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Arrriving At A More Realistic Humanoid Robot Model Through Walking Pattern Simulation And Analysis Using Multi Body Dynamic Model, Implementing Biodynamic Parameters Of Human Body

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Abstract

Scope of current work is to carryout a comparative study on pre-existing Multi Body Dynamic assembly model of Humanoid robot and the derived assembly model wherein Biodynamic Parameters of Human Body are implemented and simulation is done. Simulation pertaining to two different optimization algorithms *viz*., Genetic algorithm and Reinforcement Learning for optimized walking is carried out as part of current work. At the end of study, extent of similarity between the walking patterns of the derived model and those of the prototypes disclosed in the prior art, is assessed through the comparison of resulting responses *viz*., joint angles and linear & angular responses of constituent parts, during the activity of walking. It is found that the derived model portrays an accuracy of 95.94%, 86.81% and 99.73% with respect to the resulting responses of constittuent parts of robot assembly model *viz*., Hip, Knee and Torso, respectively, during their intended functioning. Said results demonstrate that the derived model will be a more realistic one. This makes the derived model more representative than existing model paving the way for its use by the stake holders, during the simulation and experimentation phases in the development of prototypes of humanoid robot, especially those meant for engagement in hazardous environments.

Keywords: Multi body dynamic model, Simulation, Walking pattern, Humanoid Robot, Biodynamic parameters

1. Introduction

The idea of engaging PETMAN (Protection Ensemble Test Mannequin), an Anthropometric robot, in chemical environments has become a topic of discussion, nowadays[1]. During such engagements, said Robots are exposed to artificially generated chemical agents, to perform their intended task of inspecting individual protective equipment for soldiers which are meant for their survival during chemical warfare attacks. Walking is one of the important activities to be performed by such Robots during the above-said activity of inspection[1]. Thus, it will be cherished if the developed humanoid hardware mimics the human activity of walking to the maximum possible extent. However, this is an aspect yet to be examined, as research activities specific to this topic are rare to be located in prior art. Multi Body Dynamic (MBD) models are widely used nowadays as part of realizing the prototypes as they facilitate required simulation and analysis to arrive at final prototypes demanding stringent specifications. Accordingly, in the current work, an attempt is made to derive a more realistic humanoid MBD model by implementing established values of Bio-dynamic parameters of the human body, for use by stakeholders of humanoid prototype development. To validate the derived MBD model, a comparative study is carried out.

This is done by simulating the derived model to carry out ‘Gait Analysis’ *i.e* ‘study of walking patterns’ to assess the extent of similarity between the walking patterns of the extent model and those of human subjects as well as the prototypes disclosed in the prior art, through the comparison of resulting responses *viz*., joint angles and linear & angular values of body parts, during the activity of walking.

Additionally, as it is decided to study the walking patterns corresponding to the optimized walking, two optimization algorithm tools *viz*., Genetic Algorithm (G.A) and Reinforcement Learning (R.L) are implemented during the simulation process.

2. Prior-art

As part of the present work, an exhaustive survey was carried out on literature in areas of Anthropometry, which refers to the study of the measurement of the human body in terms of the dimensions of bone, muscle, and adipose (fat) tissue[2]. Thus, Anthropometric measurements[3] form the basis for the 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. During the survey, it was observed that Wibneh[6], *et. al.*, carried out a study to establish a human anthropometric database and further investigated the anthropometric variability across ethnicity, age, and regions. Pivotal Anthropometric data *viz.*, ‘Stature’ forming part of the Anthropometric database established at the end of said study has been used in current work, while comparing different models. Ficuciello[7] *et. al.*, in their work, addressed the problem of mapping human arm motion to an anthropomorphic robot arm. Cordella[8], *et. al*, focused their study on the definition and extraction of quantitative indicators for describing optimal hand-grasping postures. Talli[9] *et. al.*, in their work, presented the design, simulation, and analysis of a 6-axis robot for an n-number of applications. A geometric approach to solving the unknown joint angles required for the autonomous positioning of a robotic arm was presented by Clothier[10] *et. al.,* vide their publication. Rapoport[11], *et. al.*, vide their work, presented a study dealing with the stiffness and damping profiles of the leg joints during the ground-contact phase of hopping. Grimmer[12], *et. al.*, in their work, stipulate that full functionality like the one in the biological system can not be provided by artificial actuators for locomotion, because of missing sensory information and power sources. Bae[13], *et. al.*, carried out a study focusing on the biodynamic responses of a seated human model to whole-body vibrations in a vehicle. Rudolfs[14], *et. al.*, published their work to develop relationships between body parameters and important anthropometric dimensions. The search for a suitable walking humanoid Robot template model for the current experimental work ended up with the identification of a similar model available at “mathworks.com[15]”, as the said Multi Body Dynamic (MBD) model possesses the capability of walking fulfilling the pre-requirement of present simulation study.

