**Monocular Vision-Based 3D Human Pose Estimation and Cumulative Damage Assessment in Industrial Workplaces**

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# ***Abstract***

Work-related musculoskeletal disorders (WMSDs) have been a major concern. However, the ergonomic risk assessment often lacks comprehensiveness in considering activity repetition and an effective way to monitor the workers’ postures. Furthermore, they are not integrated due to the cumbersome operational process when using biomechanical analysis software such as OpenSim and the complexity of estimating total lumbar compressive force. To address this issue, we present a method to estimate the total lumbar compressive force based only on image features by applying a state-of-the-art 3D Human Pose Estimation (HPE) algorithm and simplify the operational process with our self-developed ‘parameter *a* method’ for the estimation of total lumbar compressive force with the assistance of a professional ergonomist. Results show that the estimated force and ergonomic injury risk fall within a reasonable range when compared to the results obtained from the previous studies. This finding implies an enormous potential for enhancing the prevention of work-related musculoskeletal disorders (WMSDs) by adopting the proposed method, which integrates technologies, simplifies the operational process, and enables comprehensive ergonomic risk assessment.

*Keywords:*Ergonomics, Computer Vision, Cumulative Damage Assessment, Monocular Vision-Based 3D Human Pose Estimation, Workers’ Safety in Industrial Workplaces

# **Introduction**

Automation is widely introduced in industrial workplaces. However, robots cannot replace human workers due to their unique ability to deal with complex and dynamic environment [1]. Hence, as major occupational hazards which account for one-third of all injuries and illnesses in industrial workplaces in the United States [2], work-related musculoskeletal disorders (WMSDs) deserve great attention. In the United States, the median days of the workers away from work have increased from 8 days in 1992 to 13 days in 2014 due to WMSDs where this issue causes the inefficient project’s progress and the economic burden (i.e., total wage loss of $46 million in 2014) to the injured workers as well [3]. WMSDs are usually caused by working in awkward postures and overexertion in lifting or carrying heavy objects for an extended period. The effects of WMSDs on the muscles, nerves, blood vessels, tendons, and ligaments may cause permanent, irreversible consequences [4], [5].

There are several existing standard ergonomic risk assessments to deal with this problem from an ergonomics perspective, such as Rapid Entire Body Assessment (REBA) [6], Rapid Upper Limb Assessment (RULA) [7], and National Institute for Occupational Safety and Health (NIOSH) Lifting Equation [8]. In general, these ergonomic risk assessments are associated with the human pose estimation (HPE) algorithms using either wearable sensors or multiple-camera vision-based HPE technique as an automated method [9] to resolve the accuracy of manual observation [10], [11] due to the subjective decisions by the designers while doing the assessment.

There are at least three main challenges for the current solutions. First, existing automated methods equipped with REBA, RULA, and NIOSH cannot quantify industrial workers’ physical fatigue that accumulates over time while conducting a series of manual tasks. However, cumulative damage assessment is crucial as sometimes the damage is imperceptible initially but capable of leading to severe irreversible WMSDs after a certain period, even in static postures such as standing or sitting [12]. In other words, by implementing the existing ergonomic risk assessment, some postures are potentially classified into low-risk categories by mistake. Second, current methods to monitor the 3D posture of workers (i.e., wearable sensors and multiple-camera vision-based HPE) are impractical from the perspectives of comfort and convenience for the workers in their daily work [13]. In addition, multiple-camera vision-based HPE technique is not realistic for real-time monitoring at industrial workplaces due to its complex setup [14]. Third, the cumbersome operational process and the complexity of biomechanical analysis limit the practical usage of monocular vision-based 3D HPE in industrial workplaces. To address these issues, our research objective is to integrate a more comprehensive ergonomic risk assessment at the lumbar (e.g., cumulative damage assessment) and a state-of-the-art monocular vision-based 3D HPE architecture (i.e., Videopose3D) [15] to quantify the ergonomic risk of a subject, answering the following research question: Can we effectively introduce this more comprehensive ergonomic risk assessment in industrial workplaces by simplifying the complex HPE set up? Answering this question will potentially lead to a reduction in the cases of WMSDs.

