

Determining Safety Frontier for Repetitive Labor-intensive Operations: A Theoretical Approach

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Safety management is paramount because it does not only pertain to workers' safety but also impacts productivity, profitability, and employees' morale directly. Every construction project is unique and safety management strategies developed for one project do not necessarily cater to the needs of another project. To achieve a project-based safety management strategy, this research introduces a novel concept of Safety Frontier - the theoretical maximum level of safety that can be achieved in perfect conditions under good management and typical field conditions. The objective of this research is to identify and isolate the factors affecting worker's safety while performing labor-intensive operations and propose a method to determine the safety frontier empirically. A Kinect camera was used to record, a sample dataset which was manually annotated to analyze sub-operations. This research only focuses on body posture as a long-term safety issue but it reports the challenges while determining the thresholds for safety and effect of other factors on the overall safety situation. The determination of the highest level of safety can act as a yardstick benchmark to evaluate effectiveness of safety management strategies. It can assist safety managers to formulate adaptive safety management strategies and help them understand the training and supervision needs at construction sites.

Keywords: Construction Safety, Real-time data, Ergonomics, Kinematic Analysis, Safety Frontier

Introduction

In existing practice, higher level management teams develop strategies for safety management based on their previous experiences or available historical records and implements to a project adopting a top-down approach. Since every project has unique characteristics, the safety management strategies implemented for one project may not be suitable for another project. This scenario indicates that there is a lack of systematic approach to determine project-based safety management strategies because there are several factors that impact on safety, such as project site conditions, laborers' attitude and working behaviors, types of equipment employed, and availability of technology or techniques relevant to that project activities.

Occupational Safety and Health Administration (OSHA) provides a general guideline for construction operations which serve as the minimum safety requirement for a site. But, it is desirable for safety managers to learn about maximum attainable safety level on a construction site. The knowledge of what is attainable will open avenues for the safety managers to set realistic goals and strategies, to identify inefficiencies in current practices and take remedial actions to correct plans before occurrence of any undesirable events. The maximum level of safety will also serve as a leading indicator of safety by distinctly recognizing the outer envelope for safety situation on site. This paper outline a theoretical framework for discovering the maximum level of safety in context of a basic repetitive labor-intensive lifting task.

Background

Ergonomic Analysis

Safety of workers is the prime concern in labor-intensive operations. Statistical data shows that about 80% to 90% accidents in construction are due to the unsafe acts and behavior of construction workers (Heinrich et al., 1980; Helen and Rowlinson, 2005; Salminen and Tallberg, 1996). In order to reduce injuries and fatalities in construction sites, workers' unsafe behavior need to be analyzed in a systematic approach. There are several techniques to study unsafe acts, such as surveys, focus groups, video analysis, and laboratory experiments. Ergonomic work analysis has significant contribution towards risk identification in occupation safety and health management system, which enables to establish a relationship between work context and upcoming damage to physical integrity of the worker (de Miranda Prottes and de Oliveira Andrade, 2012). Barros-Oliveira and Scopel (2012) developed a tool for quantitative analysis of repetitive movement in order to evaluate muscular strain in the upper limbs of workers for poultry, which provides diagnostic support in ergonomics. Ma et al. (2008) developed a framework for dynamic evaluation of muscle fatigue in manual handling work, which helps to study the musculoskeletal disorders (MSD) due to muscle fatigue. They implemented a virtual reality system for the interaction of work with haptic interfaces and optical motion capture system (Ma et al., 2008). AnyBody Modeling system was implemented by Wagner et al. (2007) to quantify the differences between a static and dynamic analysis during the feasibility study of ergonomic analysis for the asymmetric lifting task. Pandey and Vats (2012) identified the most problematic postures in brick making tasks performed by workers through application of the OWAS (Ovako Working Posture Analysis System) method. Martin et al. (2012) employed Microsoft Kinect sensors in order to analyze the ergonomics for lifting tasks performed by workers.