It is also observed that Alfayeed[16], *et. al.* made a study on the features of gait using supervised machine learning algorithms. Pons[17], *et. al.* reviewed the principles of human locomotion. Mark[18], *et. al.*, carried out a study focusing on humanoid robots and social aspects of the human body. Yasar[19], *et. al.*, disclosed a novel approach employing a human-like strategy for terrain traversal. Ivo[20], *et. al.*, proposed an advanced gait analysis method. Mario[21], et. al., proposed a method for human gait and kinematic analysis. Chatur[i22], *et. al.*, presented an intelligent gait - phase detection algorithm. Shih[23], *et. al.*, presented the joint configuration of a 3D biped to achieve periodic walking gait . Zanchi[24], *et. al.*, described the methodology for normal gait recognition and estimation. Kajita[25], *et. al.*, introduced a new biped robot with telescopic legs. Lim[26], *et. al.*, described an online method for generating walking patterns for biped humanoid robots having a trunk. Kim[27], *et. al.*, described the dynamic model of a robot with a motion controller. Koichi[28], *et. al.*, presented an efficient online method to generate humanoid walking motions. Winter[29] presented a wide spectrum of measurement and analysis techniques. Qiao[30], et .al., presented a methodology to estimate the unknown damping and stiffness parameters of supine humans. Trube[31], *et. al.*, presented an approach to consider isometric contraction of muscles for the human body model. Nagazaki[32], *et. al.*, carried out an analysis on the crutch position in the horizontal plane. Akachi[33], *et. al.*, presented the development of a typical humanoid robotics platform. Bae[34], *et. al.*, proposed a novel method, using which, the humanoid robot can traverse uneven terrain & climb stairs. Rafael[35], *et. al.*, presented the strategy to deal with the designated manipulation tasks of typical humanoid robot. Fujiwara[36], *et. al.*, investigated a method for a human-sized humanoid robot. Hirai[37], *et. al.*, presented the mechanism of Honda humanoid robot. Hirohisa[38], *et. al.*, presented a novel humanoid robotics platform. Harada[39], *et. al.*, proposed a new style of manipulation by a humanoid robot. Hitoshi[40], *et. al.*, investigated on proxy drives of a lift truck using a typical humanoid robotics platform. Kazuhito[41], *et. al.*, presented the control system of a typical humanoid robotics platform. Human Gait dynamics was analyzed by Vaughan[42], *et. al.*, Thus it is observed from the surveyed literature that none of disclosed work is focused on simulation of MBD model of humanoid robot implementing bio-dynamic parameters of human body, as done in current work.

3. Methodology

3.1 Brief

As preliminary activity, the Humanoid Walking Robot Model of Figure 1 provided by mathworks.com[15], which was originally modelled using Simscape Multibody[15], is imported into Matlab[15] and Simulink[15] Graphical User Interface (GUI) environments.

Simulation is carried out by using the model which has been pre-trained with two optimization algorithms *viz.*, a Genetic Algorithm (G.A) and Reinforcement Learning (R.L).

Time domain spectra corresponding to the optimized walking pattern are obtained for various parts constituting the model, at the end of Simulation. This is mainly to assess the feasibility of application of two training agents mentioned above, for the current problem.

Then proposed humanoid model is derived by implementing the human body parameter values obtained from established works[11,14] of this research area, into the existing model. Simulation studies are carried out on the Gaits *i.e* Walking patterns of available Humanoid Walking Robot Template MBD Model and the derived Humanoid Robot MBD model, both of which have been pre - trained with G.A. This is also to demonstrate the feasibility of optimising the walking patterns of these two models using G.A, one preferred over its counterpart due its merits. Validation of derived MBD model is done by obtaining numerical values of joint angles and linear & angular velocities of body part models and comparing them with those of human subjects and prototypes disclosed in prior art, as mentioned earlier.