# **Development of the Ergonomic Risk Assessment**

To perform ergonomic risk assessment using the concept of cumulative damage theory, biomechanics analysis is a necessary tool to obtain the kinematics and dynamics information of the subject (e.g., accelerations, forces, and bending moment). *Figure 1.* shows the visualization of the overall pipeline of this research's ergonomic injury risk assessment. The entire pipeline can be decomposed into two models, namely, the biomechanics analysis model and the ergonomic risk assessment model based on cumulative fatigue theory. The details for each model are stated in the subsequent sections below.

(Reserved for Figure 1)

# **Biomechanics Analysis Model**

The biomechanics analysis model is illustrated in *Figure 1(a).* This model aims to obtain the forces (i.e., lumbar compressive force and bending moment about lumbar) by performing the subsequent steps.

# *Step 1: Data Pre-processing*

Since this research aims to perform a vision-based HPE technique, no motion-capture camera (e.g., Vicon camera) is required. All we need is just a regular camera with any frame rate. First, we applied the state-of-the-art computer vision architecture (i.e., Videopose3D) to perform the monocular vision-based 3D pose estimation using our prepared camera, see *Figure 2.* According to the purpose of estimating ergonomic risk at the low back, only the 3D coordinates of the bottom torso, center torso, upper torso, center head, nose, shoulders, elbows, wrists, knees, and feet were extracted. After extracting the 3D coordinates, we filtered out the 3D coordinates of four out of every five frames (i.e., only frames 1 and 6 are extracted between 10 frames) to reduce the noise, see *Figure 3.* More noise might be caused if the frame extraction frequency was too high. However, it might also lose accuracy if the frame extraction frequency was too low. Hence, we experimented to find a reasonable balance point. Please be reminded that the frame extraction frequency may vary due to several factors (e.g., computational power and camera frame rate)

(Reserved for Figure 2. and Figure 3.)

# *Step 2: Estimating Joints Acceleration based on 3-Dimensional Coordinates*

Three frames were required to estimate the linear and angular acceleration based on the central difference scheme [16]. However, one more additional frame was required as an initial condition when starting at the beginning. The reason is explained more intuitively in the following mathematical expression formulated based on the coordinate system in *Figure 4(a).* and the free body diagram in *Figure 4(b).* by taking point B as an example, where Table 1. shows the interpretation of the important symbols in *Figure 4.*

*Linear acceleration:*

(1)

(2)

(3)

Angular acceleration:

(4)

(5)

(6)

(7)

(8)

Same method for ,

(9)

(Reserved for Figure 4.)

Table 1. Definition of each important symbol in *Figure 4.*

|  |  |  |
| --- | --- | --- |
| Symbol of Body Part | Name of Body Part | Location of Center of Mass of Body Part |
| 1 | Forearm | H |
| 2 | Upper Arm | F |
| 3 | Head | D |
| 4 | Trunk | B |

In the mathematical expression of the derivation of linear acceleration, we extracted the position vector r across four frames from frame 0 to frame 3. Frame 1 to frame 3 and frame 0 to frame 2 were used to estimate the velocity of frame 2 and frame 1, respectively, at point B. The acceleration of frame 2 was then estimated using the velocity of frame 2 and frame 1. Subsequently, we only needed frame n-2 to frame n to estimate the acceleration of frame n-1 since the information of frame n-3 had been obtained from the previous case. The same concept applied to angular acceleration as well. In the derivation of angular acceleration, point A was also one of the body joints considered the reference point (i.e., lumbar). The capital letter ‘R’ in (6) was just an auxiliary vector to find the direction of the angular velocity since they shared the same direction, where its magnitude was not essential.

# *Step 3: Estimating Joints Forces using Inverse Dynamics and Parameter ‘a’ Method*

The last step of the biomechanics analysis was the inverse dynamics, namely, to find the lumbar compressive force and the bending moment about the lumbar in this case. Lumbar axial compressive force was affected by the load’s weight, the gravitational force exerted on each body joint, and the inertial force exerted on each body joint. The impact of the load’s weight was complicated in biomechanics since it was not linearly proportional to its actual weight; sometimes, it was causing an impact of up to ten times its actual weight. Hence, we decided to first deal with the forces caused by the gravitational force exerted on each body joint and the inertial force exerted on each body joint before considering the impact of the load’s weight, as shown in (10).

