

Biomechanical modelling and evaluation of construction jobs for performance improvement

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Abstract. Occupational risk factors, such as awkward posture, repetition, lack of rest, insufficient illumination and heavy workload related to construction-related MMH activities may cause musculoskeletal disorders and poor performance of the workers, ergonomic design of construction work systems was a critical need for improving their health and safety wherein a dynamic biomechanical model was required to be empirically developed and tested at a construction site of Tata Steel, the largest steel making company of India in private sector. In this study, a comprehensive framework is proposed for biomechanical evaluation of shovelling and grinding under diverse work environments. The benefit of such an analysis lies in its usefulness in setting guidelines for designing such jobs with minimization of risks of musculoskeletal disorders (MSDs) and enhancing correct methods of carrying out the jobs leading to reduced fatigue and physical stress. Data based on direct observations and videography were collected for the shovellers and grinders over a number of work cycles. Compressive forces and moments for a number of segments and joints are computed with respect to joint flexion and extension. The results indicate that moments and compressive forces at L5/S1 link are significant for shovellers while moments at elbow and wrist are significant for grinders.

Keywords: manual material handling, dynamic kinetic analysis, occupational risks, generic framework, man-machine interaction.

1. Introduction

Manual material handling (MMH) activities, such as shovelling, pulling of rope to lift materials at height, grinding and welding of steel plates, use of jack hammers to break extra concrete, and lifting of wooden planks are very common in any building construction site. In spite of using newer work methods and mechanical aids and tools, occupational injuries particularly musculoskeletal disorders (MSDs) are highly prevalent in construction site, majority of the construction jobs are carried out manually. The poor and awkward body postures, repetitive work,

heavy weight of the tool/equipment and extreme environmental conditions may result in fatigue and high level of physical stress among the workers causing pain in upper extremity and back. Biomechanical evaluation of work postures was considered to be essential for identifying and measuring forces and torques at various joints and segments of the workers.

In this paper, the details of the methodology applied for biomechanical evaluation of construction jobs being carried out under different work conditions at a construction site are presented. The forces at different body joints for a number of postures assumed by the workers are determined and analyzed.

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The possible corrective measures for improving performance of such a job with improved body postures and work methods are suggested in order to minimize the occurrence of MSDs in the long run.

2. Problem definition

The kinds of problems a person encounters while involved himself or herself with MMH tasks are many and complex in nature involving not only the basic design of the worksystem components, but also the kinds of interactions he or she may have with other components of a worksystem, mainly the 'machine' and the 'environment'. The following problems a person involved in material handling tasks may encounter in general:

- (i) musculoskeletal disorders (MSDs), such as back injury, carpal tunnel syndrome, tension neck syndrome, muscle sprain, shoulder tendonitis and vibration-induced white finger.
- (ii) anthropometric mismatch between the persons concerned and other components of worksystem, resulting in awkward work postures for prolonged period under closed or open environment,
- (iii) enormous physical stress resulting in fatigue and other damages or deficiencies in human body, either temporary or permanent in nature,
- (iii) poor human performance due to adverse environmental conditions and occupational hazards, and
- (vi) risk of accidents and health disorders associated with most of the MMH tasks resulting in poor level of fitness and work capacity.

The criticality of such problems are dependent on specific worksystems and other types of man-machine interactions and hence, many a time it is imperative that the ergonomic analysis of MMH tasks are required to be carried out empirically in a given industrial situation from the perspective of a number of evaluation criteria, such as biomechanical, physiological, and physical in order to address the above-mentioned problems. Among the various industries in India, the construction worksystems are highly labour-intensive and prone to the problems as mentioned with hardly any ergonomics-related research undertaken in this important industry [8]. In a typical construction-related job, such as bricklaying, mortar preparation, lifting and carrying of reinforcement cement concrete (RCC) bricks, grinding and

welding of steel plates, shuttering and de-shuttering, etc., workers complain mainly about pains in their lower back, upper and lower extremities, among many other types of problems are known from the complaints of the workers. Analysis of these following complaints in this context is worth mentioning:

- (i) pains in back, shoulders and wrists (while carrying out shovelling activity continually for eight hours with additional overtime for 3 hours per day in many instances),
- (ii) strain and sprain injuries (while unskilled ground-level workers carry large wooden planks, reinforcement bars, steel bolts, lift and carry reinforcement cement concrete (RCC) bricks, etc. that may have a weight of 15 kg in each occasion),
- (iii) MSDs (skilled workers like fitters, etc. while tightening and bending the reinforcement bars and welders doing welding operations for long durations while weight of a typical welding pipe is about 31 kg),
- (iv) severe fatigue and loss of energy (due to exposure to adverse environmental conditions (heat/cold stress) and workers working in an open environment), and
- (v) improperly designed safety gadgets (causing inconvenience and discomfort to workers and this may lead to accidents).

