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Biomechanical Modeling, Simulation, and Comparison of Human Arm Motion to Mitigate Astronaut Task during Extra Vehicular Activity

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Abstract**—**During manned exploration of space, missions will require astronaut crewmembers to perform Extra Vehicular Activities (EVAs) for a variety of tasks. These EVAs take place after long periods of operations in space, and in and around unique vehicles, space structures and systems. Considering the remoteness and time spans in which these vehicles will operate, EVA system operations should utilize common worksites, tools and procedures as much as possible to increase the efficiency of training and proficiency in operations. All of the preparations need to be carried out based on studies of astronaut motions. Until now, development and training activities associated with the planned EVAs in Russian and U.S. space programs have relied almost exclusively on physical simulators. These experimental tests are expensive and time consuming. During the past few years a strong increase has been observed in the use of computer simulations due to the fast developments in computer hardware and simulation software. Based on this idea, an effort to develop a computational simulation system to model human dynamic motion for EVA is initiated. This study focuses on the simulation of an astronaut moving the orbital replaceable units into the worksites or removing them from the worksites. Our physics-based methodology helps fill the gap in quantitative analysis of astronaut EVA by providing a multisegment human arm model. Simulation work described in the study improves on the realism of previous efforts, incorporating joint stops to account for the physiological limits of range of motion. To demonstrate the utility of this approach human arm model is simulated virtually using ADAMS/LifeMOD® software. Kinematic mechanism for the astronaut's task is studied from joint angles and torques. Simulation results obtained is validated with numerical simulation based on the principles of Newton-Euler method. Torques determined using mathematical model are compared among the subjects to know the grace and consistency of the task performed. We conclude that due to uncertain nature of exploration-class EVA, a virtual model developed using multibody dynamics approach offers significant advantages over traditional human modeling approaches.

Keywords**—**Extra vehicular activity, biomechanics, inverse kinematics, human body modeling.

I. INTRODUCTION

UNDERSTANDING the skill of Extra Vehicular Activity mitigate safety concerns, improve training procedures, and enhance simulator fidelity [1]. The nature of EVA is such that it remains one of the most dangerous of all operations during a space mission. The crews are required to physically depart from their spacecraft to perform tasks at or near the limits of their physical capabilities. The challenges faced by EV crew members include reduced proprioception due to inadequate stimulation of the skin, joints, and muscles, reduced range of motion due to the extravehicular mobility unit (EMU) limits on the joints etc. Analysis of astronaut's motions must be carried out before extravehicular activity in order to design the missions and build the guidelines for astronauts training. Previous studies present background information on EVA and techniques to familiarize the reader with the unique challenges of performing EVA.

Riccio G. E. et al. [1] described the development of meaningful empirical measures that are relevant to a special class of nested control systems: manual interactions between an individual and the substantial environment. Authors discussed the components of extra vehicular mass handling skill with reference to the relationship between postural configuration, and controllability of an orbital replacement unit. These empirical results as it pertains have relevance to extravehicular activity tools, training, monitoring, and planning. Hollerbach et al. [2] conducted experiment on human arm movement in a horizontal plane to know significance of the interaction torques. Authors developed a general purpose simulation program for arbitrary open loop kinematic chains, which can solve both the inverse and integral dynamics. Experimental results indicated that the interaction torques are significant for a two joint arm movement over a range of movement speeds and of movement paths. Mussa-Ivaldi et al. [3] developed an experimental method to measure the field of elastic forces associated with posture of hand in horizontal plane. Stiffness was represented both numerically, as a matrix, and graphically, as an ellipse characterized by parameters such as magnitude, shape and orientation. Findings of the experiment indicated that when a disturbance was imposed along a fixed and predictive direction, the magnitude of the stiffness was increased but only minor changes in shape and orientation occurred. Ning Lan et al. [4] proposed a model of biological motor control for generation of goal-directed multi-joint arm movements, and to study the formation of muscle control inputs and invariant kinematic features of movements. Motor commands required for calculation was divided into two stages, each of which performed a transformation of motor commands from one coordinate system to another. Observation of the numerical