According to the research of [17], the lumbar will experience a 1000N of force for every additional 5kg of load’s weight. While for the bending moment, it is experiencing a 20Nm bending moment for every additional 5kg of load’s weight. When dealing with the bending moment about the lumbar, we picked an arbitrary point as the reference point to define the position vectors from the reference point to the trunk, head, upper arm, and forearm. Similarly for the axial compressive force, we dealt with the gravitational force exerted on each body joint and the inertial moment of each body joint first before taking the load’s weight into account. However, to obtain the inertial moment of each body joint, the moment of inertia of each body segment of interest was required [18], as well as the body parameters for the estimation of the moment of inertia of each body segment (i.e., trunk, head, upper arm, forearm) such as body segment mass, body segment length, and radius of gyration about the sagittal axis, longitudinal axis, and transverse axis respectively [19].

After understanding the relationship between the axial compressive force, the bending moment, and the load’s weight, we were interested in the sum of the axial compressive force and the equivalent force of the bending moment to obtain the total lumbar compressive force. To find the equivalent force of bending moment, the parameter *a* method was introduced, where *a* was equal to the product of the cross-sectional area of the muscles at the lumbar, *A* and the distance from the point of interest to the neutral axis, *y* over the second moment of the area at the lumbar, *I*. The parameter *a* allowed professional ergonomists to fine-tune the equivalent force of the bending moment as a calibration process. We calibrated the model by fine-tuning parameter *a*'s value using the cross-validation technique. The participant was requested to stand upright and fine-tune the value of parameter *a* until the value falls in a reasonable range compared to the results in the following research [20], [21]. The participant was then asked to carry 160N and 230N of load weight, respectively, with his back was bent and straight, respectively. For safety purposes, note that the participant only carried a light object, and we simulated different weights using our self-developed algorithm. The total lumbar compressive forces at 160N and 230N were compared to the results in [21]. The calibration process is done if the total lumbar compressive forces tally nicely with the results in [20]. Otherwise, refer to [21] and fine tune the parameter *a* again. We repeated this process, and eventually, parameter *a* equaled four was found to be a reasonable value. According to (19) and (20), it explained why 920N was added to the axial lumbar compressive force in (9). Note that in this research, we only extracted the peak lumbar axial compressive force and peak bending moment for each repetition of the activity to estimate the ergonomic risk with a higher safety factor conservatively.

(10)

(11)

(12)

(13)

(14)

(15)

(16)

(17)

(18)

(19)

(20)

# **Ergonomic Risk Assessment Model**

The ergonomic risk assessment model based on cumulative fatigue theory is illustrated in *Figure 1(b)*. This model aims to quantify the ergonomic risk by taking the cumulative damage theory into account by performing the subsequent steps.

# *Step 1: Estimating Ultimate Strength Percentile at Lumbar*

In (21), Ultimate Strength Percentile (USP), *S* was obtained from the ratio of the stress of total lumbar compressive force, to the ultimate strength of lumbar, . Referring to the data of blended males and females for specimens aged from 20 to 60 in [22], the average ultimate strength of lumbar, was approximately 6000N. However, effective cross-sectional area, *A* of the lumbar was required in the first place in order to calculate the stress, where it was pretty complicated to estimate a reliable, effective cross-sectional area [23]. Therefore, to simplify the estimation of USP, we used the ratio of forces instead of the ratio of stresses by cancelling off the A referring to (22) and (23).

(21)

(22)

(23)

# *Step 2: Estimating Cumulative Damage at Lumbar*

Substituting the value *S* of USP into (24), the number of cycles to failure was estimated. Then, we obtained the damage per repetition/cycle by taking the reciprocals of the number of cycles to failure. Taking the product of the damage per repetition and the number of repetitions of activities provided us the cumulative damage, *CD* at lumbar as shown in (25) [22].

(24)

(25)

# *Step 3: Estimating Injury Risk Probability at Lumbar*

Lastly, the injury risk probability at the lumbar was estimated by substituting the value of *CD* obtained from (25) into (26) [22]. The cumulative damage and ergonomic risk assessment has been completed until this step [22].

(26)

# **Results**

As mentioned above, manual ergonomic risk assessment observation is impractical due to workforce limitation and accuracy issues (e.g., human error when assessing the postures). However, current automated methods have complex setups and need a comprehensive ergonomic risk assessment. Hence, this research aims to show the reliability of the integration of the monocular vision-based HPE and the ergonomic risk assessment based on cumulative fatigue theory, as well as the convenience of using the monocular vision-based HPE. The findings are stated below:

*Figure 4.* showed the result of the ultimate strength percentile against the repetition of an activity. From the graph, the ultimate strength percentile was nearly constant for a repeating activity. From the result in *Figure 4.*, a constant ultimate strength percentile provided us with a nearly linear relationship between the cumulative damage and the repetition of activity, see *Figure 5.*

(reserved for Figure 4., Figure 5.)