Biomechanical modelling requires a total systems approach. As it was essential to address a number of issues related to construction worksystem in systems ergonomics approach, topics like anthropometry, anatomy, work posture and body mechanics, and occupational biomechanical models were covered in this project.

3. Objectives of the study

The specific objectives set for the project are as follows:

- (i) to propose a generic framework for biomechanical evaluation for two types of construction jobs, viz., shovelling and grindings and
- (ii) to suggest and implement cost effective and ergonomically improved work methods for such

jobs reducing the risk of musculoskeletal disorders (MSDs).

As decided by the management of the Tata Steel and agreed by the IIT consulting team, the functional scope of the project includes two types of construction jobs as identified by the concerned personnel of Tata Steel. Initially, a generic research framework for biomechanical evaluation of construction jobs is needed before it is validated with respect to several construction jobs at the construction site of Tata Steel as decided by the management.

4. Formation of project team

As the management of the company has realized that occupational risk factors, such as awkward posture, repetition, lack of rest, insufficient illumination and heavy workload, directly or indirectly related to construction-related MMH activities may cause musculoskeletal disorders and poor performance of the workers, ergonomic design of construction work systems was a critical need for improving their health and safety wherein a number of biomechanical models were required to be empirically developed and tested. The project, conceived as an industry-academia joint initiative, was undertaken by a research team consisting of three members from the institute and five members from the company concerned. Whereas the members from the institute provided the knowledge of biomechanical modelling required for evaluation of repetitive and strenuous jobs and for improvement in their design, the members from the company were involved in providing support in collection of relevant data and background information.

5. Methodology for biomechanical evaluation

The methodology to carry out biomechanical evaluation of man-machine interaction consists of the following steps, dealing with both static and dynamic models, has three interrelated parts: part-I dealing with static model, part-II dealing with dynamic model, and part-III dealing with the improvement potential.

A set of construction-related MMH activities are selected based on relevance, priority and return or impact while considering human, job and workplace characteristics and other constraints. In this frame-

work, human body is treated as a series of links having six major joints, viz. wrist, elbow, shoulder, L5/S1 disc, knee and ankle. While developing the biomechanical model, the following assumptions are assumed to be valid: (i) each link is considered to have its total mass acting at its centre of mass, (ii) a centre of mass remain constant and may be represented as a single point, (iii) the body is symmetric and assumed to be in saggital plane, (iv) all joints are considered to be hinge joints, and (v) the length of each link remains constant during the movement.

The basic inputs for biomechanical modelling include anthropometric variables (providing different link dimensions and body weight), body postures (providing different joint angle data), shape, size, and weight of the load to be handled. Additional inputs such as length and location of centres of masses and radii of gyration for all the links about centres of mass are used for dynamic model. The basic inputs along with the work posture considered and method of working define the man-machine interaction for the given construction job.

Part-I: Static analysis

In this model, each body segment is treated as a separate link in the kinematic chain. The analysis could be carried out from top-down or bottom-up approach, however from the point of application of the external load and solving the equilibrium equations for each body segment, until reaching the segment that supports the body.

Step-1: The given activity is represented as a two-dimensional task and collect information on external forces acting on the body and their directions, body postures, body segment parameters (segment masses and location of centers of mass) of the person being analyzed.

Step-2: Draw free body diagram of human-machine interaction showing eventually the work postures and different forces as acting on the joints and links.

Step-3: Draw the free body diagram for different relevant links for MMH activity being carried out.

Step-4: Determine the horizontal and vertical forces in static equilibrium.

The following conditions are met in the state of static equilibrium:

$$\Sigma F_x = 0 \text{ (the sum of forces in the x-direction = 0)}$$

$$\Sigma F_y = 0 \text{ (the sum of forces in the y-direction = 0)}$$

$$\Sigma M = 0 \text{ (the sum of moments about a joint} \\ = 0)$$

Step-5: Calculate the resultant and net forces and moments at each joints.

Step-6: Compute the compressive force at L5/S1 disc. Thus, the total compressive and shear forces may be calculated using the above-mentioned steps and for all kinds of activities.