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results indicated that the model developed was capable of reproducing the major characteristics of muscle control and movement kinematics. Rahn et al. [5] developed a dynamic model of extravehicular mobility unit space suit and applied to the simulation of several extravehicular activity tasks. A modified Preisach model was introduced to describe the hysteretic torque characteristics of joints in a pressurized space suit. Simulations were performed to observe the effect of suit constraints. The results stated the effectiveness of both the space suit and the simulation technique. Nikhil Bhushan et al. [6] used a paradigm to explore the system architecture of the biological adaptive controller to make reaching movements in force fields. Authors conducted experiment on 16 subjects to compare the performance of candidate control systems that acted on a model of the neuromuscular system of the human arm. Results of the study stated that control via a supra-spinal system that utilized an adaptive inverse model which lacked some of the essential characteristics. However, the author designed a control architecture such that the adaptation of the forward model played a dominant role in the motor learning of subjects. Masataka Suzuki et al. [7] presented a theoretical framework that describes a way in which the inverse dynamics equations of motion of planar two-joint arm movements are reformulated in a simple form. A single point was assumed to define both the wrist and elbow joint centers, and thus the motion of two points in extrinsic space was represented by second-order deferential equations to provide the variables in the reformulation model. In this study author found that the adequacy of the model varied somewhat among subjects, but minor changes of the physical parameters of the arm segments enabled perfect reformulation, regardless of the specimens. Also author discussed about the potential abilities of the reformulated model to deal with the complexities in motor control with more simple control schemes. Leia Abigail Stirling et al. [8] developed an astronaut dynamics model that is appropriate for EVA motions and incorporates constraints to ensure motion feasibility. They also simulated the astronaut dynamics model for several reorientation techniques and analyzed the resulting off-axis motions and effects of the space suit. The study determined that reorientation training is important for reducing the initial performance time, increasing the physical understanding of the reorientations, and reducing the perceived motion complexity. Leia Stirling et al. [9] presented several techniques for rotating about the axes of the body and showed that motions performed by the legs create a greater net rotation than those performed by the arms. Adding a space suit to the motions was seen to increase the resistance torque and limit the available range of motion. The results stated that, the resulting motions during the EVA activity generated a reduced rotation when compared to the unsuited configuration. Timotej Kodek et al. [10] studied the dynamic and static torques in the elbow flexion-extension movements. The movements were supervised and produced by using an industrial robot manipulator that was capable of imposing a programmed arc trajectory at various velocities in the sagittal plane of the seated human subject. A range of velocities which correspond to everyday movements was tested. The results reveal that the gravitational torque contributions have a prominent effect on the arm dynamics at low elbow velocities.

A great effort among the biomechanics researchers in past few years has been devoted to the development of reliable mathematical models of the musculoskeletal system. These models often comprise specific formulations from multibody system dynamics, muscle mechanics and descriptions of musculoskeletal geometry. Specifically, a well-developed human body model helps in understanding injury mechanisms of the bony skeleton and soft tissues/organs of the crew under complex loading conditions in laboratory and real impact testing. The human body models are developed based upon measured or estimated parameter values, representing characteristics of the human body. Although the various human body models differ in many aspects, all are dynamic. The models account for inertial effects by deriving equations of motions for all movable parts, and solving these equations using an iterative method. The mathematical formulations used for these models can be subdivided into: (1) Lumped mass models: The lumped parameter models consider an appropriate mathematical modeling of human body using several rigid bodies, spring and dampers [11], [12]. This type of model is simple to analyze and easy to validate with experiments. However, the disadvantage in the limited number of degrees of freedom; (2) Finite element models: In a comprehensive approach of modeling such as Finite element method, detailed information must be available and is quite rough at an early stage. Another disadvantage of this kind of modeling is the great amount of time involved in preparing the model and the computer time required for simulation [13], [14]. When many design alternatives have to be investigated a fast simulation model is desired; (3) Multibody models: This type of model is efficient since the motion restrictions between different anatomical segments of model defined as complex kinematic joints, suitable to represent mechanical joints, or as contact/sliding pairs, used to describe realistic human like anatomical joints [15]. As can be seen, several experimental and numerical techniques have been developed to determine the astronaut tasks. A more quantitative approach to the analysis of astronaut extravehicular activity (EVA) tasks is needed due to the increasing complexity, particularly in preparation for the on-orbit assembly of the Space Station. Existing useful EVA computer programs either produce high resolution three-dimensional computer images based on anthropometric representations or empirically derived predictions of astronaut movements based on body mass and the position and velocity of the body joints, but do not provide multibody dynamic analysis of EVA tasks. However, hardly any literature is seen in the area of modeling and simulation of astronaut tasks during EVA using the approach of multibody dynamics.