Based on the results shown in Figure 4. and Figure 5., the exponential relationship between the injury risk and discrete time or frame number (i.e., red curve), as well as the relationship of the total lumbar compressive force versus frame number (i.e., green curve) under 50N loading condition was illustrated in Figure 6., where each red dot in the red curve stood for one repetition. The amber-dotted line referred to the force action limit according to NIOSH. In contrast, the blue-dotted line referred to the threshold of the injury risk probability, converted from the threshold of cumulative damage (i.e., 0.03) according to cumulative fatigue theory [22]. From *Figure 6.*, the risk was accumulated all the time based on the total lumbar compressive force using the cumulative fatigue theory.

(reserved for Figure 6. and Figure 7.)

Furthermore, the total lumbar compressive force varied according to the spine angle, compared to *Figures 6. and 7*. Refer to Table 2 in the Appendix for the exact values. By comparing the valley values in *Figure 8.* to the results of zero degree of spine angle in the no-load condition in [20], approximately 200N of deviation was noticed. This result was satisfying to us, and hence, we moved on to comparing the valley and peak values in *Figure 9.* to the force-estimation results of building the level-two and level-four walls using a 160N of Concrete Masonry Unit (CMU), respectively, in [21]. Note that for the 160N loading condition, we were referring to the results of different papers from the no-load condition as cross-validation to avoid bias. Referring to [21], at course two, where the workers needed to work in the most critical position (i.e., largest flexion angle), the range of total lumber compressive force was 2800N to 3500N (we obtained 4050N). Next, we observed that the total lumber compressive force range was 2200N to 3300N (we obtained 3700N) at course four, where the workers were standing straight. The same activities were repeated but replaced with a 230N of CMU, see *Figure 10.* The total lumber compressive force range at course 2 and course 4 were 3900N to 5500N (we obtained 5500N) and 2800N to 4000N (we obtained 5100N), respectively. For both cases under 160N and 230N loading conditions, the difference between our force-estimation results and the results in [21] ranges from 700N to 1700N.

(reserved for Figure 8., Figure 9., and Figure 10.)

# **Discussion**

The results reveal that the biomechanical analysis outcomes fall within the same range stated in previous studies for no-load. In contrast, for 160N and 230N loading conditions, the biomechanical analysis results are larger than the maximum value by hundreds of Newtons of force. For a better understanding in subsequent analysis, we shall interpret the green curve obtained in Figure 6. in the first place. Referring to Figure 7., we can tell that the valley values in Figure 6. in the green curve imply a small-flexion-angle position (i.e., straight back). In contrast, the peak values imply a large-flexion-angle position (i.e., bent back).

Our biomechanical analysis has three different loading conditions (i.e., no-load, 160N, 230N). Under a no-load condition in *Figure 8.*, we have an approximately 200N deviation compared to the results in [20]. A deviation is very typical in statistics; it may be caused by several factors such as different physical conditions of different people, the postures not being the same for different people even though they have tried their best to maintain, or 3D HPE accuracy issues. However, this previous research does not state the variance. Therefore, referring to [21], we notice that around 500N deviation from the average value is still acceptable. Hence, 200N of deviation is in the acceptable range as well. Under 160N and 230N loading conditions, the lumbar compressive force exceeds the maximum value. In this case, we tend to obtain a larger value of force. However, it is in the expectation because in [21], the authors treat the motion sequence as a set of quasi-static postures instead of dynamic postures in their biomechanical analysis. On the contrary, in our research, we take account of the inertial force referring to the free body diagram in *Figure 4.* as the effect of the inertial force plays a significant role [24]. According to [17], we learn that there is an additional 1000N of force to the lumbar for every 5kg increment (i.e., equivalent to approximately 50N) of load. Based on this fact, for instance, if the inertial force causes an additional 500N of total lumbar compressive force, it is equivalent to holding another 2.5kg of load. In fact, there is a critical impact from a 2.5kg load, referring to the difference between *Figure 9.* and *Figure 11.* it makes the valley values from lower than the action limit to higher than the action limit (i.e., amber dotted line) by approximately 500N of force which implies from a low-risk category to a high-risk category.

