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Sequencing labor-intensive production by ergonomic assessment for reduction of work-related musculoskeletal disorders

by

Justin Thomas Schomburg

A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Industrial Engineering

Program of Study Committee:
Sigurður Ólafsson, Major Professor
Richard T. Stone
Jennifer J. Blackhurst

Iowa State University

Ames, Iowa

2011

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DEDICATION

To Mom and Dad - for your unyielding love and support
and devotion to family. To Kristi and Kate - for your love, support,
and the inspiring achievements in your own pursuits.
– I dedicate this thesis.

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ABSTRACT

For labor-intensive environments, feasibility of the production schedule is determined in part by the physical human capacity to complete jobs assigned in the sequence. While the physical effect of the production schedule might be perceptible, it is likely not a decision factor when allocating jobs to the sequence. In the most basic sense, this is an inefficient use of finite human capacity but more severely, the physical factors associated with job processing requirements may be contributing to the development of a work-related musculoskeletal disorder. Identification of musculoskeletal risks is well demonstrated by ergonomic assessment but the challenge of intervention and absent in existing methods is cohesion between the demands of production and preservation of humans in the relative short-term. This thesis will therefore define novel job dispatching rules considerate of cumulative effects and musculoskeletal risk for job processing requirements based on the Rapid Entire Body Assessment (REBA). In this way, the sequence of jobs may function as an ergonomic administrative control that exposes the human processor to the minimal necessary physical burden or risk associated with the production schedule.

CHAPTER 1. INTRODUCTION

1.1 Overview

Scheduling has long served manufacturing and production activities by sequencing jobs in an arrangement necessary to meet a preferred objective. For labor-intensive environments, feasibility of the production schedule is determined in part by the physical human capacity to complete jobs assigned in the sequence. In this arrangement, the scheduler is dependent upon the human laborer to reliably complete processing requirements for each job at a given workstation in order to achieve the schedule. While the physical effect of the production schedule might be perceptible, it is likely not a decision factor when allocating jobs to the sequence.

It necessarily follows that the sequence of jobs in the production schedule may be depleting the productive capacity of the human laborer in unanticipated ways. In the most basic sense, this is an inefficient use of finite human capacity but more severely, the physical factors associated with job processing requirements may be contributing to development of a work-related musculoskeletal disorder. The pathogenesis of such a disorder is credited to repetitive movements or postures, static activities, repeated loading of soft tissues or limited allowance for recovery (Hagberg et al., 1995). More generally, the risk of musculoskeletal disorder is determined by varying physical factors but most notable are frequency, duration, and intensity of work activities (NIOSH, 1997).

Although injuries resulting from physical demands of work have a long history in industry, it wasn't until the use of epidemiologic methods in the 1970s that the extent of the problem was fully understood. These studies provided industry with a systematic method for identifying working conditions with high potential for contributing to the development of a disorder. As human labor provides an organization with productive capacity, it intuitively follows that any interference with this carries associated costs. While workplace injuries may be minor or severe, acute or cumulative in nature, they are all considered preventable and may therefore necessarily have been avoided. In response, research has developed with methods to measure or assess the physical factors of work in the interest of identifying potentially harmful conditions.

For the work-related musculoskeletal disorder of cumulative nature, it is the position of exposure-effect literature that a predictive relationship may be established between the quantification of physical work level (exposure) and the associated internal musculoskeletal effect. By quantitatively representing physical conditions of human labor and simultaneously evaluating elements of the musculoskeletal system, this research seeks to define acceptable versus hazardous working activities in the interest of reducing human physical exposure and therefore musculoskeletal risk. The expected progression of this relationship is depicted in a model defined by Armstrong et al. (1993) and is provided on the following page in **Figure 1.1**.