In this study, we use multibody dynamic approach, which helps in understanding the kinematics of the human body segments for EVA task. Simulation of the biomechanical human body model is the key of this study. In multibody dynamics approach the human body parts are connected by tree, loop or chain topologies. To mimic the EVA task a three segment human arm model comprising shoulder, elbow and wrist is considered for the study. The human body is modeled using LifeMOD® [16]. In order to compare the results obtained through the LifeMOD®, a mathematical model based on Newton-Euler method is used to study the kinematics of the human segments during EVA task. Also the joint torques obtained through experiment conducted on five subjects with three trials each for the prescribed movement are compared to know the grace and consistency of the subjects.

II. METHODOLOGY

The study is focused on the simulation of an astronaut motion during replacement of the orbital units into the worksites or removing them from the worksites. Methodology section deals with Experimentation to capture human motion, Mathematical modeling and Simulation of the biomechanical model developed for the task performed.

A. Experimentation

Five healthy human subjects, 3 males and 2 females (Age: 20±2 years; Height: 168±4 cm; Weight: 62±3 kg) without any musculoskeletal disorder took part in the experiment. Detailed instructions were given to the subjects about the task prior to the experiment. Consent is obtained from human ethics committee to conduct the experiment. The IMU's® mounted on to the subject are strapped using a special Velcro strap, ensures a firm placement of the sensor onto the body. Three IMU's®, one on the subject upper arm, second on the subject forearm and third on the subject's hand are mounted respectively. The IMU's® used are purchased from X-IMU® which has been calibrated by the manufacturer. An IMU is a electronic device consists of accelerometers and gyroscopes, sometimes also magnetometers to measure and report orientation, velocity and gravitational forces. Each IMU consists of a three axis accelerometer (±8 g), a three axis gyroscope (±2000 °/sec) and a three axis magnetometer (±8.1 G). IMUs® used have immense portability, compactness which supplies useful and accurate information. Prior to data collection, subject was given practice trials to become familiar with the task to be performed in the experiment. In this task, the subject was first asked maintain a comfortable hand posture as a reference and to move the object from the reference position to target position and then back to reference position slowly. After effective number of trails, subjects were made to perform the task and data were recorded using IMU's®. Motion capture involves recording of angular displacement during the task. Subject motion is recorded using the Inertial Measurement Unit (IMU's®). Data from the sensors are sampled at 128Hz and the MARG algorithm running on an on-board microcontroller fuses the data from the sensors to obtain accurate angular rotation. The data is transferred to a nearby computer using USB data cable. The real time data for all the three axes with the respective time stamp was saved to an excel sheet for the data analysis. The time stamps are used to synchronize the time of the three IMUs®.

B. Mathematical Modeling

In this work the human arm is described as a three degree of freedom kinematic and dynamic structure (Fig. 1) to estimate the motion of a human arm to mimic the astronaut performing an EVA task. Human arm model considered for the study comprises of three segments: upper arm, forearm and hand respectively. The torques cannot be directly measured from the sensors, the principles of Newton-Euler method are utilized to determine the joint torques.

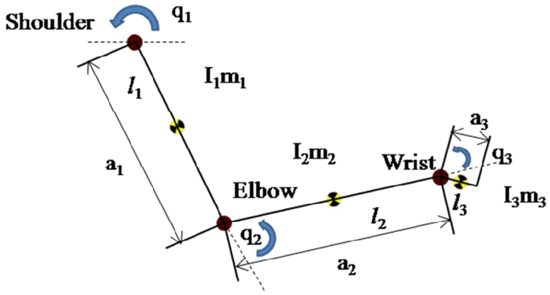

Fig. 1 Assumed Human arm segment parameters

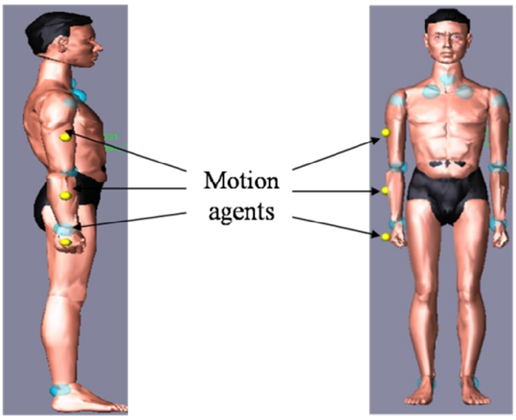

Fig. 2 Motion agents on the human arm

Mathematical model for the task is represented in the form of equation as:

