900	Lower Leg	142.240
Upper Arm	118.110	Hip	58.420	Foot	48.533

Now by giving due consideration for the overlapping of dimensions occurred while assembling MBD part models, value of net Standing height (Stature) of walking Robot model is worked out as (63.33 + 40.09 + 62.00 + 43.00 + 58.42 + 142.24 + 142.24 + 48.00) mm = 748.85 mm = 0.74885 m.

Similarly, values of another crucial parameter *viz*., 'mass' are obtained for various parts forming the MBD assembly of Humanoid model using Ansys R19.2 Work Bench[3]. Said values are obtained by considering that the part models are made of two selected materials *viz*., Structural steel (density = 7.85 g/cc and Youngs Modulus = $2x10^5$ M Pa) and Carbon Fiber (Youngs Modulus = 230 M Pa).

Table 2: Masses of different model parts forming Humanoid Robot Assembly

Model part	Mass (kg)		Model part	Mass (kg)		Model part	Mass (kg)	
	Strl. Steel	Carbon Fiber		Strl. Steel	Carbon Fiber		Strl. Steel	Carbon Fiber
Head	0.0272	0.0624	Upper Arm (Left & Right)	0.4474	0.1026	Waist	0.866	0.1987
Neck	0.0579	0.0133	Lower Arm (Left & Right)	0.3249	0.0745	Upper Leg (Left & Right)	1.0109	0.2318
Cover	0.0119	0.0027	Hand (Left & Right)	0.2903	0.0666	Lower Leg (Left & Right)	0.8999	0.2063
Shoulder	0.0722	0.0166	Trunk	1.0223	0.2344	Foot (Left & Right)	0.728	0.1669
Shoulder line	0.1358	0.0311	Hip (Left & Right)	0.4744	0.1088			
						Net Mass (kg)	6.3691	1.5167

It is to be noted here that the values of net mass for the above two cases lie far away from that of original Humanoid Robot model provided by Matlab® R2021a™ [2]. However, it is noteworthy that the works of Seward[4], *et. al*., is to be considered with respect to this aspect. From the anatomy of Human Robot disclosed by said authors[4], it may be noted that the major share of net mass 963.3 kg) is allotted to driving motors (41 kg) and energy providing batteries (23.3 kg), which are not considered as essential for current MBD models. Also it has to be accounted that mass components pertaining to gear boxes, joints, sensors, cables and control electronics, *etc*., need not be included in MBD CAD models. Also, as suggested by said authors[4], total skeleton mass with respect to the Robot frame will be in the order of just '2 kg' only, while considering composite materials. Summarizing, it may be stipulated that the weight of MBD CAD model considered, seems to be logical for the considered height of 0.74885 m.

However, alternate check is also carried out by comparing the other parameter *viz*., BMI value of human subjects from the Anthropometric database established by Wibneh[6], *et. al*. with the BMI values derived for the MBD CAD Robot model from Table 1 & Table 2, wherein two different materials are considered, for the same net height of 0.74885 m, as follows:

$(BMI)_{\text{Strl. Steel model}} = (6.3691/ 0.74885^2) = 11.3576$ kg/ m^2

$(BMI)_{\text{Carbon Fiber model}} = (1.5167/ 0.74885^2) = 2.7046$ kg/ m^2

The values are compared with the BMI value of human subject available in the Anthropometric Database established by Wibneh[6], *et. al*. and summarised in Table 3 given below.

Table 3: Comparison of BMI values for three cases

Sl. No.	**Subject/ Model**	**BMI Values (kg/ m^2)**
1	Typical Human subject considered by Wibneh[6], *et. al.*	23.00
2	Template Walking Robot CAD model considered to be made of Structural Steel	11.3576
3	Template Walking Robot CAD model considered to be made of Carbon Fiber	2.7046

From the above values, it is apparent that the BMI value of Template Walking Robot CAD model considered to be made of Structural Steel lies closer to that of human subject than that of its counterpart *viz*., Template Walking Robot CAD model considered to be made of Carbon Fiber. However further trials have been carried out to analyse the other aspects and to arrive at final conclusion, as briefed below.

2.3 Modal Analysis

Modal analysis has been carried out next, on various part models constituting the Template Walking Robot CAD model assembly, considering two different materials *viz*., Structural Steel & Carbon Fiber, mentioned above, to arrive at the values of Natural frequencies of above said part models. Six modes are selected for the task. As mentioned earlier, this is mainly to check whether the fundamental Natural frequencies of adjacent body part models lie well away from each other. Said environment is essential for parts of prototype to ensure that the condition of resonance is avoided during their functioning while realizing the hardware model of designed Robot CAD model.

Results are given in the Results section.