Frontier Approach

Frontier approach is a novel concept in the construction domain. Whereas, several research studies have been conducted regarding "production frontier" in the agricultural domain. The production frontier is considered as a bounding function and is defined as the maximum output obtained from a given set of inputs (Coelli, 1995; Kumbhakar et al., 1991) in which cost function acts as an input parameter and profit function acts as an output parameter. The lower the cost function and the higher the profit function means the production frontier is higher (Coelli, 1995).

In construction domain, Son and Rojas (2011) introduced terminology "productivity frontier" and defined it as the theoretical maximum productivity that could be achieved under perfect conditions. Time and motion study was a basis for the estimation of productivity frontier (Mani et al., 2014). Time and motion studies (Oglesby et al., 1989) are generally conducted to collect and analyze site data (Shahidul and Shazali, 2011). Time and motion studies dtermine the actual time required to accomplish a specific task (Oglesby et al., 1989) by observing performance of well-trained laborers (Finkler et al., 1993).

Mani (2015) adapted a concept of inverse mean-variance optimization, hierarchical analysis, and probability distribution theory in order to yield a robust calculation of the productivity frontier. According to inverse mean-variance optimization, the lower one moves in a hierarchy of structure, the more variability one sees within the contributing components (Mani, 2015). Greater variability is beneficial because it allows for the identification of the shortest theoretical durations, which means highest productivity when time is a measurable metric.

Objective and Scope

The objective of this paper is to present a framework to determine the theoretical maximum level of safety that can be attained on a construction site. The framework focuses on repetitive labor intensive operations and considers only ergonomic and kinematic aspect of labor safety. The paper does not validate the framework but presents practical implementation of the proposed technology and method in a lab setup for a basic lifting operation.

Theoretical Definitions

Safety Frontier: Similar to perfect conditions defined for productivity frontier by Mani et al. (2014), it is the level of safety attained in "*perfect conditions*". This framework defines "*perfect conditions*" as an ideal state where all factors affecting construction workers' safety are at their most favorable levels, such as good weather, highly motivated and trained workers with flawless artisanship, optimal safe utilization of materials and equipment, ergonomically safe posture or poses of workers, no interference from other trades, no design errors, no equipment failures, no fatigue, no injury, no loss of life, and precise understanding of the design intent, among others. Because of *system inefficiencies* inherent to the construction process, perfect conditions are not achievable in the field.

System inefficiencies: In general, *system inefficiencies* imply the loss in level of safety due to factors that are not under the control of a project manager, such as environmental conditions (high humidity, cold or hot temperatures), breaks, workers' health, absenteeism driven by health or family issues, interference from other trades, design errors, behavior and intention of workers, and unsafe or uncertainty conditions due to mechanical failures of equipment, among others. Based upon characteristics of activity or task, the number and type of factors vary. For example, the influencing factors for a box lifting task can be working behavior and health conditions of that laborer, disturbances by other people on the way during hauling, hot or cold temperature, and high humidity.

OSHA Standards: *OSHA Standard* is the minimum safety level required by OSHA standards for a given task and field conditions. *Observed safety* is the level of safety actually observed in the field. It can be below or above minimum level of safety required by OSHA standards. Manual or real-time sensor data might be required to measure and record observed safety, depending upon the factor to be examined.

Good Management: *Good management* is considered here as the best acceptable level of proficiency of project team members.

Typical field conditions: Typical field conditions are circumstances around project site as per industry standard excluding events of natural disasters and labor-union conflicts.

Operational inefficiencies: *Operational inefficiencies* make up the difference between achievable and observed safety. *Operational inefficiencies* refer to the loss in level of safety due to factors that are under the control of a project manager, such as poor sequencing of activities, inadequate and improper or unsafe utilization of equipment or tools, excessive overtime, untrained or unskilled workers, poor lighting conditions, mismatch between skills and task complexity, and carelessness of workers, among others. In case of a box lifting task, if the worker does not know how to properly (ergonomically safely) lift and haul the box and if that worker does not care about working procedure, then these factors can play significant role for operational inefficiencies. These inefficiencies can be minimized by providing training on time. Figure 1 shows the different lifting level of lifting posture.