$$B(q)\ddot{q}+C(q,\dot{q})\dot{q}+g(q)=\tau$$

where, B (q) is the inertia matrix, C $(q,\dot{q})\dot{q}$ is the Coriolis and centrifugal force matrix, g(q) is the gravitational force, τ is the driving torque. Human arm motion is distinctly established by kinematic variables of segments such as joint angular positions q1, q2 and q3, velocities $\dot{q}1$, $\dot{q}2$ and $\dot{q}3$, and accelerations $\ddot{q}1$, $\ddot{q}_2$ and $\ddot{q}3$ which are functions of time, but for simplicity reasons we denoted with q instead of q(t). They can be expressed as column vectors with indices 1, 2 and 3 referring to the shoulder, elbow and wrist respectively. Here q, $\dot{q}$, $\ddot{q}$ can be represented as column vectors with indices as 1, 2 and 3 referring to the shoulder, elbow and wrist joint respectively.

$$q = \left[q_{1,} q_{2,} q_3\right]^T$$

$$\dot{q} = [\dot{q}_1, \dot{q}_2, \dot{q}_3]^T$$

$$\dot{q} = [\dot{q}_1, \dot{q}_2, \dot{q}_3]^T$$

The moments of inertia are represented as a (3 x 3) $B(q)$ matrix. The diagonal elements of the matrix represent the moment of inertia at joint i axis, while the other two joints are fixed, whereas the non-diagonal ones account for the acceleration effect of joint i on joint j. For a 3-DOF human right arm the inertial matrix elements were derived as follows:

$$B(q) = \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix}$$

$$b_{11} = I_1 + I_2 + I_3 + l_2^2 m_1 + \left(a_2^2 + l_2^2\right) m_2 + \left(a_1^2 + a_2^2 + l_2^2\right) m_3$$
$$+ 2a_1\left(l_2 m_2 + a_2 m_3\right) c_2 + 2 l_3 m_3 \left(a_2 c_3 + a_1 c_{23}\right)$$
$$b_{12} = I_2 + I_3 + l_2^2 m_2 + \left(a_2^2 + l_3^2\right) m_3 + a_1\left(l_2 m_2 + a_2 m_3\right) c_2$$
$$+ 2a_2 l_3 m_3 c_3 + a_1 l_3 m_3 c_{23}$$
$$b_{13} = I_3 + l_3^2 m_3 + a_2 l_3 m_3 c_3 + a_1 l_3 m_3 c_{23}$$
$$b_{21} = I_2 + I_3 + l_2^2 m_2 + \left(a_2^2 + l_3^2\right) m_3 + a_1\left(l_2 m_2 + a_2 m_3\right) c_2$$
$$+ 2a_2 l_3 m_3 c_3 + a_1 l_3 m_3 c_{23}$$
$$b_{22} = I_2 + I_3 + l_2^2 m_2 + \left(a_2^2 + l_3^2\right) m_3 + 2\, a_2 l_3 m_3 c_3$$
$$b_{23} = I_3 + l_3^2 m_3 + a_2 l_3 m_3 c_3$$
$$b_{31} = I_3 + l_3^2 m_3 + a_2 l_3 m_3 c_3 + a_1 l_3 m_3 c_{23}$$
$$b_{32} = I_3 + l_3^2 m_3 + a_2 l_3 m_3 c_3$$
$$b_{33} = I_3 + l_3^2 m_3$$

Multiplying this matrix with the joint accelerations q̈ yields a vector of inertialcontributions in all three joints:

$$\tau_B = B(q)\ddot{q}$$

$$\tau_B = \left[\tau_{b1} \quad \tau_{b2} \quad \tau_{b3}\right]^T$$

The second matrix, C (q,$\dot{q}$) describes the centrifugal effects in its diagonal coefficients, while non-diagonal ones account for the Corioliseffect induced on joint 'i' by the velocity of joint j. For the given configuration the elements were specified as

$$C\,(q,\dot{q}) = \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix}$$

$$c_{11} = -\{a_1 \left[\left(l_2 m_2 + a_2 m_3\right) s_2 + l_3 m_3 s_{23}\right]_2 + l_3 m_3 \left(a_2 s_{23}\right)_3\}$$
$$c_{12} = 0.5\{-2a_1 \left[\left(l_2 m_2 + a_2 m_3\right) s_2 + l_3 m_3 s_{23}\right]({}_1 + {}_2)$$
$$-2 l_3 m_3 \left(a_2 s_3 + a_1 s_{23}\right)_3\}$$
$$c_{13} = -l_3 m_3 \left(a_2 s_3 + a_1 s_{23}\right)_{123}$$
$$c_{21} = a_1 \left[\left(l_2 m_2 + a_2 m_3\right) s_2 + l_3 m_3 s_{23}\right)_1 - a_2 l_3 m_3 s_{33}$$
$$c_{22} = -\, a_2 l_3 m_3 s_{33}$$
$$c_{23} = -a_2 l_3 m_3 s_{3123}$$
$$c_{31} = l_3 m_3 [\left(a_2 s_3 + a_1 s_{23}\right)_1 + a_2 s_{32}]$$
$$c_{32} = a_2 l_3 m_3 s_3 ({}_1 + {}_2)$$
$$c_{33} = 0$$

