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Finite Element Analysis of Conceptual Lumbar Spine for Different Lifting Position

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Abstract: The Lower-back pain (LBP) which is caused by lifting loads manually is one of the common issues faced by industrial workers. The objective of this paper is to determined the maximum stress and displacement on human lumbar by using computer aided engineering (CAE) software called Msc. Patran/Nastran. The 3D modeling of the lumbar spine from transferring data points of 3D scanner is reconstructed. The stress used for lifting loads from 20 to 60 kg is ranging between 2.52 to 74.1 MPa. The results showed that the end plate at 5th lumbar is experiencing the maximum stress development. This analysis is relevant to the industries especially manufacturing sector in order to provide a direction for ergonomists in the modification of jobs for workers who perform manual lifting. In order to gain a higher precision, it is suggested in the future that the lumbar spine is to be built based directly on a loaded CT scan and biodynamic loading situation with vibration and impact.

Key words: Human Finite Element Analysis % Maximum Stress (Von Mises) % Lumbar Spine Model

INTRODUCTION

The phenomenon of lower back pain (LBP) is increasingly important due to the appropriate motions of body. Improper manual lifting is considered an important risk factor for the occurrence of low back pain [1-4]. Any job involves heavy labor or manual material handling (MMH) may be at high risk category entails lifting [5]. Researchers found that the highest prevalence being lifting activities, 45% for upper back pain (UBP) with a cumulative of 84% for LBP in a Malaysian food manufacturing company. During manual handling, the back muscles protect the spine from excessive flexion; but in doing so, it imposes a high compressive force on it [6]. The biomechanics in human spine is a study of stability, motion and deformation in the human spine, generated by both internal and external forces acting on and through spinal connective tissues [7]. The transverse plane divides the body into upper and lower or superior and inferior parts. The median plane divides the body into left and right portions [8].

People in industrial sector are always facing the danger of LBP. This is mainly due to the lack of awareness on this problem and workers often not following rules and regulations such as lifting and placing heavy parts without using the right tools and techniques. Employees must also know the capabilities of themselves before they do a job. Analyzing the structure of lumbar using finite element analysis (FEA) shows the capability of the lumbar spine that holds large loads. In this paper, the analyses shown are based on loads at the lumbar spine whether lumbar posture is static or stoop. Finite element is the best method that can be used to visualize stress distribution and also displacement on lumbar spine. Employees will, then, know their own limit of their ability to do a task and always ensure that they maintain a good spine posture. LBP is a major cause of working injury and disability among the industrial population and gives impact of socioeconomic issue because of lower productivity and compensation claim [9]. Suaidicani *et al*. [10] studied about low back pain in industrial sector, where they found 51 % had experienced low back pain in a normal calendar

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year [10]. Recently, similar results were also obtained by Wai *et al*. [11] where they concluded that domestic recreation activities like lifting, pushing and pulling might be important potential confounders in studies on occupational risk factors for low back pain. Mazloum *et al*. [12] investigated about occupational low back pain among workers in small sized factories. From their investigation, they found that the highest frequency of low back pain among 109 claimed was in the age of 30 to 34 years old, with the height between 165-175cm and weight range between 81-90 kg [12].

Lifting load is causing more to low back pain issue than other occupational risk factors like pulling, pushing, repetitive motion and falling. One of the causes is workers do not know the exact technique and capability of the spine when lifting the loads manually. The other important factor is the exact dimension of the object from hand to the central body. This balanced shift towards is very important in order to control low back pain. Besides that, workers in the industrial sector sometimes carry the large load without any supporting tool or device that can help and able to reduce the required energy. Lin *et al*. [13] interviewed the characteristics of manual lifting activities in the patients with low back pain by using survey questionnaires. From their analysis, they described the characteristic of lifting jobs and their risk factors were related to the occurrence of back injury. It shows that the higher frequency belongs to the manufacturing sector with 24.1% compared to other working sectors such as construction, agriculture, service industry and others. The characteristics of manual lifting should be considered for ergonomic modification. Therefore, the main objective of this paper is to find the maximum stresses (Von Mises) and displacements on human lumbar by using computer aided engineering (CAE) software called Msc. Patran/ Nastran.

