The simulation and evaluation of fatigue/load system in basic nursing based on JACK

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Abstract. The potential occupational hazards of job fatigue and musculoskeletal strain may occur in the long-term basic nursing work of nursing staff. Now from the perspective of human factor engineering, combining with the ergonomics simulation software Jack, the metabolic energy expenditure module is used to calculate the work energy consumption, and the Fatigue Analysis module is used to verify the fatigue of nursing staff. Aiming at the process of nursing staff massaging patients in the basic nursing work, the overall design scheme based on Jack simulation model was proposed, each sub-task was detailed, and the relevant parameters were determined. The results show that the design can directly reflect the energy consumption, body condition and fatigue recovery time of nursing staff in each sub-task, so as to avoid the overload of nursing staff.

1. Introduction
With the daily progress of society and the continuous improvement of living conditions, people's attention to health and safety is gradually increasing. Occupational diseases or accidents caused by human problems have subsequently received widespread attention. According to the report of HSE [1] and 1993 WA State Fund [2] claims, over 50% industrial workers have suffered from WMSD. After analysis by Chaffin [3], overexertion of muscle force or frequent high muscle load is the main reason to cause muscle fatigue, and furthermore, it results in acute muscle fatigue, pain in muscles and the worst functional disability in muscles and other tissues of human body. Although the work intensity of nurses is not as strong as the operators in industrial enterprises. However, due to the particularity of the working environment and the work target, nurses have to use their own physical strength to complete the patient's turn and change the sheets. Standing for a long time, bowing your head, bending over, or even crossing the barriers of railings to reach distant objects can easily cause work-related musculoskeletal disorders (WMSDs) [4-6] for nursing staff. A report by the U.S. Bureau of Labor Statistics (2016) showed that 356,910 WMSD-related cases were reported in 2015, accounting for 31% of all cases. The total work time lost was approximately 600,000 hours, and more than one third of the total compensation was allocated to WMSDs. Occupational diseases and their hazards deeply trouble workers. On the one hand, it affects the work efficiency of workers, on the other hand, it seriously affects their health.

Occupational fatigue and work-related musculoskeletal disorders have attracted the attention of domestic and foreign research scholars. A lot of research has also been carried out.
Mina [7] and Wexler [8] have proposed a new muscle fatigue model based on Ca$^{2+}$ cross-bridge mechanism and verified the model with stimulation experiments, which is mainly based on physiological mechanism. Taku [9-10] used a muscle fatigue model based on the force-PH relationship in computer graphics, which can be used to visualize muscle fatigue during work. Aiming at the problem of inability to mechanize operations due to the hilly terrain of northeastern India, Malmqvist [11] monitors the changes in the propagation speed of muscle fiber action potentials based on the power spectrum analysis of the EMG signal and the calculation of the spectral moment. Then the load of the shoulder muscles of construction workers was studied to evaluate local muscle fatigue during work. Yi [12] measured the change in single-arm tension before and after pulling the car and the maximum endurance time (MET), and recorded physical fatigue degree based on the Borg CR-10 ratings of perceived exertion (RPE). Finally, the MET prediction equation for muscle fatigue in single-hand cart operation was constructed. Through the above research, it is found that there are few studies on worker fatigue in the service industry, and the measurement process of related physiological parameters is complicated. It is more difficult to study human fatigue. Therefore, it is very important to find an effective method to assess and predict the risk of WMSD to prevent muscle fatigue.

Therefore, this article intends to combine virtual simulation technology [13-15] in a quantitative manner on the basis of existing research, and take basic nursing work in hospitals as an example. The metabolic energy expenditure model in Jack was used to rationally evaluate the nursing staff's energy consumption status, and then the fatigue analysis tool was used to analyze the nursing staff's fatigue recovery time. Ultimately, it is hoped to reduce the risk of WMSDs for nursing staff, and to provide a reference for improving a safe and healthy working environment.

2. Systematic method research

2.1. Jack software
Jack is a mainstream simulation tool based on the theory of human factor engineering, integrating three-dimensional simulation, virtual human modeling, and human factors ergonomic analysis. With Jack, you can design and analyze the job site, and import the CAD model of your own designed product through its software port.