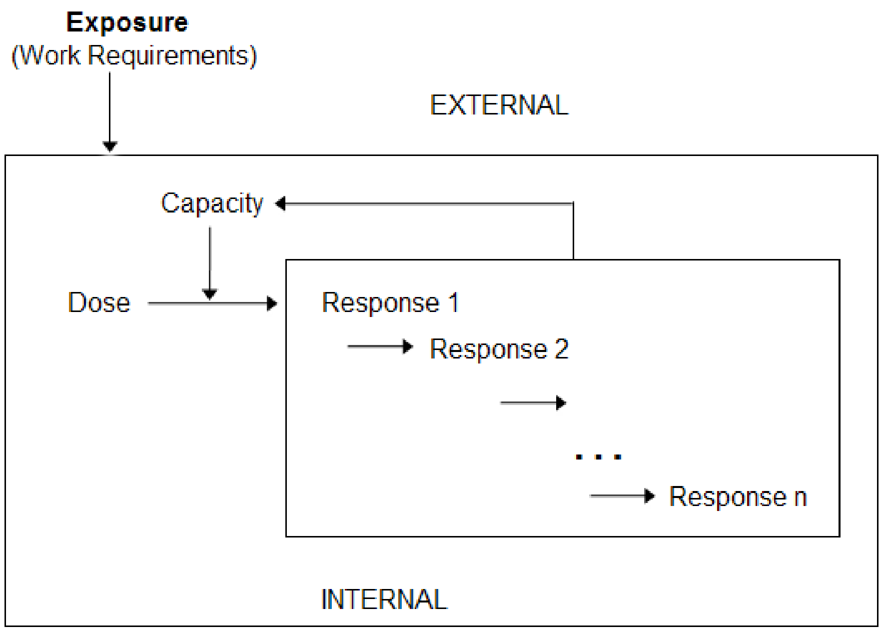

Figure 1.1: *A conceptual model of the relationship between external physical exposure level and internal effect due to successive activities from: Armstrong et al. (1993).*

The challenge associated with research in physical exposure – musculoskeletal effect is found in the developing measurement methods of physical activity but also in the limits of quantifiable understanding of internal musculoskeletal response due to the short-term and long-term exposure pattern. As this understanding relates to the production schedule, there is a need for further understanding with respect to the job sequence and/or the interaction of tasks on a smaller scale. While this is not yet afforded by research, it is a necessary condition for scheduling models to subsequently determine the musculoskeletal risk associated with a production schedule as would be provided by a human characteristic based performance measure.

More traditionally, the response to labor-intensive work has been through ergonomic assessment by identification of physical risk followed by intervention at some level. The methods available for ergonomic assessment of physical work activities are many and within the category of active (direct or observational measure) surveillance techniques. While these methods may vary in the detail level captured, they all seek to provide acceptance criteria to differentiate acceptable work conditions from those of potential risk requiring modification. For the engineer or ergonomist in industry, the choice of ergonomic intervention will likely require more than determining the best available option, consideration must also be given to the means and perception of affected humans to the intervention. In response, research has developed with options to eliminate the identified musculoskeletal risk through engineering controls, as the best response, or otherwise to manage elements of human exposure to the identified risk through administrative controls.

For humans engaged in physical labor, ergonomics is arguably the strongest advocate in production environments and is generally interested in the elimination of musculoskeletal risk by offering interventions as engineering controls. Prescribing intervention(s) for the identified musculoskeletal risk varies widely but may be as basic as the purchase of a new tool for improved posture or more involved and require new equipment or workstation redesign. The extent of intervention responses to working condition enhancement is a significant contribution that is well demonstrated in literature and practice, as few cases exist where ergonomics can offer no alternatives.

However, prospective ergonomic interventions of promising design or those exhibiting strong performance in controlled testing is unfortunately no indication of successful implementation in practice. While the deployed engineering control may offer the best long-term risk resolution it carries the associated cost of time and resources needed to progress through validation stages to demonstrate a benefit. Ultimately, success is determined by the human laborer who chooses to accept or reject the change. This may be found in varying degrees in industry but is also identifiable in research. In a study of labor-intensive work in a furniture manufacturer and suggesting a series of proposed interventions analyzed to improve working postures, human laborers ultimately rejected the suggested interventions for reasons attributed to a piece rate compensation system (Mirka et al., 2002a; Mirka et al., 2002b). It is worth mentioning that not all engineering controls are met with such complication. However, it is the duty of the engineer or ergonomist to strike the balance between the needs of the organization and the necessary level of intervention in order to successively mitigate risk.