Human Spine Anatomy: The human spine is a complex and functionally significant segment of the human body. The function of the spine is to protect the central nerve, which runs through an opening in each of the interconnecting vertebrae [14]. It also serves as the axial support for the skeleton and provides flexibility and bending of the back. The spinal cord or spine is a long, thin, tubular bundle of nervous tissue and support cells that extends from the brain (the medulla oblongata specifically). The brain and spinal cord together make up the central nervous system as shown in Figure 1 [15]. The spinal cord functions primarily in the transmission of

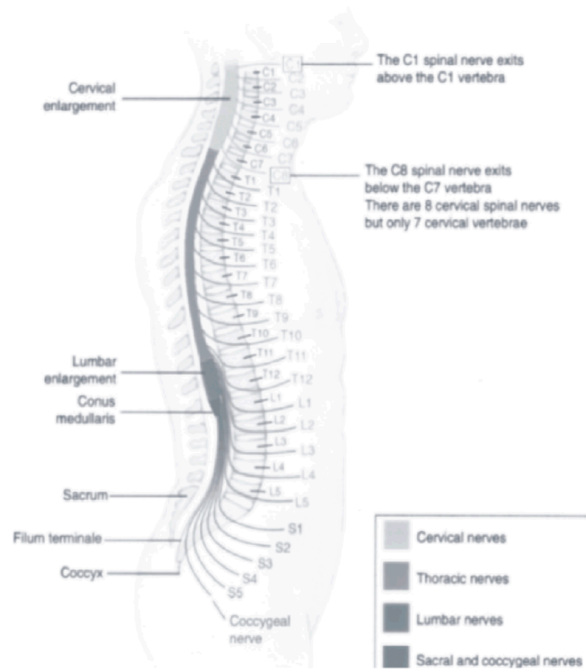
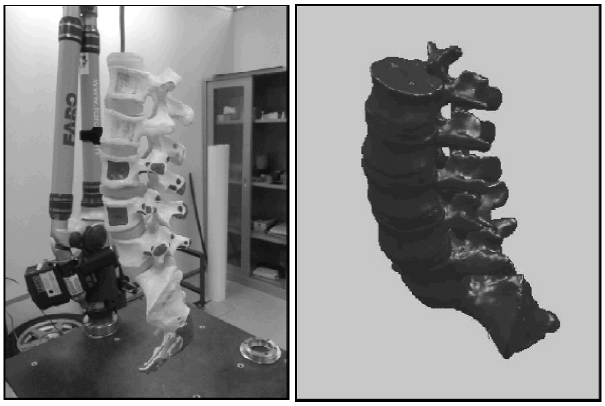


Fig. 1: The spinal cord in sagittal view [15]

neural signals between the brain and rest of the body [16]. It also contains neural circuits that can independently control numerous reflexes and central pattern generators. The lumbar vertebrae are the largest segments of the movable part of the vertebral column. They are characterized by the absence of the foramen transversarium within the transverse process and by the absence of facets on the sides of the body. They are designated from L1 to L5, starting from the top. The first lumbar vertebra is levelled with the anterior end of the ninth rib. This level is also called the important transpyloric plane since the pylorus of the stomach is at this level [17].