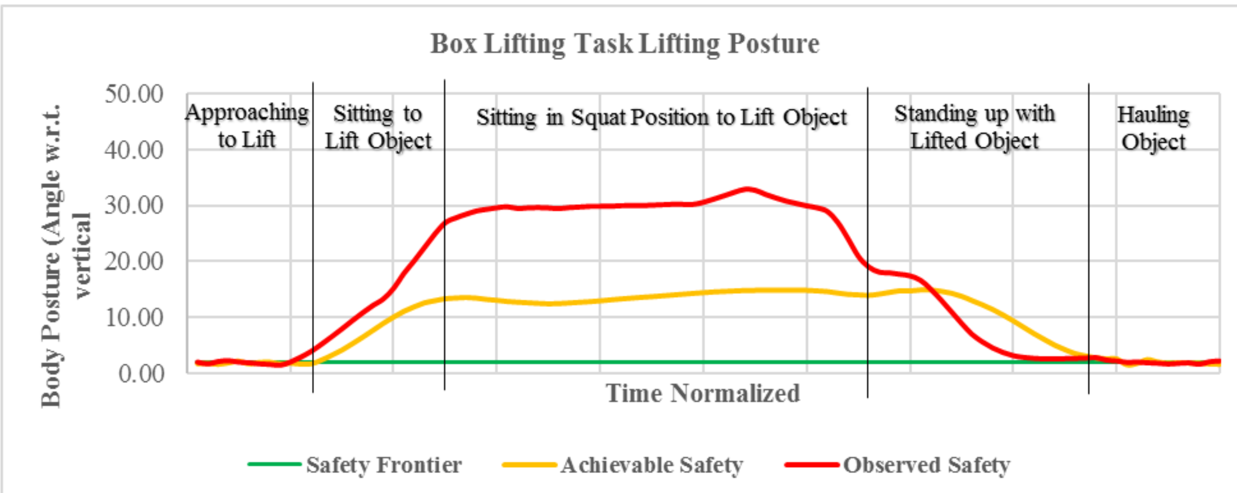

Figure 1: Graph showing safety frontier, achievable safety and observed safety

Theoretical Framework

Figure 2: Schematic workflow of the framework

Operation Analysis

Operation Analysis pertains to hierarchical breakdown of an operation for in-depth study of the parts that build the operation. Hierarchical analysis breaks up construction activities into a multi-level hierarchy of subsystems—i.e., their elemental components (Mani, 2015). The difference between a traditional work breakdown structure (WBS) used in construction and the hierarchical analysis presented by Mani et al.

(2014) used in the proposed framework lies in the level of detail. Several research teams have created a taxonomy of components within a construction project. For example, Tucker and Guo (1993) classified construction activities into area, activity, and task. Ahmad et al. (1995) proposed five levels: project, division, activity, basic task, and elemental motion. Everett and Slocum (1994) broke down construction field operations into seven hierarchical taxonomies: project, division, activity, basic task, elemental motion, orthopedics, and cell. The proposed research goes two levels deeper than Tucker and Guo (1993) since it uses four levels beginning at the activity: activity, task, action, and movement. Tucker and Guo (1993) defined a task as the lowest and simplest level, whereas the proposed framework defines a movement as the lowest level. Hence, only four hierarchy levels are defined in this proposed framework similar to Co-PI's previous research related to productivity frontier (Mani et al., 2014).

- An activity: A collection of tasks that represents the specific units of work with spatial limits and/or dimensions (Tucker and Guo 1993).
- A task: The lowest recognizable work-related characteristic. A combination of integrated tasks makes up an activity (Ahmad et al. 1995).
- An action: A motion that performs a single element of a task. A combination of integrated action makes up a task.
- A movement: The lowest level of the construction operational taxonomy that corresponds to the divisible gestures of the body performing an action.