Basically, ‘Gait/ Walking Pattern’ refers to the manner of limb movements made during locomotion. These can be quantified from the Time domain spectra obtained for the joint angles and the linear & angular velocity responses corresponding to certain walking pattern.

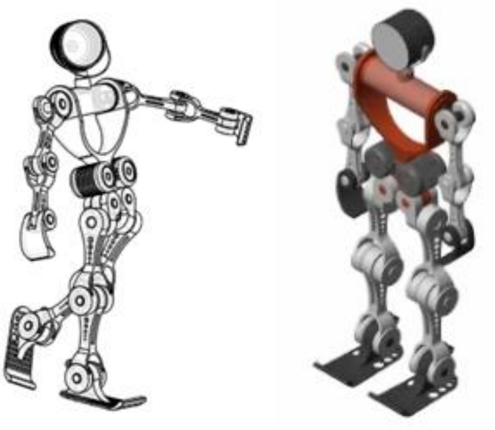

Figure.1: Walking Humanoid Robot Model of Mathworks.com[15]

3.2 Use of Optimization Algorithms

As the current study focuses on optimized walking pattern, concept of Optimization is used in the current work. Optimization is a process which identifies a point that minimizes or maximizes a function. Add-on Optimization tool of Matlab[15] is used for the purpose. G.A and Surrogate search are two common search ways applied in the process. Latter one uses the basics of Sampling Theory. Thus care should be exercised while selecting proper Sampling method. Hema[43], *et. al.*, made a detailed study on different sampling methods and selection of appropriate one. However, Surrogate search method possesses the drawback that the convergence is not fast[44]. Accordingly, in the process of optimizing the walking of the Robot, G.A is chosen as first choice for training the model and R.L as the second one.

3.3 Parameters set while training with G.A & R.L

Maximum generation of 20, population size of 100 and fitness limit of -1000 are chosen for G.A. The G.A parameters are set such that the Limits of Rotation being, Hip Frontal - Upper Limit= 30 deg., & Lower Limit = -90 deg., Knee - Upper Limit = 90 deg., & Lower Limit = 5 deg., Ankle - Upper Limit = 20 deg., & Lower Limit = -20 deg., Shoulder Frontal Upper Limit = 110 deg., & Lower Limit = -30 deg., Shoulder Sagittal - Upper Limit = 90 deg., & Lower Limit = -30 deg.,

Same values have been followed during the application of R.L as training agent.

With respect to the properties of mass segments, densities of 990 kg/m^3 and 1900 kg/m^3 have been respectively used for lower and upper body parts as default values for the default walking robot model. However, for derived MBD model, an average density value of 1099 kg/m^3 has been considered for upper body parts and an average value 1083 kg/m^3 has been considered for lower body parts, based on reports of Rudolfs**[14]**, *et. al.* so that the model mimics the human body with respect to these parameter values. A world damping value of 3 Ns/m has been used. (However, a value of 6 Ns/m is followed for this for the case of R.L). During Simulation, value of 1.54 m is considered as Robots initial height, a value of 0.025 sec. is followed as control and sensing discretization time and 60 sec. is considered as maximum simulation time. Same values have been followed during the application of R.L as training agent.

- With respect to the spatial contact force block parameters, it is fact that these parameters affect simulation and learning speed. Higher damping generally improves learning but slows down simulation. High static and dynamic friction values tend to improve learning. As trade-off, the contact parameters are considered such that contact stiffness = 1e5 N/m, contact damping = 1e5 Ns/m, contact transition width = 1e-3 m, contact static friction = 1, contact dynamic friction = 0.9, critical velocity = 1e-3 m/s & contact radius = 0.01 m, for both of the cases of G.A and R.L.
- The controllers are considered for unit damping of 1 Nm/rad.
- For default Walking robot model, Hip frontal stiffness of 80 Nm/rad, Knee stiffness of 80 Nm/rad and Ankle stiffness of 80 Nm/rad i.*e* the default values are followed as Controller parameters for both of the cases of G.A and R.L.

However, while considering the Multi Body Dynamic (MBD) walking Robot model as Virtual Human model and using G.A, these stiffness values are taken as 277 Nm/rad, 471 Nm/rad and 587 Nm/rad respectively, as suggested by Rapoport[11], *et. al.*

With respect to the Torque values, hip frontal, Knee and Ankle torque limits have been uniformly taken as 100 Nm as default values for the default model for G.A and R.L.