MATERIALS AND METHODS

Faro Arm is a mechanical 3D passive electrogoniometer with anthropomorphic structure mounted on a heavy and stable clamping device which makes the sensor easy to move and handle for digitalization. The model of lumbar spine is placed on the table and need a proper scan to create a 3D modelling. The lumbar is scanned using the Faro Arm to get the exact dimension and converted to Solidwork format. The model contains two portions namely the 5-cortical bones and the 4-disc. Figure 2 shows the model of lumbar spine before



(a) (b)

Fig. 2: (a) Model of Lumbar Spine and (b) 3D Modeling after Scan

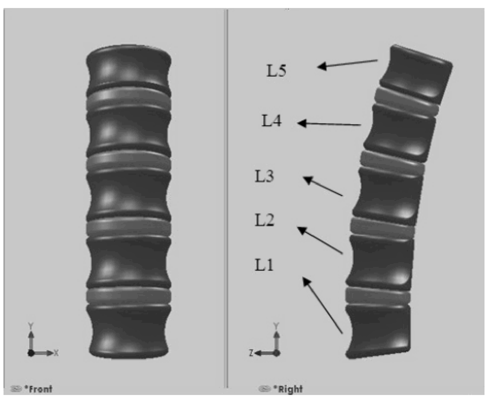


Fig. 3: Three dimensional (3D) modeling of lumbar spine

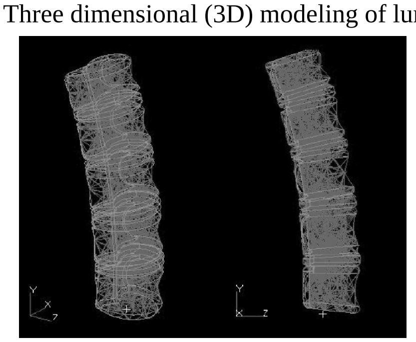


Fig. 4: Tetrahedron element mesh solid for lumbar spine

and after scan process in the 3D modelling. After placing the internal load, the fifth lumbar is then fixed as described by the boundary conditions.

The material properties for cortical bone and disc are assigned to the part (lumbar spine) as shown in Table 1. With these values, the analysis by Msc. Nastran software is executed and the model is automatically meshed into solid tetrahedron element and the summary of the process can be visualized on the PC screen. The loads applied are

Table 1: Material properties of cortical bone and disc

Material	Elastic Modulus (E) x10^3 N/mm^2	Poison Ratio (<)
Cortical Bone	12	0.30
Disc	4.2	0.45

Table 2: Simension of lumbar spine

Vertebra	Dimension (Mm) Length	Width	Height
L1	40.7	28.9	24.9
L2	39.8	29.8	25.4
L3	43.1	32.3	25.6
L4	43.5	31.7	26.5
L5	44.1	32.5	28.6

based on the object that was being lifted. The load weight ranges from 20 to 60 kg with an internal load between 2699 to 7938 N. The SolidWorks and Msc. Patran software is used to reconstruct a model of human spine (lumbar) and to conduct finite element analysis (FEA). Parasolid file is the application format that the pre and post processing can interface between Solidwork and Msc. Patran. Thus, converting the file is an important task before an analysis can take place for the next step. Figure 3 shows the anatomy of the vertebrae lumbar spine from the 3D model which is reconstructed to import in Msc. Patran with the dimension of lumbar spine as shown in Table 2.

The Msc.Patran/Nastran software allows the solid modelling in three dimensional (3D) modelling as well as two dimensional (2D) models. It gives a complete information contained in a solid model that allows automatic production drawing, interference check, analysis and extraction of manufacturing data. Figure 4 shows the Tetrahedron element mesh solid for lumbar spine with the global edge length of 0.05 mm. Force is applied at the upper of lumbar spine and the value is based on the internal load. Restraint, an external limit on the movement of a structure or portion, were placed on the lower of lumbar spine in all degree of freedom (DoF) and translation using constant displacement. A static analysis calculates the stresses displacements and strains of the model with response to the specified constraints and loads. This analysis explains the characteristics of the model that can withstand the stress level or the break point with any movement of the part.

The two main results focusing in this analysis are maximum stress (Von Mises) and displacement. Von Mises stress is an equivalent stress by combination of all the stress components. The Von Mises yielding criterion states that a material reaches its elastic limit if the

Von Mises stress is equal to the material's yield stress in simple tension. While displacement is the movement of a point on the model, measured as the change in position relative to the point's location on the undeformed model, displacement is calculated by default during an engine run followed by the comparison on these results.