which after applying the velocity vector $\dot{q}$ defines the joint torque dynamic contributions

$$\tau_C = C\,(q,\dot{q})\,\dot{q}$$

$$\tau_C = \left[\tau_{c1} \quad \tau_{c2} \quad \tau_{c3}\right]^T$$

The gravitational contribution is expressed with a three element column vector. Every element of the τ_G vector represents the moment generated at the joint i axis as a result of the segment gravity:

$$G(q) = \left[\tau_{g1} \quad \tau_{g2} \quad \tau_{g3}\right]^T$$

$$\tau_{g1} = g_0\{[\left(l_1 m_1 + a_1\left(m_2 + m_3\right)\right] c_1 + \left(l_2 m_2 + a_2 m_3\right) c_{12} + l_3 m_3 c_{123}\}$$
$$\tau_{g2} = g_0[\left(l_2 m_2 + a_2 m_3\right) c_{12} + l_3 m_3 c_{123}]$$
$$\tau_{g3} = g_0 l_3 m_3 c_{123}$$

In the above equations the following abbreviations were used: $c_1 = \cos(q_1)$; $s_1 = \sin(q_1)$; $c_{12} = \cos(q_1 + q_2)$; $s_{12} = \sin(q_1 + q_2)$; $c_{123} = \cos(q_1 + q_2 + q_3)$; $s_{123} = \sin(q_1 + q_2 + q_3)$.

Anthropometric data such as segments lengths a_i, masses m_i, segment inertial values I_i and centre of gravity (COG) locations l_i are tabulated in Appendix.

C. Biomechanical Modeling

The objective of the study demonstrates the significant values of simulation of the astronauts' EVA tasks using the multibody dynamic analysis. LifeMOD® which works on multi rigid-body theory is used for simulating the biomechanical model. Since LifeMOD® has the capability to build the musculoskeletal model of varying range of anthropomorphic data of human system. The task involves an astronaut moving the replaceable unit into the worksites and removing them from it using his arm under his feet fixed in orbit along some slide way or plane. Based on the multi rigid-body system theory, the arm motion model can be established by including the following two components - three segments: upper arm, forearm, hand and three revolute joints of shoulder, elbow and wrist. Each joint in the three revolute joints has the following three revolute degrees of freedom: rotations around the transverse axis, sagittal axis, and frontal axis in the human body coordinate system, respectively.

In this model, each joint of the upper limb can rotate around the sagittal axis and the frontal axis in human body coordinate system. In LifeMOD® the virtual human arm model is developed through generation of body segments connecting them with joints. The established human body model can be combined with the physical environment for dynamic interaction. Motion agents are generated on the human arm to act as driving agents for the model. Fig. 2 shows the motion agents on the human arm. Through the Inverse and Forward dynamics simulations joint torques are determined.

III. RESULTS AND DISCUSSION

In order to study the kinematics of the astronaut arm, the results of the mathematical model and the virtual human arm model developed using LifeMOD® are dealt in this section. To estimate the motion of a human arm, a mathematical model of the human arm described as a three degree of freedom kinematic and dynamic structure (Fig. 1) based on Newton-Euler principles is utilized. Joint torques of the human segments are determined using Newton-Euler principles, as they cannot be directly measured from sensors. In order to simulate the virtual human arm model developed, motion data captured using IMU's® from experimentation are provided to the motion agents. Inverse dynamics simulation is performed to record the angulations provided through motion agents. Similarly, the input from the IMU's® is applied to other two motion agents. Forward dynamics simulation is run to determine the torque of the human body segments for the performed EVA task. In forward dynamics simulation the motion agents are deactivated and the motion is provided through the recorded angulations of the joints during inverse dynamic simulation. Figs. 3 and 4 show the subject conducting the experiment and simulation through LifeMOD® respectively.