However, for Virtual Human model using G.A and R.L, these torque values are uniformly taken as 96 Nm, as derived from the works of Grimmer[12], *et. al.* and Rudolfs[14], *et. al.*

- During the Simulation using G.A and R.L, though 60 sec. is considered as maximum simulation time, criteria are defined for the simulation to terminate early. Accordingly, certain conditions *viz.,* humanoid torso dropping vertically or travelling laterally or rotating in any axis more than a set of predefined values or humanoid stops moving have been set as pre-defined conditions, such that for early termination, one or more of these conditions need to be satisfied. Thus the stopping criteria are set such that they are met when there is either a height change of 0.5 m or a lateral travel of 1 m or rotation in any axis to more than 30^0 or there is time out of 2 sec. or there is time out distance of 1 m.
- With respect to the Reward Scaling values, a Reward weight of ‘1’ has been assigned for Forward and Time step Reward weights. Penalty weights of 0.0005, 25 & 2.5 for power, vertical & lateral displacements, have been assigned respectively, for both of the cases of G.A and R.L.

- Additionally other options are chosen while training with R.L, such that, Discount Factor = 0.99, Mini Batch Size = 128, Experience Buffer Length = 1e6, Target Smooth Factor = 1e-3. Noise Options are such that Mean Attraction Constant = 5, Variance = 0.4, Variance Decay Rate = 1e-5. Training Options are such that Max Episodes = 4000, Score Averaging Window Length = 100, Save Agent Value = 500 and Stop Training Value = 1000.

3.4 Simulation on Walking Humanoid Robot Model using G.A and R.L

Simulation is carried out on Walking Humanoid Robot Model for optimized walking using both G.A and R.L as training agents.

The results are given in the Results section.

3.5 Simulation on Walking Humanoid Robot MBD model for Default and Human Bio-dynamic parameter values using G.A

From the successful outcome of simulation briefed in previous para, the feasibility of application of G.A and R.L as training agents for the current problem is established. Thus, the capabilities of said training agents to arrive at optimised walking patterns for similar cases are demonstrated.

However, as investigated by Xiang[45], as a result of his dedicated comparative study on use of G.A and R.L for typical training purpose, G.A could possess higher learning efficiency than it’s counterpart as the learning activity is carried out by multiple agents in the former case, whereas the latter trains only once at a time. Also G.A could be easy to implement and easier to modify by changing the mutation probability. Further, R.L could take a longer time to design. Also, even small changes would lead to a big difference in performance in this case and without a good reward system, the agents would perform poorly, as observed by said author[45]. Thus, G.A can be considered as possessing more merits over R.L, for training applications. Accordingly, Simulation is carried out on Walking Humanoid Robot MBD model for optimized walking for both the cases of Default and Human Body parameter values *i.e* for derived MBD model, using G.A as training agent, in this section.

The results are given in the Results section.

4. Results and Discussion

4.1 Simulation implementing G.A and R.L Training Agents using Matlab[15]

Sample output graphs obtained at the end of Simulation of Humanoid Robot model using G.A and R.L as training agents are given in Figures 2, 3, 4 & 5. Said sample graphs illustrate the Position & Velocity responses of ‘Torso’ obtained using G.A and Position & Velocity responses of ‘Torso’ obtained using R.L, respectively.

4.2 Simulation using G.A for Default and Human Body parameter Values using Matlab[15]

Sample Result graphs obtained for the ‘acceleration response’ of body part model *viz*., ‘Torso’, at the end of simulation carried out using G. A for the Default and Human Body parameter Values with Matlab® R2021a™ [15] tool are given in Figure 6 and Figure 7. This demonstrates the feasibility of application of G.A as training agent for current problem with respect to both Default and Human body parameter values.

Also, as part of current simulation task, numerical values of Maximum Abduction- Adduction angles & Angular Velocities of three human body joints *viz*., Hip, Knee and Ankle for different walking speeds along with linear velocity of Torso for free walking speed are obtained, with GA as Training agent, for validating the derived MBD model. The values are depicted in Table 1 and Table 2. The values are compared with those obtained for human subjects and prototypes as disclosed in established works[46 - 48].