Part-II: Dynamic analysis

Dynamic biomechanical models are inherently more complex than static models. In addition to external forces acting on the body (the loads applied to the hands and effects of body weight) and posture, it also considers the effects of motion dynamics (kinematics and kinetics) including velocity and acceleration.

Step-1: The given activity is represented as a two-dimensional task and collect information on external forces acting on the body and their directions, body postures, body segment parameters (segment masses and location of centers of mass) of the person being analyzed.

Step-2: Draw free body diagram of human-machine interaction showing eventually the body postures and different forces as acting on the joints and links.

Step-3: Draw the free body diagram for different relevant link for shovelling activity being carried out.

Step-4: Determine the horizontal and vertical forces in static equilibrium.

The following conditions are met in the state of static equilibrium:

$$\Sigma F_x = m * a_x \text{ (where } m \text{ is the mass of the} \\ \text{segment and } a_x \text{ is linear acceleration in} \\ \text{x-direction)}$$

$$\Sigma F_y = m * a_y \text{ (where } m \text{ is the mass of the} \\ \text{segment and } a_y \text{ is linear acceleration} \\ \text{in y-direction)}$$

$$\Sigma M = I_{cm} * \theta \text{ (where } M \text{ are the moments} \\ \text{about center of mass, } I_{cm} \text{ is the moment of} \\ \text{inertia of the segment about its center of} \\ \text{mass and } \theta \text{ is the angular acceleration of the} \\ \text{segment)}$$

Step-5: Calculate the resultant and net forces and moments at each joints.

Step-6: Compute the compressive force at L5/S1 disc

Step-7: Evaluate the forces as computed in respect of their of their threshold values as applicable.

Part-III: Improvement potential

Step-8: Identify different risk factors for the selected construction job and their criticality.

Step-9: Identify preventive and remedial measures to minimize or eliminate the effects of risk factors (first step in the design improvement process).

The methodology for biomechanical evaluation of construction jobs is explained with the help of a flow chart shown in Figure-1.

6. Phases in the study

The project consists of a number of phases, such as data collection and analysis like representation of work postures with free body diagrams, formulation of moment and force equilibrium equations for each link, measurement of resultant moments on joints, calculation of compressive and shear forces on lumbar disk (L5/S1), evaluation of forces while comparing with the threshold values for each joint, analysis of risk factors, and identification and implementation of preventive and remedial measures for improved ergonomic performance. A number of steps, such as data collection through videography, study of various body movements, use of Ariel Performance Analysis System (APAS) for calculation of linear as well as angular velocity and acceleration at various joints and segments, calculation of resultant forces and torques using dynamic biomechanical model as developed, identifying the joints which are overstressed, proposing and implementing improved work methods with respect to shovelling and grinding jobs were undertaken. As a direct consequence of such an evaluation, ergonomic design of construction worksystems was improved with expected significant control of MSDs among the workers in the long run. In this context, a systematic and generic approach for constantly monitoring the force magnitudes at different body links and joints through dynamic kinetic analysis of 'human-machine' interaction in work posture was found to be very useful from both research and implementation perspectives.