Results obtained through numerical and software simulation are presented in this section. The graphical results obtained by experimentation using IMU's® is validated with the simulation of the developed virtual biomechanical model using LifeMOD®. Comparison of Joint torques for the upper arm (shoulder), forearm (Elbow) and hand (Wrist) for one subject data are shown in Figs. 5-7.

Fig. 3 Subject performing experiment with IMU's®

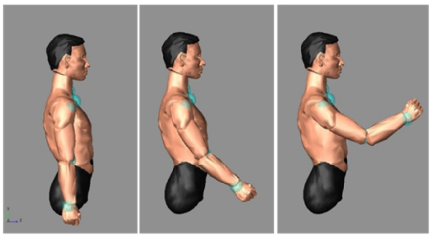

Fig. 4 Human arm simulation using LifeMOD®

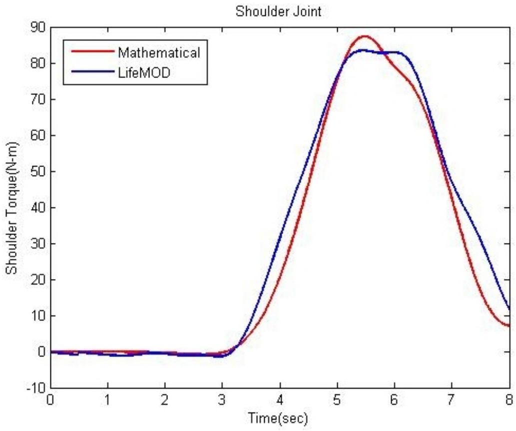

Fig. 5 Comparison of Shoulder joint torque

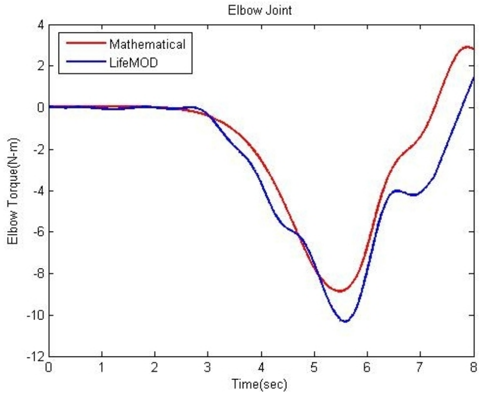

Fig. 6 Comparison of Elbow joint torque

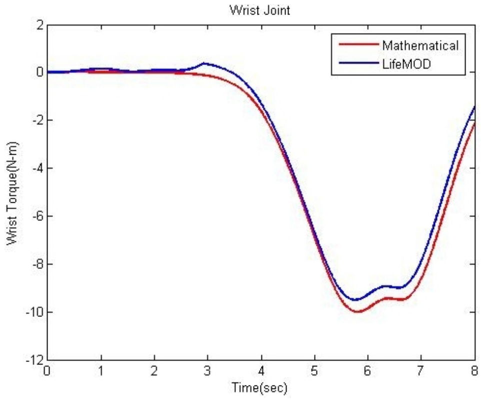

Fig. 7 Comparison of Wrist joint torque

In the experiment, although subjects are moving their hands in a vertical plane, still three components of the positional values are available since the device takes the reference frame at the shoulder. Additionally, the device records the positional values at the elbow and wrist. Comparison of the joint torques for the subjects obtained through numerical simulation are presented in this section. It can be observed the Figs. 5-7 that the trends of torque changes in simulation model agree with the mathematical model for all the three segments.