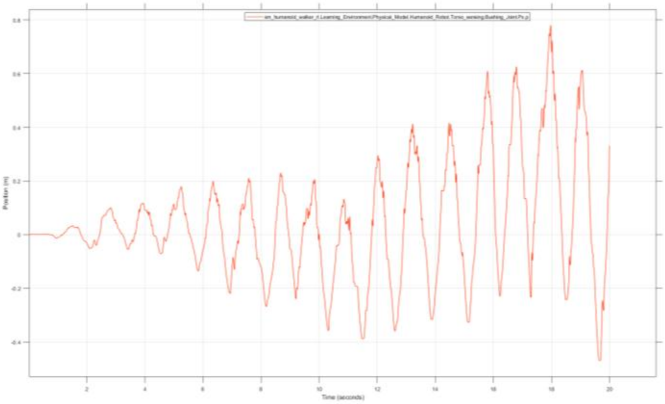

Figure.2: Position Response (x) of part ‘Torso’ in meters using G.A

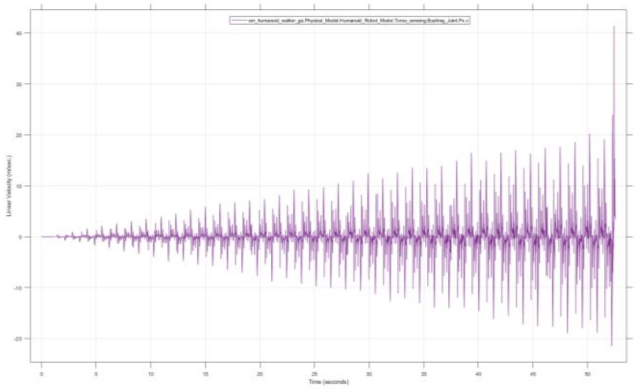

Figure.3: Velocity Response (x) of part ‘Torso’ in m/sec using G.A

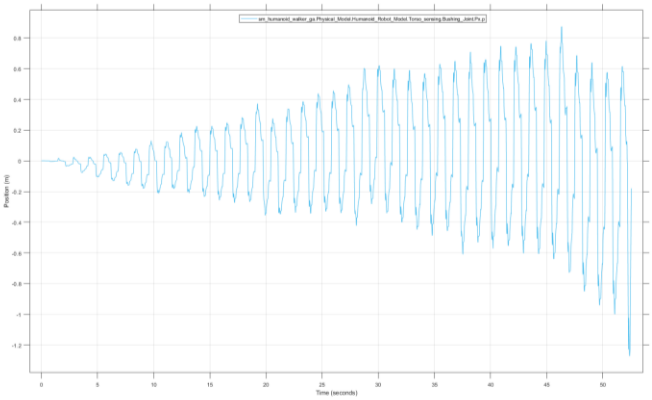

Figure.4: Position Response (x) of part 'Torso' in meters using R.L

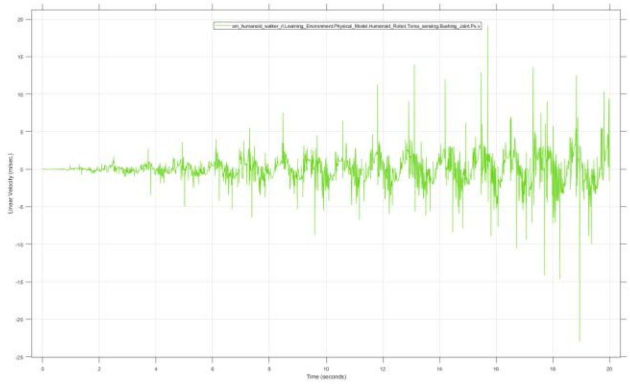

Figure.5: Velocity Response (x) of part 'Torso' in m/sec using R.L

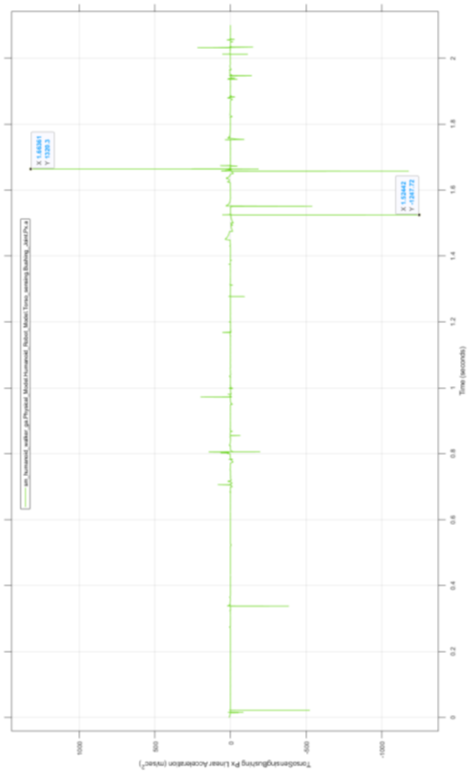

Figure.6: Acceleration response (X) in m/sec^2 for 'Torso', using G.A, for 'Default Parameter values'

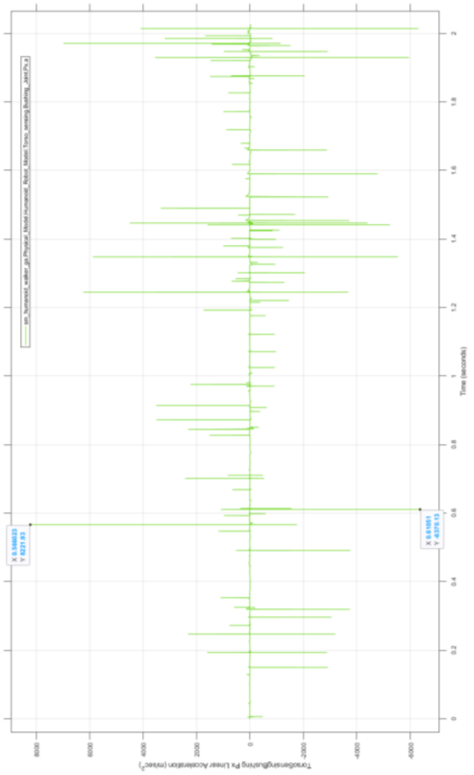

Figure.7: Acceleration response (X) in m/sec^2 for 'Torso', using G.A, for 'Human Body Parameter values'

Table 1: Maximum Abduction- Adduction angles and Angular Velocities of Hip and Knee joints obtained for different walking speeds, with GA as Training agent

	Hip						**Knee**					
	Left			**Right**			**Left**			**Right**		
	Rz Angle (deg)		Rz Angular Velocity (deg/sec)	Rz Angle (deg)		Rz Angle (deg)	Rz Angle (deg)		Rz Angular Velocity (deg/sec)	Rz Angle (deg)		Rz Angular Velocity (deg/sec)