With the support of Jack, users can precisely define digital humans of different sizes in the virtual environment, and then arrange digital humans to complete designated tasks. Users can also design on-demand work site, environment, product model, etc. Through dynamic simulation, it helps users accurately master the posture and movements of digital humans. Furthermore, users can use different modules of Jack to conduct in-depth analysis and evaluation of the simulated operation process as needed. For example, it can be judged whether the digital person is tired or the posture is comfortable during the work. This information helps to judge the rationality of human factors engineering product design, which lays the foundation for human factor engineering research [16-17]. This paper will use the two modules of energy metabolism prediction and fatigue analysis in Jack for simulation analysis.

2.2. Human fatigue assessment analysis
An important indicator of fatigue is metabolic energy expenditure. At present, the model proposed by Professor Garg [18] of the University of Michigan is widely used in the world. The model divides the total metabolic energy consumption into work energy consumption and posture energy consumption [19-20]. Operational energy consumption -- the whole process of the operation is decomposed into dynamic elements that can determine the energy consumption, and this dynamic element energy consumption is accumulated and summed to obtain operational energy consumption; Postural energy consumption -- calculated by the product of postural energy consumption coefficient, weight and time. Thus, the prediction model of human energy consumption is as follows:

$$\bar{E}_{\text{Task}} = \frac{E_{\text{task}}}{T} = \frac{\sum_{i=1}^{n} E_i + \sum_{j=1}^{n} E_{\text{position}} \times t_j}{T}$$  (1)
\[ E_{\text{posture}} = K_{\text{posture}} \times WT \]  

(2)

Where, \( E_{\text{task}} \) represents the average energy consumption of completing a job, kcal/min; \( E_{\text{Task}} \) represents total job energy consumption, kcal; \( T \) represents the total time needed to complete the task, min; \( E_i \) represents the energy consumption for the \( i \) action, kcal; \( E_{\text{posture}} \) stands for posture energy consumption, kcal; \( T_j \) represents the time needed to maintain the \( j \) posture, min; \( K_{\text{posture}} \) stands for energy consumption coefficient of posture (standing, sitting, bending and stretching are 0.024, 0.023 and 0.028 respectively); \( WT \) represents the operator's weight in kg. The workload that the human body can bear in unit time must be within a certain range, that is, the workload needs to be less than a limit value. The upper limit of metabolic energy consumption proposed by Garg, to a certain extent, has become the standard to judge whether the human body is tired or not. Its calculation formula is as Formula (3). The calculation formula of WB2A is Formula (4):

\[ E_{\text{max}} = 9.7 \times (WB \times WB2A + 0.7 \times WB(1-WB2A)) \]  

(3)

\[ WB2A = T_b / (T_b + T_a) \]  

(4)

Where, \( T_b \) represents the working time of the trunk, \( T_a \) represents the working time of the arm, and the value of WB is shown in Table 1:

| Working time (h) | 0.1 | 0.2 | 0.5 | 1.0 | 2.0 | 8.0 |
|-----------------|-----|-----|-----|-----|-----|-----|
| WB              | 1   | 0.85| 0.7 | 0.5 | 0.4 | 0.33|

Compare the size of \( E_{\text{task}} \) and \( E_{\text{Max}} \) to determine whether the body is tired or not. If \( E_{\text{task}} < E_{\text{Max}} \), the human body is in a state of fatigue and needs immediate rest to relieve its overload operation.