Kinematic Analysis

Kinematic Analysis using an inverse dynamic procedure is used to compute the relative forces at intersegmental joints on a human body (Zhang and Hsiang, 2008). The human skeleton forms a system of rigid body in which Newton's laws can be applied to distribute forces through the body and analyze the stress at all joints as a result of a load. Simulation of such stress due to a repetitive lifting activity over a prolonged period of time will yield an insight on lifting style and resultant stress pattern. Such kinematic analysis are common in biomechanical research. By simulating for different lifting positions, best position for minimizing stress in each joint can be determined. The combination of such minimal stress positions for all joints will yield a theoretical body posture that will be a combination of minimal stress position for each joint. In reality, such a position might not be feasible for a human body to achieve. So, this position cannot serve as the safety frontier for this particular task. It should also be noted that kinematic analysis can also be done to minimize the stress level in the overall body instead of one joint. But since the goal of the paper is to conduct a joint level optimization, individual simulation to minimize each joints will yield the reference positions for safety frontier. In terms of productivity, the only factor to minimize is time (Mani 2015). But in safety, there is no single factor that will yield safe position for all body joints.

Rotation of the joints can be computed by using the following equation where R is the resultant rotation while α, β and γ are the rotations about x, y and z axis respectively. The multiplication is not commutative.

$$R(\alpha,\beta,\gamma) = \begin{pmatrix} cos\alpha cos\beta & cos\alpha cos\beta cos\gamma - sin\alpha cos\gamma & cos\alpha sin\beta cos\gamma - sin\alpha sin\gamma \\ sin\alpha sin\beta & sin\alpha sin\beta sin\gamma - cos\alpha cos\gamma & sin\alpha sin\beta cos\gamma - cos\alpha sin\gamma \\ -sin\beta & cos\beta sin\gamma & sin\beta cos\gamma \end{pmatrix}$$

Field Data Collection

After simulation data pertaining to workers' posture need to be collected on site. Data can be collected by vision-based techniques, marker-based techniques or depth cameras. The pilot study done for this paper was conducted using a Kinect camera. Kinect is a depth camera and has been used in recent construction research experiments to track worker posture (Ray and Teizer, 2012). Figure 3 shows major joints in human body that are worth tracking for ergonomic analysis (fingers excluded). Kinect can track the skeleton without having to use any sensor mounted on the subjects. But it is limited in the range that it can capture. Kinect can capture skeleton at around 30 frames per second. Figure 3 also shows screenshots from Kinect for standing position, position while performing an OSHA recommended lifting operation and an unsafe lifting operation.

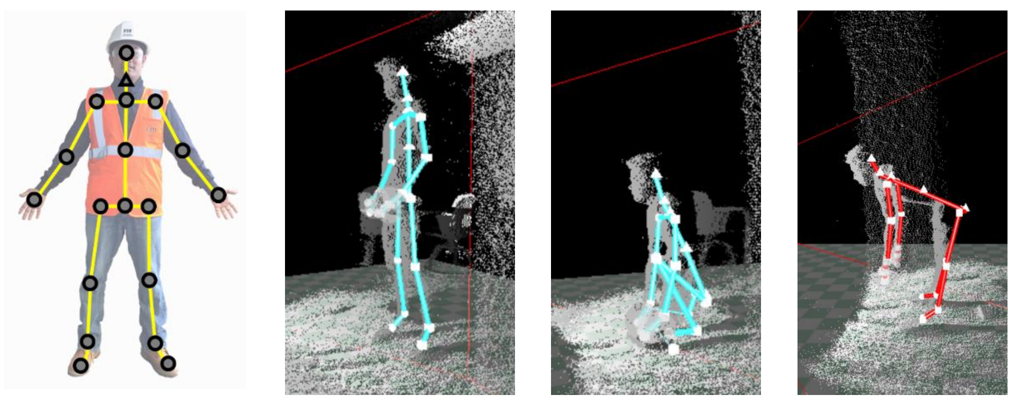

Figure 3: (left to right) Major joints in human skeleton, joints captured by Kinect camera for (i) standing, (ii) good lifting and (iii) bad lifting positions