2.4 Response Spectrum Study

Response spectrum study is carried out using the same tool *viz*., Ansys R19.2 Work Bench[3], to study the performance of structural steel and Carbon Fiber as Humanoid Robot Hardware materials.

The tool calculates the response spectrum based on modal responses. Results provided by the solver are displayed as contour plots. The results shall be in terms of maximum response. During the simulations using two materials of Structural steel and Carbon Fiber, the excitation is applied in the form of displacement with the magnitudes of 50, 100, 50, 100, 50, 100 & 50 mm at the frequencies of 0.5, 1, 1.5, 1.0, 2.5, 3.0 & 3.5 Hz uniformly. Response Spectrum is obtained for Normal stress, Normal Elastic Strain and Total Deformation.

Results are given in the Results section.

3. Results And Discussion

3.1 Analysis of part models using Ansys WB[3]

3.1.1 Modal analysis

Sample Bar Chart showing the frequency at each calculated mode for particular Model part *viz*., 'Head' with selected material as 'Structural Steel', is shown in Figure 3.

Natural Frequency values obtained for various part models constituting the Humanoid Robot Assembly CAD model are summarised in Table 4.

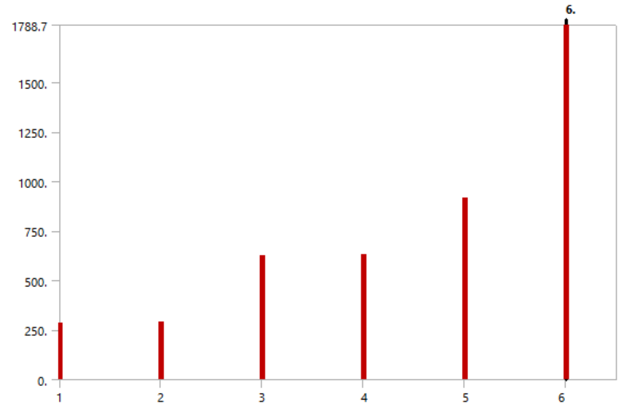

Figure 3: Bar Chart showing the frequency at each calculated mode for model part 'Head' with material 'Structural Steel'.

However, it may be noted that the values, especially, Fundamental Natural Frequency values of parts differ much from the values of 7.5 Hz (whole body), 7 - 13 Hz (Torso), 8 - 12 Hz (head), 6 Hz (pelvic), *etc*., of human body parts obtained in established works[9]. It is to be observed here that in all such prior works, human body is discretised into good number of lumped masses connected by springs and dashpots representing the tissues connecting various body parts. Also the bio-dynamic parameters like stiffness and damping co-efficient of said parts are implemented during the analysis. But in current work, to derive Virtual human CAD model, existing CAD model of Robot is updated by implementing only the crucial parameters like Stiffness & Torque values of Hip, Knee & Ankle and whole body densities with respect to the Upper & Lower body parts, for which the available CAD model has been originally designed. Also, it is noteworthy that aim of current stage of study is to verify whether the condition of resonance is avoided between various body part models for both materials, keeping above said parameter values same, in the current work. The outcome of study will be pivotal during the phase of hardware realisation of Robot CAD model.

Accordingly, from the tabulated values, it is apparent that the fundamental Natural frequencies of adjacent body part models lie well away from that of each other so that resonance would be avoided during their functioning while realizing the hardware model of designed Robot CAD model, with both Structural Steel and Carbon Fiber as constituent materials.

Table 4: Natural Frequency values of various part models

		Mode & Frequency (Hz)					
Part Name	Mode	1	2	3	4	5	6
Head	Strl. Steel	287.15	291.79	625.81	632.71	916.61	1788.7
	Carbon Fiber	247.45	277.94	501.71	614.95	822.07	1510.5
Neck	Strl. Steel	327.88	330.01	739.24	763.56	1548.4	1551.5
	Carbon Fiber	348.87	363.07	550.72	618.71	1389.5	1515.7
Cover	Strl. Steel	1.5061e+006	1.5064e+006	1.5066e+006	1.5067e+006	1.5068e+006	1.507e+006
	Carbon Fiber	1.0274e+006	1.0279e+006	1.0295e+006	1.03e+006	1.0321e+006	1.0327e+006
Shoulder	Strl. Steel	2863.7	3065.7	5513.4	12230	18093	20058
	Carbon Fiber	3930.7	5516.5	5608.5	14209	19052	21432
Shoulder Line	Strl. Steel	738.35	1102.5	2038.1	2085	3154.1	3493.3
	Carbon Fiber	529.96	851.83	1424.3	1496.1	2348.9	2687.1
Upper Arm	Strl. Steel	314.29	414.53	582.94	840.29	1518.1	1656.8
	Carbon Fiber	257.21	297.04	465.2	610.99	1117	1389.3
Lower Arm	Strl. Steel	508.92	742.15	765.58	1306.3	2170.4	2420.2
	Carbon Fiber	419.18	535.07	607.94	961.54	1806.8	1844.6
Hand	Strl. Steel	1253.7	1685.4	1973.8	2446.1	2725.4	5595.8
	Carbon Fiber	873.96	1198.6	1433.1	1888.6	2105.4	4238.6
Trunk	Strl. Steel	184.69	217.61	253.52	345.95	941.5	946.59
	Carbon Fiber	147.17	180.56	184.86	251.01	679.97	696.64
Hip	Strl. Steel	37724	39785	43173	44242	48562	48670
	Carbon Fiber	27430	28636	30761	33718	33760	34848
Waist Line	Strl. Steel	6308.9	7384.8	9235.1	12545	13404	17494
	Carbon Fiber	4423	5306.5	6954.4	10281	13824	14020
Upper Leg	Strl. Steel	250.16	304.77	411.32	507.85	1038.6	1253.5
	Carbon Fiber	192.96	242.91	300.45	374.07	768.02	941.04
Lower Leg	Strl. Steel	360.83	456.97	582.37	864.44	1444.5	1627.4
	Carbon Fiber	269.56	358.18	418.39	624.63	1052.9	1192.3