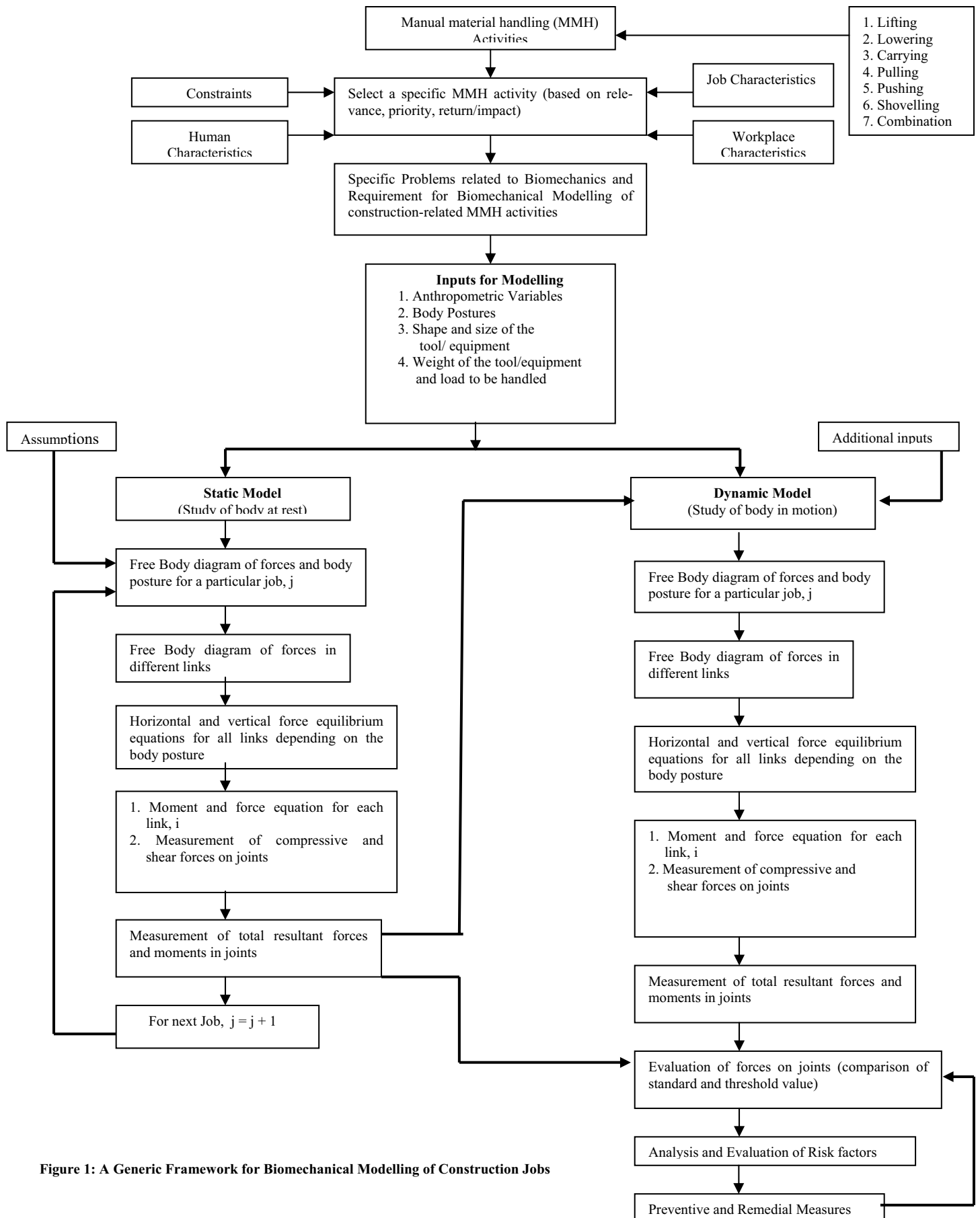


Figure 1: A Generic Framework for Biomechanical Modelling of Construction Jobs

7. Results and discussions

The compressive force on L5/S1 disc, being a critical factor for assessing the risk of low-back pain and other MSDs, is determined through dynamic analysis.

The moments at four specific joints, viz. wrist, elbow, shoulder and L5/S1 disc are computed for both flexion and extension movements for each shoveller are shown in **Table 1**. As the frequency of joint movement varies across the joints and segments considered over the workcycles, the minimum, the maximum and the average values of the moments are computed for each segment.

Variations in these values over the shovellers as well as the joints are required to be studied so that the risk of MSDs for a shoveller can be pinpointed with reference to one or more joints that may be withstanding excessive compressive force beyond its threshold value during shovelling. The risk of MSDs can also be correlated with the age, work postures, the types of shovels being used as well as the working environment, particularly the effect of work surface (even/uneven) on work posture and forces on joints.

For each segment and joint movement, moments along the corresponding segment as well as compressive force at L5/S1 disc are computed. For hand segment, the distribution of the maximum, minimum and average moments for wrist flexion (89 frames out of 110 frames) and wrist extension (21 frames out of 110 frames) are obtained which are found to be within the threshold value of -76 Nm (extension) to 66 Nm (flexion) for shoveller-1. Similarly, for shoveller-2 wrist flexion (101 frames out of 101 frames) and for shoveller-3 wrist flexion (60 frames out of 108 frames) and wrist extension (48 frames out of 108 frames) are also within the threshold value. For lower arm and upper arm segments, elbow flexion and extension as well as shoulder flexion and extension are within the threshold value of 43 Nm (flexion) to 106 Nm (extension) and 50 Nm (flexion) to 100 Nm (extension) respectively. The trunk is flexed for all the frames as observed that increased moments and stress on the lumbar region (L5/S1 link) for all the three shovellers as torque/moment greater than 50Nm in the upper extremity is considered to be significant factor resulting in higher compressive forces [16]. This has resulted in higher compressive force at L5/S1 disc. Shoveller-3 is found to have maximum compressive force of 3,445 N at L5/S1 as compared to shoveller-1 (1,147 N) and shoveller-2 (1,331 N) as compared to the maximum threshold of 3,400 N which is potentially hazardous irrespective of age or

gender [17]. In this context, shoveller-3 is more susceptible to MSDs, such as ligament and muscle sprain, muscle strain, mechanical back syndrome and herniated discs.