Speed (m/sec)	Abduction	Adduction		Abduction	Adduction		Abduction	Adduction		Abduction	Adduction	
0.4	(-) 61.5	(+) 18	+ 800 to - 900	(-) 54	(+) 30	+1100 to - 910	-	(+)5 to (+) 90 = 85	+ 1460 to - 1460	-	(+) 5 to (+) 90 = 85	+ 1300 to -1740
0.6	(-) 71.5	(+) 30	+ 1200 to - 925	(-) 66	(+) 30	+ 1100 to - 850	-	(+) 5 to (+) 90 = 85	+ 1350 to - 2640	-	(+) 5 to (+) 90 = 85	+ 1300 to - 2450
0.8	(-) 46	(+) 30	+ 800 to - 520	(-) 30	(+) 30	+ 1100 to - 430	-	(+) 5 to (+) 57 = 52	+ 1020 to - 1470	-	(+) 5 to (+) 52 = 47	+ 1350 to - 1900
1.0	(-) 46.5	(+) 30	+ 1020 to - 640	(-) 30	(+) 30	+ 1190 to - 475	-	(+) 5 to (+) 57 = 52	+ 1200 to - 2180	-	(+) 5 to (+) 52 = 47	+ 850 to - 1980
1.2	(-) 46.5	(+) 30	+ 580 to - 620	(-) 30	(+) 30	+ 1100 to - 675	-	(+) 5 to (+) 57 = 52	+ 1080 to - 1380	-	(+) 5 to (+) 56 = 51	+ 1300 to - 1800
1.4	(-) 46.5	(+) 30	+ 930 to - 730	(-) 30	(+) 30	+ 1090 to - 730	-	(+) 5 to (+) 57 = 52	+ 1260 to - 1800	-	(+) 5 to (+) 53.5 = 48.5	+ 1360 to - 1820
1.6	(-) 46.5	(+) 30	+ 875 to - 525	(-) 30	(+) 30	+ 1135 to - 735	-	(+) 5 to (+) 57 = 52	+ 1200 to - 1640	-	(+) 5 to (+) 53.5 = 48.5	+ 1300 to - 1870