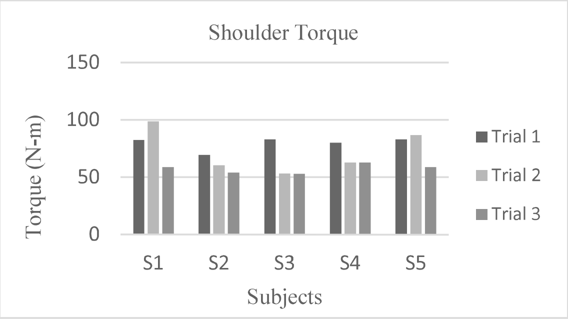

Fig. 8 Comparison of subjects Shoulder joint torque

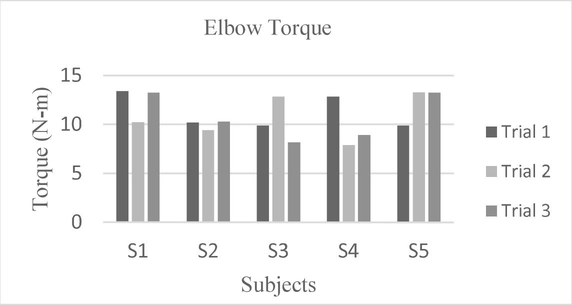

Fig. 9 Comparison of subjects Elbow joint torque

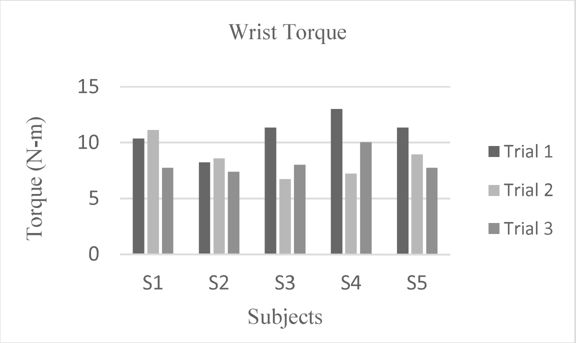

Fig. 10 Comparison of subjects Wrist joint torque

Comparison of Joint torques for the upper arm, forearm and hand for five subjects are shown in Figs. 8-10. Table I shows the torque values for three trials of five subjects. From Figs. 8-10, it is observed that the torque value of the shoulder is much greater than that of the elbow and wrist. This is due to the reason that torque is directly proportional to force and angular displacement. In the model, the reference frame is shoulder segment and have to carry the weights of elbow and wrist. Therefore, greater force is needed for shoulder that means shoulder exerts greater torque when compared to elbow and wrist to perform the task. Other reason is that the angular displacement of the shoulder is greater than the other two segments. It is observed that subject one has the highest and subject two has the lowest average torque. It is necessary to mention that subject two had some prior knowledge regarding human arm movement and its related experiments. From Figs. 8-10, it can also be seen that for the subjects three, four and five who did not have any prior experience of the task performed, have comparatively greater torques to that of subject two. Subjects one had some hesitation due to not having a clear picture of the experiment caused in tension; therefore, extra torque is applied to execute the work. The increasing and decreasing trend of torques for all the five subjects is observed from Figs. 8-10. This is due to the reason that the changes of torque follow the same trend as the changes of position for all subjects which is practically visible. From observation we can state that the subject two has good grace and consistency compared to other subjects for the performed task.

TABLE I
TORQUE VALUES FOR THREE TRIALS OF FIVE SUBJECTS

Sub	Shoulder			Elbow			Wrist		
	T_1	**T_2**	**T_3**	**T_1**	**T_2**	**T_3**	**T_1**	**T_2**	**T_3**
1	82.6	98.6	58.7	13.4	10.2	13.2	10.3	11.1	7.7
2	69.4	60.32	53.7	10.2	9.4	10.3	8.2	8.5	7.4
3	83.1	53.1	52.8	9.8	12.8	8.1	11.3	6.7	8.0
4	79.9	62.5	62.5	12.8	7.8	8.9	13.0	7.2	10.0
5	83.1	86.7	58.7	9.8	13.2	13.2	11.3	8.9	7.7

IV. CONCLUSIONS

In this paper, biomechanical model is developed to simulate the astronaut motion during moving the replaceable unit into the worksites and removing them from it. Owing to the fact that the planar model structure is mathematically far less complex to describe than any other alternative, some studies suggest that the motor control system in the human brain actually uses a simplified version of such a model in determining the inverse dynamics problem. LifeMOD® which works on multi rigid-body theory is used for developing and simulating the biomechanical model. LifeMOD® is a plug-in to the MSC ADAMS® physical engine and has capability to simulate complex models accurately. Inverse and forward dynamic simulations are performed to determine the Joint torques. In order to validate biomechanical model developed, a mathematical model based on Newton-Euler principles is used. It can be seen that the results obtained for the biomechanical simulation is in good agreement with the mathematical model. Obtained results satisfy the expected trend for the required action executed. Subject having good grace and consistency can be used as one of the criteria for astronaut selection and can be trained for further activities. This research has a great value for on-ground training and planning of astronaut tasks in orbit. The practical implementation of the proposed system is currently ongoing and preliminary results look very promising. This may include investigation of reaching movements and passive movements to be modeled and studied.