Whether based on perception or reality, ergonomic interventions promoting safe work practices are often associated with reductions in productive output. Therefore, any ergonomic response to established practices in production systems is often confronted with the competing interests of human safety versus productivity. This condition continues to receive healthy discussion in literature, found not to be in conflict (Bhatnager et al., 1985) and identified as the obstacle for implementation (Lutz et al., 2001). The burden of addressing this concern may not be a condition in determining research value but is an appreciable hurdle for those in practice. Confronted with multiple stakeholder interests or due to limited supporting resources, the engineer or ergonomist may instead choose to intervene with administrative controls.

Contributions of administrative controls to the identified risk of musculoskeletal disorder generally seek to redistribute labor-intensive activities across a larger number of human processors or to assign recovery periods to the human when no other assistance is available. The basis for these methods is often supported by the operations research framework to incorporate human characteristics into model construction. Afforded by these methods is the application of a strategy provided in the original research but applicable to diverse environments and conditions. In this way, administrative controls are typically less effective in reducing musculoskeletal risk as compared with engineering controls but appeal to practitioners as a general and flexible intervention alternative.

Often omitted from the discussion of administrative controls is a proper context for contribution of these methods and the ability to reduce risk for humans in developing a work-related musculoskeletal disorder. While administrative controls may claim to manage elements of musculoskeletal risk associated with the physical factors of work, the instances of risk continue to exist as do the opportunity for injury. Therefore, the contribution of administrative controls to this problem should be limited to the preliminary stabilization of human physical exposures to identified risks while supporting or motivating the long-term intervention by engineering controls. Ultimately, the requirement for effective administrative controls is the satisfaction of some reduced level of human physical exposure to the identified risk while minimally disrupting the productive demands of the organization.

As the human laborer in production systems is a complex and valuable asset, the pursuit to understand, define, quantify, and preserve this resource affords an almost limitless research potential. In this way, opportunities to preserve the human during processing activities of labor-intensive work may still be identified. Specifically, while the production sequence may possibly be depleting human productive capacity or harmfully contributing to development of work-related musculoskeletal disorders, a proper understanding of these conditions is needed. Combining this understanding with the flexibility afforded by production scheduling and job sequencing, musculoskeletal activity considerate strategies may provide job arrangements that limit the human physical exposure to the otherwise present risk attributed to the production schedule.

Therefore, the premise of this thesis is that the human laborer, assigned to process jobs in the production schedule may be provided relief from risk of musculoskeletal disorder solely through a strategic sequence of equivalent jobs in the production schedule. Based on the identification of any potential for musculoskeletal risk, an ergonomic considerate production sequence might complimentarily support and assist long-term risk reduction efforts. Such a sequencing method would seek to assign the minimal necessary physical burden to the human from the schedule sequence while still satisfying the given customer demand for products. With the successful implementation of a long-term ergonomic intervention as engineering control, sequencing strategies to manage the identified risks would still be allowed to continue but with greater expected flexibility due to elimination of a prior risk.

1.2 Objective

The long-term goal of this research is to reduce the potential for developing a work-related musculoskeletal disorder by managing the cumulative element of physical exposure from successive jobs as allocated in the sequence of the production schedule. The first part in achieving this overall objective is to quantitatively represent the physical activity of distinctive jobs for the entire body by assessing the human processor. The second part is to present decision rules for dispatching available jobs as related to the frequency and risk level associated with repeated, similar physical activities.

1.3 Thesis Organization

The remainder of this thesis is organized in the following manner. Chapter 2 will provide a review and discussion of existing literature to identify a basis for support or gaps and limitations of established methods. Chapter 3 will define a production setting as a foundation for ergonomic assessment of work and subsequent sequencing methods to manage the cumulative element of physical exposure from successive jobs in the production period. Chapter 4 will discuss the opportunity to extend the methods of Chapter 3 to more complex production environments and the associated benefits or limitations under these conditions. Chapter 5 will provide a summary of the methods and discussion of future research opportunities related to the contribution of job sequencing as an ergonomic administrative control.