3.1.2 Response Spectrum Study

Sample contour plot obtained at the end of Simulation for the body part viz. 'Head' is given in Figure 4.

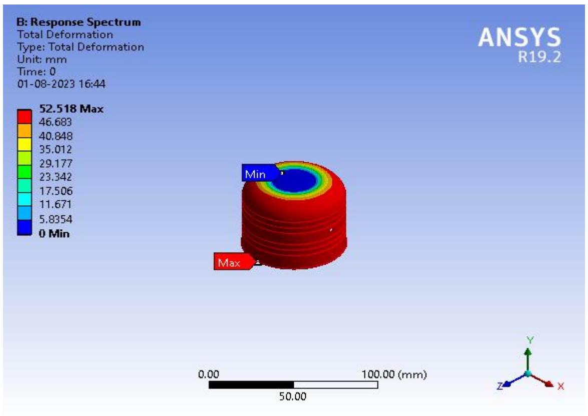

Figure 4: Sample Response Spectrum Contour plot for model part 'Head' with material 'Structural steel'

Numerical values obtained with respect to the Force reaction, Normal stress, Normal Elastic Strain and Total Deformation for crucial body parts are given as ***Appendix***. From Appendix, it may be observed that the benefit of considerable reduction in resulting linear Force Reaction can be achieved, by selecting Carbon Fiber as constituent material for almost all the parts, excluding 'Lower Leg'. For other parts, the benefits achieved range from 46.97% (minimum) to 98.49% (maximum). Similarly, we are able to achieve considerable amount of reduction in resulting linear Normal stress, by selecting Carbon Fiber as constituent material for almost all the parts except 'Head' and 'Neck', though the benefit is 3.52% only for 'Lower Leg'. For other parts, the benefits achieved range from 35.06% (minimum) to 93.76% (maximum). We are able to achieve considerable amount of reduction in resulting linear Normal Elastic Strain, by selecting Carbon Fiber as constituent material for almost all the parts, except 'Head', though the benefit attained is only 15.67% for 'Neck'. For other parts, the benefit achieved ranges from 45.01% (minimum) to 90.95 % (maximum). With respect to the Total deformation, it is observed that we can attain considerable amount of reduction in resulting Total Deformation, by selecting Carbon Fiber as constituent material for the 'Shoulder Line', 'Upper Arm' and 'Lower Arm', with benefit achieved ranging from 0.69% (minimum) to 2.13 % (maximum) though the Total deformation values are increased for other parts, with the revision in constituent material.

4. Conclusion and Future Scope

In current work, a comparative study is carried out on BMI values of MBD humanoid models, considered to be made of two different materials *viz*., Structural Steel and Carbon Fiber to pick up the preferred one out of the two. Modal Analysis and Response Spectrum study are then carried out on part models constituting MBD humanoid assembly model considered to be made of two different materials as above. At the end of Simulation, it is observed that the benefits achieved by switching over of material choice to Carbon Fiber reach a value of 98.49% at maximum. Thus at the end of study, it is concluded that a combination of materials can be suggested for different parts of humanoid, by meeting trade-offs between various resulting Response criterion, considering the end use of hardware. Said observations shall facilitate the stake holders of humanoid prototype development. Combination of novel materials may be studied to arrive at weight - effective humanoid model, as future work.