From the analysis above, our proposed framework provides reasonable and expected results. In other words, the ergonomic risk assessment based on cumulative damage is vital because it classifies the risk into two categories (i.e., low risk and high risk) and quantifies it into a percentage. Moreover, it helps us to understand that the current damage is the outcome of accumulating the previous damage so that we will notice the hazards consciously when doing any activity at the workplace. In addition, we should also recognize the contributions of the monocular vision based HPE and our biomechanical analysis algorithm using parameter *a* method for providing us the satisfying ergonomic risk assessment results. Hence, this research has the same perspective as [18], [19] for the parameters of human body (e.g., segments’ mass, segments’ length, radii of gyration); [22], [25], [26] for the ergonomic risk assessment based on cumulative fatigue theory; [21], [27]–[30] for the conclusion of awkward postures (e.g., larger spine flexion angle) lead to higher total lumbar compressive force, higher risk, and lower productivity; and [13] for the effectiveness of monocular vision-based HPE compared to the existing HPE methods. Overall, the success of the integration of ergonomic risk assessment based on cumulative fatigue theory and monocular vision-based HPE will decrease the case of WMSDs by widely adopted at industrial workplaces.

However, some things still could be improved in our research. Parameter *a* method needs the assistance of a professional ergonomist using his/her professional experience. However, it could be more efficient to a certain extent in terms of the limitation of the workforce. Although we have done the cross-validation to show the reliability of our framework, it is still an indirect proof as we are using a different dataset from those papers. To address these issues, here are some recommendations for future work. We can train a Deep Neural Network (DNN) model so that the machine-learning agent can decide the value of parameter *a* in different situations and resolve the dataset problem by performing the cross-validation using the same and large enough dataset to consolidate the conclusion of this research.

# **Conclusions**

As an effort to reduce WMSDs in industrial workplaces for workers’ safety, we presented an approach to integrate a more comprehensive ergonomic risk assessment based on cumulative fatigue theory and monocular vision-based HPE. Specifically, we used only one camera and one computer to extract the 3D coordinates of a subject. Next, we developed our algorithm and presented a parameter *a* method to handle the biomechanical analysis with the 3D coordinates as the input, where this process required the assistance of a professional ergonomist. This approach provided us with the estimated total lumbar compressive force results, which could be used to estimate the ergonomic risk based on the cumulative fatigue theory. Biomechanical results showed that the total lumbar compressive force was within the expected range, slightly larger than the average values in previous studies after considering the inertial force since we considered the dynamic posture instead of the quasi-static one. These satisfying results helped to provide a reliable ergonomic risk outcome based on the model suggested in previous studies, which in turn declared this integration's success as a less cumbersome and simplified operational process compared to the existing biomechanical analysis software such as OpenSim. To conclude, this research contributes to introducing an integrated approach to make a more comprehensive ergonomic risk assessment potentially get adopted in industrial workplaces, leading to a safer working environment for the workers. With these findings, the authors believe that these are the driving factors to reduce the environmental complexity at industrial workplaces, especially in construction sites this kind of dynamic environments, by understanding as many human factors as we can, which in turn will benefit the workers’ safety, industry’s productivity, and optimize the workers’ performance if they always stay healthy physically.

# **Acknowledgment**

We would like to acknowledge the funding support from Nanyang Technological University – URECA Undergraduate Research Programme for this research project.

# **Appendix**

Table 2. Total lumbar compressive force at different spine angle in one repetition

|  |  |  |
| --- | --- | --- |
| Frame | Spine Angle (degree) | Total Lumbar Compressive Force (N) |
| 0 | 0.000 | 0.000 |
| 10 | 4.770 | 3670.542 |
| 20 | 5.311 | 3672.599 |
| 30 | 4.994 | 3670.875 |
| 40 | 5.872 | 3690.237 |
| 50 | 21.033 | 3815.825 |
| 60 | 60.369 | 4009.774 |
| 70 | 87.975 | 4049.339 |
| 80 | 95.640 | 4059.851 |
| 90 | 81.951 | 4027.405 |
| 100 | 43.887 | 3954.410 |
| 110 | 13.020 | 3761.584 |
| 120 | 3.071 | 3674.923 |

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