As compared to shovellers, grinders mainly assume a static posture where trunk is assumed to be flexed at an angle of 51.23 degrees subsequently for all workcycles. The moments at four specific joints, viz. wrist, elbow, shoulder and L5/S1 disc are computed for both flexion and extension movements for each grinder are shown in **Table 2**. Moments are found to be high for wrists, elbows and shoulder joints for all the three grinders. Although, compressive forces at L5/S1 joint for three grinders are within the threshold value of 3400 N, the grinders may suffer from severe back pain because of static and awkward work posture. However, grinders may have several kinds of MSDs, such as tendonitis, tennis elbow, forearm entrapment syndrome, shoulder tendonitis and tension neck syndrome due to repetitive hand movements and forceful gripping of the tool/equipment.

Corrective measures, such as improved work postures and revision of work-rest schedules are required to be adopted for such construction jobs so that the risk of MSDs is minimized in course of time.

8. Lessons learned

With the project executed successfully, a number of lessons were learned by the research team. Biomechanical modelling and evaluation is essential for assessing the actual biomechanical capability of a construction worker. Any set of guidelines to be useful for construction-related MMH jobs needs to be developed through empirical biomechanical modelling. Responses need to be collected from the concerned workers on a regular basis to understand the changing pattern of occupational risks over time as well as to identify the problems related to joint stress.

9. Conclusions

It is observed that biomechanical analysis has resulted in identification of specific MSDs and their causes for each shoveller and grinder indicative of validity of the proposed research methodology. It is envisaged that such a study needs to be extended for other occupations like masons, carpenters, welders and ground-level helpers at the construction site.

Table 1
Comparison of moments and compressive forces for different segments for Shoveller-1 (S1), Shoveller-2 (S2), and

Segments	Joint Movements	Frequency of Joint Movements			Moments along the segments (in N-m)								
					for								
		S1	S2	S3	(S1)			(S2)			(S3)		
				Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	
Hand	Flexion	89	101	60	0.83	0.003	0.25	0.55	1.27	0.30	0.65	0.11	0.30
	Extension	21	0	48	-0.004	-0.56	-0.25	0	0	0	-0.05	-0.37	-0.2
Lower arm	Flexion	89	101	60	2.75	0.006	0.82	1.83	4.29	0.98	2.14	0.02	0.99
	Extension	21	0	48	-0.02	1.89	-0.85	0	0	0	-0.02	-1.2	-0.7
Upper arm	Flexion	7	17	0	0.80	0.05	0.38	0.70	0.07	0.44	0	0	0
	Extension	103	84	108	-0.04	-4.26	-1.63	-0.06	-5.67	-1.53	-0.6	-4.4	-2.79
Trunk	Flexion	110	101	108	50.17	35.26	48.83	60.91	51.4	55.19	187	19.6	62.8
Compressive Force (L5/S1 disc)					1147	808	1002.3	1331	1170.8	1237.4	3445	421	1342.2

Table-2
Comparison of moments and compressive forces for different segments for Grinder-1 (G1), Grinder-2 (G2),

Segments	Joint Movements	Frequency of Joint Movements			Moments along the segments (in N-m)								
					for								
		G1	G2	G3	(G1)			(G2)			(G3)		
				Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	
Hand	Flexion	37	36	31	0.48	0.1	0.26	0.43	0.15	0.28	0.65	0.11	0.30
	Extension	2	4	4	-0.04	-0.56	-0.3	-0.01	-0.41	-0.28	-0.05	-0.37	-0.2
Lower arm	Flexion	24	28	60	4.13	0.13	0.30	3.35	0.21	0.2	3.98	0.01	0.3
	Extension	15	12	24	-0.13	-0.7	-0.2	-0.14	-0.6	-0.1	-0.12	-0.8	-0.43
Upper arm	Flexion	25	26	19	4.89	0.15	2.42	4.76	0.17	2.48	4.23	0.13	2.18
	Extension	14	14	16	-0.0037	-5.25	-1.67	-0.0061	-5.67	-1.73	-0.003	-4.0	-1.23
Trunk	Flexion	39	40	35	20.16	10.24	6.7	20.91	51.4	55.19	20.34	19.6	62.8
Compressive Force (L5/S1 disc)					789	350	750	679	259	571	702	362	698