APPENDIX

TABLE II
ANTHROPOMETRIC SEGMENT DATA OF THE SUBJECT

Subject	Height (cm)	Weight (kg)	Segment	Mass (kg) (m_i)	Length (m) (a_i)	Inertia (kg-m^2) (I_i)	COG (m) (l_i)
1	1680	64	Upper Arm	1.66	0.26	1.04E-02	0.16
			Lower Arm	1.32	0.23	7.66E-03	0.14
			Wrist	0.38	0.09	3.71E-04	0.05
2	1710	63	Upper Arm	1.63	0.27	1.65E-02	0.16
			Lower Arm	1.32	0.23	7.87E-03	0.14
			Wrist	0.38	0.10	3.77E-04	0.06
3	1650	59	Upper Arm	1.57	0.24	9.05E-03	0.15
			Lower Arm	1.29	0.22	6.67E-03	0.13
			Wrist	0.37	0.09	3.27E-04	0.05
4	1700	60	Upper Arm	1.57	0.27	1.65 E-02	0.16
			Lower Arm	1.29	0.23	7.87 E-03	0.14
			Wrist	0.37	0.10	3.77 E-04	0.06
5	1680	62	Upper Arm	1.66	0.26	1.04E-02	0.16
			Lower Arm	1.32	0.23	7.66E-03	0.14
			Wrist	0.38	0.09	3.71E-04	0.05

REFERENCES

[1] Riccio G E, Vernon Mcdnald P, Peters B T, "Understanding skill in EVA mass handling", volume 1: theoretical and operational foundations. NASA TP-3684, 1997.

[2] John M. Hollerbach, Tamar Flash," Dynamic Interactions Between Limb Segments During Planar Arm Movement", Biological Cybernetics, springer-verlag, volume 44, pp.67-77, 1982.

[3] F.A. Mussa-Ivaldi, N. Hogan, E. Bizzi, "Neural, Mechanical and Geometric factors subserving arm posture in humans", The Journal of Neuroscience, volume 5, page 10, pp. 2732-2743, 1985.

[4] NingLan, "Analysis of an optimal control model of multi-joint arm movements", Biological Cybernetics, springer-verlag, volume 76, pp.107-117, 1997.

[5] David B. Rahn. "A Dynamic Model of the Extravehicular Mobility Unit (EMU): Human Performance issues during EVA", *Master thesis, Massachusetts Institute of Technology,* June 1997.

[6] Nikhil Bhushan, Reza Shadmehr, "Computational nature of human adaptive control during learning of reaching movements in force fields", *Biological Cybernetics*, springer-verlag, volume 81, pp.39-60, 1999.

[7] Masataka Suzuki, Yoshihiko Yamazaki, Ken'ichi Matsunami, "Simplified dynamics model of planar two-joint arm movements", *Journal of Biomechanics*, volume 33, pp.925-931, 2000.

[8] Leia Abigail Stirling. "Development of astronaut reorientation methods: A computational and experimental study". *Doctorial Dissertation, Massachusetts Institute of Technology, June 2008.*

[9] Stirling L, Willcox K, Newman D J, "Development of a computational model for astronaut reorientation", *Journal of Biomechanics,*43 (2010), 2309–2314.

[10] TimotejKodek, Marko Munih, "An analysis of static and dynamic torques in elbow flexion-extension movements", Simulation modelling practice and theory, 11(2003), 297-311.

[11] XiangyuXie, "Absorbed power as a measure of whole body vehicular vibration exposure", Thesis, Concordia University Montreai, Quebec, Canada, June 2001.

[12] Wael Abbas, Ossama B. Abouelatta, Optimization of Biodynamic Seated Human Models Using Genetic Algorithms, *Engineering*, 2010, 2, 710-719.

[13] Jay (Zhijijan) Zhao, GopalNarwani, "Development of a human body finite element model for restraint system R&D applications", *TAKATA – Automotive Systems Laboratory, Inc*., Paper Number 05-0399.

[14] Dirk Fressmann, Thomas Munz, "FE human modelling in crash – Aspects of numerical modelling and current applications in automotive industry",*6 – LS DYNA Anwenderforum Frankenthal 2007.*

[15] Jorge Ambrósio and Miguel Silva, "Multibody dynamics approaches for biomechanical modeling in human impact applications", *IUTAM Proceedings on Impact Biomechanics*: From Fundamental Insights to Applications, 61–80.

[16] Vadiraj. B, Omkar S.N, Kandagal S.B, and Kiran M.C, (2012) 'Human response characteristics to impact conditions during spacecraft takeoff and impact landing', International journal of aerospace innovation, Volume 4, number3+4, 2012, pp.95-102.

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