2.3. Energy prediction tool

In Jack, the metabolic energy expenditure module was developed to achieve energy consumption prediction. It can predict the metabolic energy consumption requirements of work based on the characteristics of the staff and the description of simple tasks that include work. It can also intuitively predict the operating energy consumption of workers. Before using this module, you need to decompose the job tasks and enter the relevant parameters, as shown in Table 2:

| classification       | content                             |
|----------------------|-------------------------------------|
| Human attributes     | gender, height and weight           |
| Body posture         | sit, stand, bend and walk           |
| Arm movement         | push/pull, hold and lift            |
| Job time             | total/sub-task time, each posture time |
| Job type             | lifting, carrying and walking       |

2.4. Work fatigue analysis tool

The Fatigue and Recovery Analysis tool evaluates whether a given job has enough recovery time to prevent worker fatigue. This module calculates the recovery time required for a job and compares it to the rest time available. If there is not enough rest time in the work cycle, workers are at risk of fatigue. If the available rest time exceeds the required recovery time, it is assumed that the job provides enough recovery time to avoid fatigue. On the contrary, it is assumed that the work poses a risk of fatigue. At this point, it is suggested to reduce the work load, modify the task frequency, body movement and other parameters.
3. Job simulation design

3.1. System structure design
When assessing the work load of the operator, it is necessary to understand the basic information of the worker, operation process, working environment, working time, etc. Secondly, in the process of virtual simulation, the complex model is simplified, and the workers complete all the activities according to the regulations. Finally, the metabolic energy expenditure and fatigue analysis were used to analyze the work energy consumption and fatigue recovery time during the load assessment of the operation staff. The overall design process was shown in Figure 1:

![Figure 1. Overall design of the simulation system.](image1)

3.2. Model establishment
In the operation of massage for the patient, the nurse should first lift the patient lying on the bed and adjust her posture, and then massage the patient's two shoulders to promote blood circulation. The employees of Hospital A are all Chinese, so the selected objects of virtual humans are set to Chinese. A random sample of 10 female nursing staff obtained their height and weight ranges from 154 to 159 cm and 48 to 55 kg. This range is consistent with the size of the 50th percentile virtual person for women. Therefore, the nursing staff established the 50th percentile virtual person model of women, which is shown in Figure 2. The patient used the 95th percentile basic female staff, whose height was 165.9 cm and weight was 66 kg.

![Figure 2. Design of nursing staff and field environment.](image2)
The general task can be divided into the following subtasks: Subtask 1: It takes 0.5s for the nursing staff to bend over to the patient in front of the bed; Subtask 2: It took 0.5s for the nursing staff to adjust her posture and prepare to lift the patient up; Subtask 3: It took 1s for the nursing staff to lift the patient to a sitting position; Subtask 4: It takes 0.03s for the nursing staff to adjust the proper posture again to stabilize the patient; Subtask 5: The nurse massages both shoulders of the patient, which takes 2s. The job flow simulation model is shown in Figures 3 and 4.

![Figure 3. MEE module simulation process of job flow.](image1)

![Figure 4. Simulation process of F&A module of job flow.](image2)

3.3. Parameter design
When designing the parameters of the model, it is necessary to input the key actions of the flow in order to carry out system simulation. For example, when a nurse bends over a patient's bed, the nurse bends her back into position, which is shown in Figure 5.

3.4. Component relation design
The design of component relationship is very important in simulation. In this simulation model, the nurse's hat and mask should be created through pro-E at the beginning, and then the static simulation model should be created through Jack's 【Import】 function. The imported hat and mask need to set
part relationship with the digital person created in Jack, so as to become a whole with the digital person. The design relationship of the hat is shown in Figure 6.

![Figure 5. Back bending parameter design.](image)

![Figure 6. Component relationship design.](image)

4. Job fatigue analysis

4.1. Analysis of human metabolic energy consumption

Based on the design process and relevant parameters, the dynamic simulation experiment was carried out with the help of Jack. The MEE module was used to obtain the analysis results of energy consumption under various postures, including the total energy consumption and energy consumption of each sub-task. The analysis results are shown in Figure 7.

It can be seen from Figure 7 that the energy consumption of work is 0.069kcal, standing is 0.025kcal, bending is 0.099kcal, and energy consumption of non-sitting posture is 0.095kcal. The total energy consumption is 0.164kcal, and the operating time is 0.06716667min. Therefore, the energy consumption per unit time is 2.437kcal/min. Then, according to the energy consumption prediction
Formulas (3) and (4), the energy consumption is limited to 7.111 kcal/min. By comparing the average energy consumption value, it can be seen that the energy consumption of nursing staff meets the load demand of human body and is in a safe state. However, from the evaluation interface, it can be seen that the energy consumption of nursing staff is at a medium level, and there may be hidden dangers of fatigue and muscle strain. Therefore, it is necessary to deeply analyze the fatigue load of nursing staff.