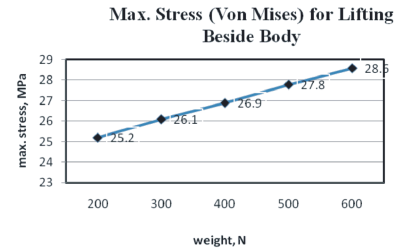
RESULTS AND DISCUSSION

Maximum stress (Von Mises): The maximum stresses (Von Mises) for the two different methods of lifting the load at various lever arm distances are shown in Table 3. It includes the values of lifting the load beside the body and for lifting in front of the body with 0.4 and 0.5 m distance of lever arm. Their corresponding plots of weight, N vs. maximum stress are shown in Figure 5. The calculation of von mises stress is based on equation (1).

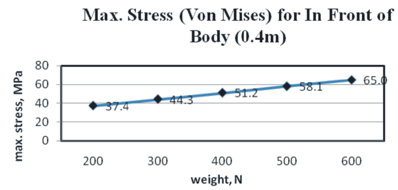
$$s = \sqrt{0.5\left[(s_x - s_y)^2 + (s_y - s_z)^2 + (s_z - s_x)^2\right]} + \sqrt{+3(t_{xy}^2 + t_{yz}^2 + t_{zx}^2)} \quad (1)$$

These results are following the linear trend between the weight and maximum stress for the load lifting beside the body whereas the distance of lever arm for 0.4 and 0.5 m show a higher declined angle. The linearity between these results are slightly increasing from 35° declined for lever arm distance of 0.4 m which further increasing to 45° decline for lever arm distance 0.5 m.

Displacement: Displacement is the movement of a point on the model, measured as when there is a change in position relative to the point's location on the undeformed model. The displacement for two methods of lifting the load which is lifting the load beside the body and in front of the body with 0.4 and 0.5 m distance of lever arm are shown in Table 4. In situation where a person is lifting the load beside a body with 20 to 60 kg which internal load ranging from 2699 to 3065 N, the maximum stress (Von Mises) distributed at 4th and 5th lumbar is 25.2 to 28.6 MPa as shown in Table 3. It is clear that the end plate at 5th lumbar is having the maximum stress. In contrast, a small amount of stress is distributed at 3rd lumbar when the person is carrying load of 20 kg. The maximum stress (Von Mises) for loading the weight in front of the body with 0.4 m distance from the lever arm is from 37.4 to 65.0 MPa for internal load which is ranging from 4001 to 6959 N. It also shows the maximum stress (Von Mises) for 0.5 m distance lever with internal loading between 4327 to 7938 N is increasing steadily downward along the lumbar spine. The value is from 40.4 to 74.1 MPa. Meanwhile, the displacement results show when lifting load beside the body for 20 to 60 kg the distance ranges from 3.16 to 3.59 mm as shown in Table 4. While the lifting load in front of the body with 0.4 m distance from lever arm ranges is further increased from 4.68 to 8.14 mm and for 0.5m distance of lever arm is from 5.06-9.29 mm. The displacement is larger in 1st lumbar followed by 2nd, 3rd and 4th lumbar in an ascending order.