Data Filtering and Analysis

Skeleton data obtained from the sensors (Kinect in this case) needs to be filtered to remove outliers and extract only the operations of interests for the research. For lifting operations, it is assumed that no ergonomic issues arise while the worker is in standing position. So, only data pertaining to lifting operations need to be extracted for analysis. Data pertaining to each joint needs to be analyzed separately. Figure 4 shows a typical lifting operation. The chart on the right shows the posture data pertaining to torso of the participant. OSHA regulation states that a good lifting posture is a squat position with one knee resting on the floor. By following the posture, it is supposed that stress on the back can be minimized. But, exposure to such a posture for a prolonged period of time can affect the knees and other joints. Such detailed analysis of human posture can only be done through real-time tracking and kinematic analysis.

Figure 4: (left) Screenshot of a lifting operation, (right) posture data pertaining to the lifting operation

Safety Frontier Determination

Safety frontier can, now, be determined by comparing the optimum angle obtained from kinematic analysis to the data obtained from actual site. As mentioned earlier, position that allows minimization of stress in all individual joints might not be achievable or be awkward for a human body. So the objective function will be to minimize the overall stress to the human body. But the position obtained from kinematic analysis need to be cross-validated in the field to assess if such a position is achievable. It should be noted that safety frontier is a theoretical upper threshold and not a practically achievable level of safety. So, the posture that is observed from the field and yields minimal stress to the joints will be considered as the safety frontier. Determination of safety frontier will allow identification of system and operational inefficiencies due to which the safety frontier is not achievable. The causes of operational inefficiency and remedial steps towards eliminating them will pro-actively help safety management to identify potential hazards or hazardous behavior. Safety frontier can hence, act as a leading indicator of safety and governs the upper threshold of safety towards which efforts need to be made. Quantitative methods of obtaining safety frontier from kinematic analysis and field data needs to be researched. Since safety has been isolated from productivity, time has not been considered as a factor for safety analysis. That means, as long as the work is done in safest possible manner, time taken for the work has been neglected in this method. In reality, productivity and cost are critical factors that govern the feasibility of projects. Further extension of this theory needs to incorporate multivariate analysis to determine safety frontier.

Outlook

Knowledge of the outer envelope that governs the safety situation on a construction site can help a construction manager understand the realistic limits that he/she should target on site. Quantification of safety measures in this detail will open new avenues of construction research in wearable technologies and big data analytics. This theoretical framework can be expanded to any type of repetitive construction tasks that does or does not involve human interference. Despite the knowledge of maximum theoretical attainable level of safety, the practical attainable level of safety still remains unknown. Further research in this avenue of research can potentially quantitatively reveal what is attainable on site. Nevertheless, the safety frontier provides a construction manager the comparative basis to evaluate the effectiveness of the safety management strategies and eventually motivate him/her to encourage his/her workers to get as close as possible to the maximum attainable safety.

References

Ahmad, A. N. B, Scott, J. N., and Bradley, D. A. (1995). "Task decomposition in support of automation and robotics in construction." *Proceeding to 12th ISARC on Automation and Robotics in Construction*, IMBiGS, Poland, 407- 414.

Barros Oliveira, P. A., and Scopel, J. (2012). "Quantitative analysis of repetitive movement as a tool for diagnostic support in ergonomics." Work 41 (Supplement 1), 2341-2348.

Coelli, T. J. (1995). "Recent development in frontier modeling and efficiency measurement. *Australian Journal of Agricultural Economics*, Wiley Online Library, 39(3), 21-245.

de Miranda Prottes, V., Oliveira, N. C., and de Oliveira Andrade, A. B. (2012). "Ergonomic work analysis as a tool of prevention for the occupational safety and health management system." *Work*, *41*(Supplement 1), 3301-3307.