4.2. Analysis of postural fatigue/recovery time
To test whether nurses experience fatigue while performing basic care and whether they have sufficient recovery time to avoid fatigue, the fatigue analysis tool is being used for an in-depth analysis. This tool can be used to clearly determine the recovery time need and recovery time available for the task. In a cycle of basic nursing tasks, subtasks 5 duration 2s, relatively long, and at the completion of the task, nurse need to grasp the patient, carry on the acupuncture point massage, as well as keep the bending position unchanged for a long time. It is very easy to cause fatigue, so it is necessary to analysis of posture fatigue, recovery time. The result is shown in Figure 8.

![Figure 7. Total energy consumption analysis.](image1)

![Figure 8. Fatigue recovery time analysis.](image2)
In a simulated subtask to finish top four work, nursing staff have enough time to recover before work fatigue, when the simulation runs to the subtasks 5, line is displayed as red, namely the current massage for the patient has made nursing staff get tired. Nursing personnel in the current work is lack of enough recovery time to alleviate fatigue. Because this stage only simulates a cycle of nursing work, the simulation time is shorter, if multiple loop simulation, and as the length of time, the nursing staff will appear muscle strain fatigue phenomenon. So nursing staff should timely adjust the position and rest appropriately after a period of work, which can effectively prevent muscle fatigue.

5. Discussions

According to the simulation evaluation results, although the designed standard work meets the energy consumption requirements, there are still hidden dangers of fatigue. That is, there is a problem with the design of a massage where the nursing staff needs to stabilize the patient and perform acupuncture points. In this link, the nurse needs to keep their bending posture unchanged for a long time. This design is easy to cause fatigue and damage the muscles of the workers. Therefore, through load simulation, this paper determines that the current nursing homework needs further improvement.

This paper applies the energy consumption prediction model and the fatigue recovery time model to the nursing operation process, it not only verifies whether the energy consumption of the operation meets the requirements of the human body, but also finds out the problems that exist during the operation. In turn, it provides load feedback from the operators, turns the nursing operation process into a self-optimized closed-loop system, and makes the work out more rational. At the same time, this article conducts load simulation and evaluation on nursing work, realizes the institutionalization of load evaluation, and further highlights the application value of load evaluation. The fatigue load assessment of the human body is no longer exclusive to certain processes, but has become an important means for all processes to protect the health of each worker. Therefore, load assessment can ensure that all workers work healthily and efficiently under a more reasonable standard operating system.

Second, although the use of simulation methods to evaluate workloads has its shortcomings, compared to other methods of evaluating workloads, simulation methods are relatively objective and efficient. Compared with the method of questionnaire survey, jack-based nursing staff workload assessment can reflect the workload more objectively and avoid the uncertainty of subjective evaluation. However, when using physiological measurement methods to assess workloads, equipment will interfere with maintenance tasks, and will be time-consuming and labor-intensive. Therefore, using simulation-based methods has more practical applications.

6. Conclusions

This article uses simulation method to decompose the action parameters of nurses performing basic nursing tasks. Then use the metabolism and fatigue recovery time module in the Jack to calculate the energy consumption of the nursing staff's work and the required fatigue recovery time, and then realize the assessment of the workload. Compared with other evaluation methods, the simulation method can quantitatively evaluate the workload and is more efficient. Of course, there are some shortcomings in using Jack to evaluate the work of nursing staff, such as the inability to evaluate the impact of environmental factors on the workload. When environmental factors have a greater impact on the workload of nursing staff (such as high temperature or severe cold), the assessment results should be revised. This is also an area that needs improvement in the future.

Acknowledgements

This work was supported by National Natural Science Foundation of China (Grant No. 71671089, 71171110).
References

[1] HSE, Self-reported work-related illness in 2004/05. Technical report, Health, Safety and Executive, http://www.hse.gov.uk/statistics/swi/tables/0405/ulnind1.htm, 2005.