(a)



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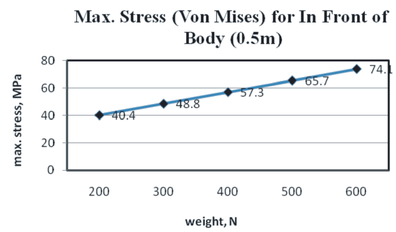


(c)

Fig. 5: Plot of weight vs. maximum stress (von mises) for lifting (a) beside the body (b) in front of the body (0.4mm) and (c) in front of the body (0.5m)

Comparison of Maximum Stress (Von Mises): Figure 6(a) shows the comparison of maximum stress (Von Mises) between the two methods of lifting described in this work. The value of loads is linearly increasing with the maximum stress (Von Mises). From the graph, it is clear that the end point between lifting beside the body compared with lifting in front of body is too far, that is the lifting load beside the body is much better than lifting in front of the body. When the internal loads are increased, the value of maximum stress is also increasing which is illustrated in Figure 6(a). On the other hand, Figure 6(b) shows the comparison of these displacement values for the two methods of lifting that are discussed earlier. The graph shows the larger value when the person lifting load in front of the body compared with lifting besides due to the distance of centre gravity and lumbar centre measurement.

Table 3: Maximum Stress (Von Mises) for lifting beside body, in front of the body with 0.4m and 0.5m

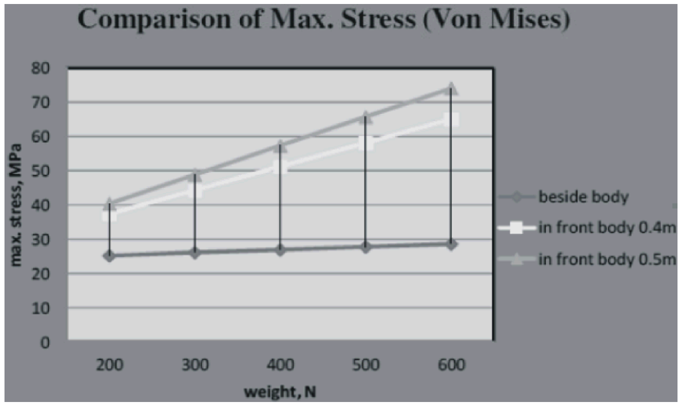
Lifting Position	Weight (Kg)	Internal Load (N)	Stress (Von Mises) (Mpa) Min	Max
Beside the Body	20	2699	0.114	25.2
	30	2791	0.118	26.1
	40	2882	0.123	26.9
	50	2973	0.126	27.8
	60	3065	0.130	28.6
In front of body with 0.4m distance of lever arm	20	4001	0.169	37.4
	30	4741	0.02	44.3
	40	5480	0.232	51.2
	50	6219	0.263	58.1
	60	6959	0.294	65.0
In front of body with 0.5m distance of lever arm	20	4327	0.183	40.4
	30	5230	0.221	48.8
	40	6133	0.259	57.3
	50	7035	0.297	65.7
	60	7938	0.335	74.1

Table 4: Displacement values for lifting beside body, in front of the body with 0.4m and 0.5m

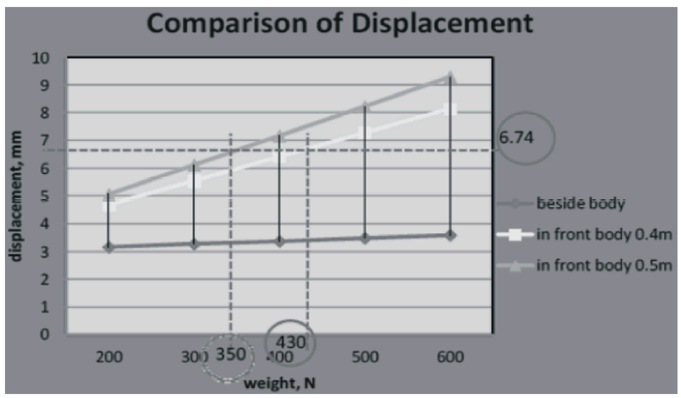
Lifting Position	Weight (Kg)	Internal Load (N)	Displacement (Mm) Min	Max
Beside the Body	20	2699	0	3.16
	30	2791	0	3.27
	40	2882	0	3.37
	50	2973	0	3.48
	60	3065	0	3.59
In front of body with 0.4m distance of lever arm	20	4001	0	4.68
	30	4741	0	5.55
	40	5480	0	6.41
	50	6219	0	7.28
	60	6959	0	8.14
In front of body with 0.5m distance of lever arm	20	4327	0	5.06
	30	5230	0	6.12
	40	6133	0	7.17
	50	7035	0	8.23
	60	7938	0	9.29