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(Appendix):

Part Name	**Material**	**Numerical value of resulting linear Force Reaction (N)**	**Label**	**% Reduction in value achieved through material revision = ((A-B) / A) x 100%**	**Numerical value of resulting Normal Stress (MPa)**	**Label**	**% Reduction in value achieved through material revision = ((C-D) / C) x 100%**	**Numerical value of resulting Normal Elastic Strain (mm/mm)**	**Label**	**% Reduction in value achieved through material revision = ((E-F) / E) x 100%**	**Numerical value of resulting Total Deformation (mm)**	**Label**	**% Reduction in value achieved through material revision = ((G-H) / G) x 100%**
Head	Strl. Steel	88.107	**A**	87.96	0.0018807	**C**	-149.40	3.6529×10^{-9}	**E**	-455.53	49.082	**G**	-0.09576
	Carbon Fiber	10.608	**B**		0.0046904	**D**		2.0293×10^{-8}	**F**		49.129	**H**	
Neck	Strl. Steel	4.3465	**A**		0.10459	**C**	-187.33	9.9437×10^{-7}	**E**	15.67	29.968	**G**	-0.76415
	Carbon Fiber	0.80796	**B**	81.41	0.30052	**D**		1.1502×10^{-6}	**F**		30.197	**H**	
Shoulder	Strl. Steel	9064.8	**A**	90.96	69.757	**C**	49.34	6.4872×10^{-4}	**E**	51.12	36.098	**G**	-0.99729
	Carbon Fiber	819.22	**B**		35.339	**D**		3.166×10^{-4}	**F**		36.458	**H**	
Shoulder Line	Strl. Steel	484.89	**A**	83.81	50.811	**C**	82.04	2.2544×10^{-4}	**E**	82.08	30.765	**G**	2.129043
	Carbon Fiber	78.659	**B**		9.1215	**D**		4.0384×10^{-5}	**F**		30.11	**H**	
Upper Arm	Strl. Steel	781.96	**A**	98.49	1.6814	**C**	93.49	1.2365×10^{-5}	**E**	90.95	29.334	**G**	0.688621
	Carbon Fiber	11.8	**B**		0.10946	**D**		1.1195×10^{-6}	**F**		29.132	**H**	
Lower Arm	Strl. Steel	331.55	**A**	80.07	4.799	**C**	64.91	2.3422×10^{-5}	**E**	78.01	30.247	**G**	1.583628
	Carbon Fiber	66.083	**B**		1.6841	**D**		5.1509×10^{-6}	**F**		29.768	**H**	
Hand	Strl. Steel	3495.7	**A**	86.16	22.932	**C**	93.76	3.75×10^{-6}	**E**	61.84	25.486	**G**	-0.41591
	Carbon Fiber	483.89	**B**		1.4311	D		1.4311 x 10-6	F		25.592	H	
Trunk	Strl. Steel	32.065	**A**	82.26	6.6534×10^{-2}	**C**	92.68	3.3528×10^{-7}	**E**	59.69	44.914	**G**	-0.18702
	Carbon Fiber	5.6886	**B**		4.8685×10^{-3}	**D**		1.3514×10^{-7}	**F**		44.998	**H**	

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(Appendix) (Contd.):

Part Name	Material	Numerical value of resulting linear Force Reaction [@] (N)	Label	% Reduction in value achieved through material revision = ((A-B) / A) x 100%	Numerical value of resulting Normal Stress (MPa)	Label	% Reduction in value achieved through material revision = ((C-D) / C) x 100%	Numerical value of resulting Normal Elastic Strain (mm/mm)	Label	% Reduction in value achieved through material revision = ((E-F) / E) x 100%	Numerical value of resulting Total Deformation (mm)	Label	% Reduction in value achieved through material revision = ((G-H) / G) x 100%
Waist Line	Strl. Steel	29497	**A**	67.81	11.693	**C**	35.06	7.4717×10^{-5}	**E**	85.08	1.6526	**G**	-73.2845
	Carbon Fiber	9494.5	**B**		7.5937	**D**		1.1142×10^{-5}	**F**		2.8637	**H**	
Upper Leg	Strl. Steel	810.91	**A**	46.97	7.1898×10^{-2}	**C**	80.72	6.7726×10^{-7}	**E**	45.01	19.77	**G**	-2.67071
	Carbon Fiber	429.96	**B**		0.16744	**D**		3.7238×10^{-7}	**F**		20.298	**H**	
Lower Leg	Strl. Steel	260.85	**A**	-40.94	3.2276×10^{-2}	**C**	3.52	6.3899×10^{-8}	**E**	51.04	18.725	**G**	-1.81575
	Carbon Fiber	367.64	**B**		3.114×10^{-2}	**D**		9.6514×10^{-8}	**F**		19.065	**H**	

[@] Total Force Reaction value refers to the Sum of values in ‘X’, ‘Y’ & ‘Z’ Axes
Percentage Reduction achieved in resulting values of Force reaction, Normal stress,
Normal Elastic Strain and Total Deformation through change of constituent part material from Strutural Steel to Carbon Fiber