Table 2: Maximum Abduction- Adduction angles and Angular Velocities of Ankle joint obtained for different walking Speed, with GA as training agent (with linear velocity of Torso for free walking speed)

Body part		Parameter		Speed (m/sec)						
				0.4	0.6	0.8	1.0	1.2	1.4	1.6
Ankle	Left	Rz Angle (deg)	Abduction	(-) 20	(-) 20	(-) 20	(-) 20	(-) 20	(-) 20	(-) 20
			Adduction	(+) 20	(+) 20	(+) 20	(+) 20	(+) 20	(+) 20	(+) 20
		Rz Angular Velocity (deg/sec)		+ 2150 to - 2000	+ 2200 to - 1950	+ 2180 to - 2000	+ 2380 to - 2200	+ 2400 to - 2000	+ 2180 to - 2200	+ 2200 to - 2050
	Right	Angle (deg)	Abduction	(-) 20	(-) 20	(-) 20	(-) 20	(-) 20	(-) 20	(-) 20
			Adduction	(+) 20	(+) 20	(+) 20	(+) 20	(+) 20	(+) 20	(+) 20
		Rz Angular Velocity (deg/sec)		+ 2250 to - 1950	+2100 to - 2650	+ 2200 to - 1980	+ 2070 to - 1870	+ 2070 to - 1870	+ 2400 to - 2050	+ 2200 to - 2000
Torso Sensing Bushing (Pz) – Linear Velocity (m/sec) for free walking speed				3.64						

Liu[46], *et. al.*, at the end of simulation of walking of eight subjects, arrived at mean walking speeds (m/sec) as 0.54, 0.75, 1.15 & 1.56 categorised as very slow, slow, free and fast walking speeds, respectively. Thus a walking speed of 1.15 m/sec of 'free' walking can be considered as 'normal walking speed'.

Batbayar[47], *et. al.*, as an outcome of their study on ten human subjects, arrive at the results that the maximum 'Adduction - Abduction' angles of Hip, Knee & Ankle joints as 5.3±4.8º, 16.6±10.2º & 10.3±5.8º respectively for 'normal walking speeds. Considering the results of current work, values of 'Adduction - Abduction' angles obtained for 'Knee' joint corresponding not only to the walking speed of 1.2 m/sec (rounded off value of normal walking speed of 1.15 m/sec), but also for all 7 walking speeds are found to be 'Zero'. Here it is to be accounted that the derived model used for simulation is that of mechanical structure with its anatomy designed such that Abduction degree of freedom is totally arrested. Hence these values pertaining to 'Knee' joints are arrived as 'zero'.

From the works of Liu[46], *et. al.*, it is observed that for walking speeds (m/sec) of 0.6, 0.8, 1.2 & 1.6, for the 'Hip' joint, the maximum values of 'Adduction - Abduction' angles are obtained as 6º, 8º, 9º &12º respectively as resulting values. This shows an increase in angular response values with increase in walking speed. However, any uniformity is not observed with respect to the hike in magnitudes, in the above works. But with respect to the derived model of current work, following observations are made during simulation. Originally, rounded - off walking speeds (m/sec) *i.e* 0.4, 0.6, 0.8, 1.0 1.2 1.4 and 1.6 are chosen for current work such that they include mean walking speeds (m/sec) considered by above said authors as very slow (0.54 ≈ 0.6), slow (0.75 ≈ 0.8), free (1.15 ≈ 1.2) and fast (1.56 ≈ 1.6).

In such case, it is observed that the derived model performs such that the maximum 'Adduction - Abduction' angles of joints, either (i) show a steady rise with respect to their values during the phase of reaching the slow speed from very slow one, after which they exhibit stable angular change or (ii) they maintain stable values throughout all walking speeds, with the exception to 'Knee' joint, for reason mentioned earlier. Same trend is observed with respect to the left and right joints. This portrays that the derived model is fit for performing more predictable and uniform walk during their operation.