Comparison of Displacement: It has been found that employees are not aware of the method or technique of lifting the load used in the industrial sector. According to Larivière *et al*., (2002), the maximum displacement of lumbar spine in all levels between lumbar 1 to lumbar 5 is 6.74 mm [18]. Based on the results, the maximum force that lumbar spine can stand is around 350 N or 35 kg with internal load 5682 N for lifting in front of the body with 0.5m lever arm distance and around 430N or 43 kg with internal load 5702 N for lifting in front of the body with 0.4 m lever arm distance [19].

The present study compares lifting load beside and in front of the body with different lever arm distances. Based on the hypothesis, the internal load depends on the distance of lever arm. It can be summarized that stress and displacement values increase as the internal load applied increases. Repetitive load lifting normally occurs in industrial sector, a kind of exercise and routine performance in their work that involves the lifting far from the body, which can produce low back pain. Farfan [21] estimates that the normal range of strength capability of the erector spinal muscle (internal load) at the lumbar is 2200 to 5500 N [20]. If the person lifts a load of 450 N, the calculation of internal load that the muscle force would reach 5,000 N, which is at the upper limit of most people's muscle capability. In axial compression, failure occurred first in the end plate [21]. Several studies have been conducted to establish safe lifting situations such as by NIOSH [22-25]. It shows that for those under 40 years of age, end plate damage begins to occur at about 3422 N of



(a)



(b)

Fig. 6: Lifting position comparisons of (a) maximum stresses (von mises) and (b) displacements

compressive load on the spine. When the compressive load reaches 6375 N, approximately 50% of those exposed to the load will experience vertebral end plate micro fracture. If the compressive load on the spine is further increased to 9317 N of loading almost all of those exposed to the loading will experience a vertebral end plate micro fracture. To avoid the low back pain problem, a person is advisable to maintain good posture in sitting, standing, walking, lifting object and other daily activities.

From this study, it is confirmed that the internal load applied is larger when a person is lifting in front of the body if compared to the standing erect carrying a weight beside the body. When the object is being carried beside the body, instead of lifting it, the bending moment on the lumbar spine is reduced. This is due to the centre of gravity of the upper body to the centre of motion in the lumbar (lever arm) is minimized. The shorter the level arm for force produced by the upper body and weight of a given object, the lower the loads on the lumbar spine. When a person is lifting an object bends the body forward 35E, the force produced by the weight of the object plus the weight of the upper body create a bending moment on the disc, increasing the loads on the spine. This ending moment is greater than that produced when the person lifting the object beside the body.

CONCLUSION

It can be concluded that the maximum force that lumbar spine can withstand before fracture is around 350 N or 35 kg with internal load 5682N. For lifting in front of body with 0.5 m lever arm distance is around 430 N or 43 kg with internal load 5702 N for 0.4 m lever arm distance. The load acting on the lumbar spine during lifting is a combined result of the object weight, the upper body weight, the back muscle forces and their respective lever arm distance to the disc center. Therefore, the distance of the object from the body is one of the important ergonomic factors. This distance should be considered in designing a container or other things that are often lifted. If a container is compact, a worker can minimize the spinal load moment by keeping the object's center of mass close to their body. If the container must be lifted from the floor and it is too large to pass between the knees, it requires the person to lift the object in front of the knees. This causes a larger spinal load moment than would be the case if the object could be lifted between the knees. This analysis is relevant to the industries especially manufacturing sector in order to provide direction for ergonomist in the modification of jobs for workers who perform manual lifting. For future work, it is suggested that the lumbar spine is built based on directly loaded from the CT scan and biodynamic loading situation with vibration and impact to get better results.

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