Everett, J. G., and Slocum, A. H. (1994). "Automation and robotic opportunities: construction versus manufacture." *Journal of Construction Engineering and Management*, 120 (2), 443-452.

Finkler, S. A., Knickman, J. R., Hendrickson, G., Lipkin, M. Jr., and Thompson, W.G. (1993). "A comparison of work-sampling and time-and-motion techniques for studies in health services research." *Health Service Research*, PMC, 28(5), 577-597.

Heinrich, H. W., Petersen, D., and Roos, N. (1980). *Industrial accident prevention*. McGraw- Hill, Inc., New York.

Helen, L., and Rowlinson, S. (2005). *Occupational health and safety in construction project management*. New York, 157-158.

Kumbhakar, S. C., Ghosh, S., and McGuckin, T. J. (1991). "A generalized production frontier approach for estimating determinants of inefficiency in U.S. dairy farms." *Journal of Business & Economic Statistics*, *American Statistical Association*, 9(3), 279-286.

Ma, L., Bennis, F., Chablat, D., and Zhang, W. (2008, April). "Framework for dynamic evaluation of muscle fatigue in manual handling work." *Industrial Technology, 2008. ICIT 2008. IEEE International Conference, IEEE*, 1-6.

Mani, N. (2015). *A Framework for Estimating Labor Productivity Frontiers*. Ph.D. Dissertation, Lincoln, USA: University of Nebraska-Lincoln.

Mani, N., Kisi, K. P., and Rojas, E. M. (2014). "Estimating labor productivity frontier: A pilot study." *Proceeding to Construction Research Congress*, ASCE, Georgia, 807-816.

Martin, C. C., Burkert, D. C., Choi, K. R., Wieczorek, N. B., McGregor, P. M., Herrmann, R. A., and Beling, P. A. (2012, April). "A real-time ergonomic monitoring system using the Microsoft Kinect." *Systems and Information Design Symposium (SIEDS), 2012 IEEE,* 50-55.

Oglesby, C. H., Parker, H. W., and Howell, G. A. (1989). *Productivity improvement in construction*. New York: McGraw-Hill.

Pandey, K., and Vats, A. (2012). An owas-based analysis of workers engaged in brick making factories, faizabad district of uttar pradesh, india. *Journal of Ergonomics*, *2012*.

Ray, S. J., & Teizer, J. (2012). Real-time construction worker posture analysis for ergonomics training. *Advanced Engineering Informatics*, 26(2), 439-455.

Salminen, S., and Tallberg, T., (1996). "Human errors in fatal and serious occupational accidents in Finland." *Ergonomics*, 39 (7), 980–988.

Shahidul, M. I., and Shazali, S. (2011). "Determinants of manufacturing productivity: Pilot study on labor-intensive industries." *International Journal of Productivity and Performance Management*, 60 (6), 567-582.

Son, J. W, and Rojas, E. M. (2010). "Impact of optimism bias regarding organizational dynamics on project planning and control." *Journal of Construction Engineering and Management*, ASCE, 137 (2), 147-157.

Tucker, R. L., and Guo, S. J. (1993). "Automated needs determination using analytical hierarchical process (AHP) approach." *Automation and Robotics in Construction*, Elsevier, Houston, TX, 39-46.

Wagner, D. W., Reed, M. P., and Rasmussen, J. (2007). *Assessing the importance of motion dynamics for ergonomic analysis of manual materials handling tasks using the AnyBody Modeling System* (No. 2007-01-2504). SAE Technical Paper.

Zhang, Y., & Hsiang, S. M. (2008). A New Methodology for Three-dimensional Dynamic Analysis of Whole Body Movements. *International Journal of Sports Science and Engineering*, *2*(2), 87-93.