With respect to angular velocity, comparison is made between the results of simulation of currently derived model and those of experimentations carried out by Niu[48], *et. al.*, on wheel-legged robot proposed by them. Legged and wheeled are the two modes in which robot developed by them is capable of operating. Parameters selected by them are such that 0.4 m/sec and 2.2 m/sec are the two maximum speeds set for legged and wheeled modes respectively. Resulting curves obtained in the above work are found to be stable & smooth and free from mutations, due to the wheeled structure of said robot designed for smooth manoeuvrability. But the currently derived model is not so, as it's anatomy is designed to imitate legged configuration of human subjects.

Similarly, with respect to the numerical values of Angular velocities, resulting maximum value of Angular velocity at upper leg (accommodating points at which the body parts *viz.*, 'Hip' and 'Knee' interface with the leg), within a walking time span of first 2 sec is found to be 20 rad/sec *i.e* 1146.5 deg/sec., as reported from the result graph for the in-plane model of above work[48], for the legged mode maximum speed parameter value of 0.4 m/sec. Corresponding values of resulting positive peak angular velocities (for clockwise rotation) obtained for the model currently derived, for same walking speed of 0.4 m/sec are found to be 800 deg/sec for left side of 'Hip' and 1100 deg/sec for right side of 'Hip', as illustrated in Table 1. Thus an error of [(1146.5 - 800) / 1146.5] x 100 % = 30.22 % or an accuracy of (100 - 30.22) % = 69.78 % is depicted by the currently derived model for the left side of 'Hip'. Similarly for the Right side of 'Hip', an error of [(1146.5 - 1100) / 1146.5] x 100 % = 4.06 % or an accuracy of (100 – 4.06) % = 95.94 % is depicted.

Similarly for the 'Knee', corresponding values in deg/sec are 1460 & 1300 for left and right sides, as illustrated in Table 1. Thus an error of [(1146.5 - 1460) / 1146.5] x 100 % = 27.34 % or an accuracy of (100 - 27.34) % = 72.66 % is depicted by the currently derived model for the left side of 'Knee'. Similarly for the Right side of 'Knee', an error of [(1146.5 - 1300) / 1146.5] x 100 % = 13.39 % or an accuracy of (100 - 4.06) % = 86.81 % is depicted.

For validating the current model with respect to linear velocity, resulting maximum value of Linear velocity of 'Torso' which is obtained as 3.64 m/sec is compared with that at the end point of 'upper leg' of configuration proposed by Niu[48], *et. al.*, *i.e* at the location where 'Torso' interfaces with upper leg, which is obtained as 3650 mm/sec or 3.65 m/sec, by the authors. Thus the currently derived model mimics the robot developed by the said authors with an error of [(3.65 – 3.64) / 3.65] x 100% = 0.27% *i.e* with an accuracy of (100 - 0.27)% = 99.73%, with respect to resulting magnitudes of Linear velocity.

Thus, at the end of validation using results of prior art works of this field, it is apparent that the currently derived MBD model of humanoid robot performs the function of ideal walking, to an appreciable extent. Thus the derived model exhibits itself as more realistic model fit for use in simulation tasks prior to realising prototype of humanoid robot for application in hazardous working environments, as mentioned in opening paragraphs.

5. Conclusion and Future Scope

In the current work, a comparative study is carried out on pre-existing Multi Body Dynamic assembly model of Humanoid robot and the derived assembly model wherein Biodynamic Parameters of Human Body are implemented and simulation is done. Simulation is done for Optimized walking patterns using two optimization algorithms *viz.*, G.A and R.L. Assessment done at the end of study on the extent of similarity between the walking patterns of the derived model and those of the prototypes of prior art, through the comparison of resulting responses *viz.*, joint angles and linear & angular responses of constituent parts, during the activity of walking, reveals that the derived model portrays an accuracy of 95.94%, 86.81% and 99.73% with respect to the resulting responses of constituent parts of robot assembly model *viz.*, Hip, Knee and Torso, respectively, during their intended functioning. Thus, the derived MBD model is more representative than existing model and therefore can be used for simulation and experimentation by stake holders in the development of prototypes of humanoid robot. Fine tuning of other parameters of derived MBD model can be undertaken as future work, to make the resulting model as one still closer to replica of human subject. Also, apart from G.A and R.L., other state-of-art training agents may be used for optimizing the walking pattern of humanoid robot MBD model and a study also may be made on their performances, as future work.

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