[2] State of Washington Department of Labor, “Fitting the job to the worker: An ergonomics program guideline.” Technical report, RGWEB, http://www.ergoweb.com/resources/reference/guidelines/fittingjob.cfm, 2005.

[3] Don B Chaffin 1987 Manual Materials Handling and the Biomechanical Basis for Prevention of Low-Back Pain in Industry—An Overview[J]. American Industrial Hygiene Association Journal Vol. 48 (No. 12) 989-996

[4] Jin X M, Wang S, Zhang Z B, et al. 2019 Research status of economic burden of work-related musculoskeletal disorders[J]. Chinese Occupational Medicine 46(01) 117-120

[5] Qu Y and Wang Z X 2017 Research progress of work-related musculoskeletal injury biomarkers[J]. Environmental and Occupational Medicine 34(09) 817-825

[6] AlNekhilian Atheer1, AlTamimi Anfal1, et al. 2020 Work-related musculoskeletal disorders among clinical laboratory workers[J]. Avicenna Journal of Medicine Vol. 10 (No. 1) 29-34

[7] Mina Karami, Begoa Calvo, Hassan Zohoor, Keikhosrow Firoozbaksh and Jorge Grasa 2019 Assessing the role of Ca2+ in skeletal muscle fatigue using a multi-scale continuum model[J]. Journal of theoretical biology 76-83

[8] Ding J, Wexler A S and Binder-Macleod S A 2000 A predictive model of fatigue in human skeletal muscles[J]. Journal of Applied Physiology Vol. 89 (No. 4) 1322-1332

[9] Komura Taku, Shinagawa Yoshihisa and Kunii Tosiyasu L 1999 Calculation and visualization of the dynamic ability of the human body[J]. Computer Animation and Virtual Worlds Vol. 10 (No. 2) 57-78

[10] Komura T, Shinagawa Y and Kunii T L 2000 Creating and retargetting motion by the musculoskeletal human body model[J]. The Visual Computer Vol. 16 (No. 5) 254-270

[11] R Malmqvist, I Ekholm, L Lindstrm, I Petersn, R Ortengren, T Bjur, P Herberts and R Kadefors 1981 Measurement of localized muscle fatigue in building work[J]. Ergonomics Vol. 24 (No. 9) 695-709

[12] Yi C N, Li K W, Shi S L, et al. 2017 Modeling the maximum endurance time of static single-hand cart operation[J]. Chinese Safety Science Journal 27(02) 64-69

[13] Wang W, Tang X F and Li Y 2006 Human Fatigue Analysis based on Maintenance Simulation[J]. Journal of System Simulation (S1) 245-248

[14] Lv Z G, Li Y and He H G 2008 Research on Physical Fatigue Recovery Method based on Virtual Maintenance Simulation[J]. Computer Simulation (03) 271-274

[15] Sun R S, Zhang Y T, Liu Z, et al. 2019 Simulation study on workload assessment of civil aviation crew[J]. Chinese Journal of Safety Science 29(12) 7-12

[16] Wu Z F, Zhao H G and Zheng G L 2019 Behavior modeling and simulation implementation of virtual humans in human-machine task simulation[J]. Journal of Graphics 40(02) 410-415

[17] Wang J P, Qin W H and Sun L B 2018 Motion control and walking simulation of virtual human based on biomechanics[J]. Journal of Computer Aided Design and Graphics 30(06) 1110-1117

[18] A Garg, D B Chaffin and G D Herrin 1978 Prediction of metabolic rates for manual materials handling jobs[J]. American Industrial Hygiene Association journal Vol. 39 (No. 8) 661-674

[19] Zhang W Q, Fan S H, Xiong J W, et al. 2018 Energy consumption model and simulation study of handling operations[J]. Chinese Journal of Safety Science 28(10) 38-43

[20] Lv Q W, Fan S H, Zhao L L, et al. 2019 Simulation and evaluation of process standard workload based on MEE/JACK[J]. China Work Safety Science and Technology 15(04) 154-159