CHAPTER 2. REVIEW OF LITERATURE

Beginning with the use of epidemiologic methods to study work conditions and the occurrence of injury, both industry and science became interested with an old problem in new ways. With the magnitude of workplace injuries quantified, research evolved to investigate the relationship between human exposure to work demands (physical factors) and the potential for developing an acute or chronic injury also known as mechanical trauma. The manifestation of physical exposure(s) for the human laborer may be a musculoskeletal disorder and carries associated costs that are considered avoidable. In response, research has contributed suggestions for reducing human exposure to physical factors of work with the expectation that fewer musculoskeletal disorders will result. This is accomplished in practice through the application of engineering controls or by risk management techniques of administrative controls.

Review of existing literature well demonstrates the importance of risk elimination by engineering control but supports fewer alternatives for ergonomic administrative controls. The following discussion will therefore present the epidemiologic basis for occupational injuries, efforts to quantify physical exposure as related to developing musculoskeletal disorders, options for ergonomic assessment methods to identify risk, followed by incorporation of human characteristics into operations research based methods. The conclusion of this review will identify the opportunity for a novel administrative control that is appropriately aligned with the needs of industrial practitioners, currently unmet by existing contributions in research.

2.1 Work-Related Musculoskeletal Disorders and Physical Exposure

Humans, as production resources possess skills and subject knowledge as well as physical ability that combined, contribute to productive capacity. It intuitively follows that any interference with productive capacity carries an associated cost to the organization. Therefore, it is preferable from both productivity and human preservation motivations to maintain working demands within the human physical capacity. However, this is not always achievable.

With the use of epidemiologic methods in the 1970s, insight was gained into the relationship of occupational demand (physical factors) on humans and the associated potential for developing musculoskeletal disorders (NIOSH, 1997). The extent of the problem for industry is significant where the incidence of recorded work-related musculoskeletal disorders is observed to be increasing (Hagberg et al., 1995). While workplace injuries may be minor or severe, acute or cumulative in nature, they are all considered to be preventable and therefore might necessarily have been avoided.

The term “musculoskeletal disorders (MSDs) refers to conditions that involve the nerves, tendons, muscles, and supporting structures of the body” (NIOSH, 1997). The conditions for a disorder to be considered work-related are qualified by the World Health Organization: “they may be partially caused by adverse working conditions; they may be aggravated, accelerated or exacerbated by workplace exposures; and they may impair working capacity" (WHO, 1985). Therefore, no region of the human body is immune to disorder but higher occurrence has been found in the low back and upper extremities such as the neck, shoulders, elbows, forearms and hand/wrist (Buckle and Devereux, 2002). However, the insight gained from epidemiology studies has been accompanied by challenges in determining the individual instances of exposure and the magnitude of internal effect that contributed (cumulatively or acutely) to the critical event of musculoskeletal disorder.

The term *exposure* "refers to the external factors of work that produce internal doses (e.g. metabolic demands or tissue loads)" (Li and Buckle, 1999a). Alternative definitions for exposure may be found in literature just as research and science continue to seek a consensus on this condition. What remains is the need to represent entire body exposure quantitatively and ultimately decode the relationship connecting physical exposure to internal musculoskeletal effect. This is supported in a critical assessment of literature considering physical exposure and the lack of quantitative data where Winkel and Mathiassen (1994) recommend level, repetitiveness, and duration as the necessary elements to effectively quantify exposure. Reaffirming this, Westgaard and Winkel (1996) stress the need to consider the expanded physical exposure problem using multiple variables as opposed to prior research that traditionally recommended only reduction in exposure level. In response to the need for more quantitative measures, Wells et al. (1997) propose a metric for equal comparison, in Newtons of force, between ergonomic assessment methods ranging from self-report questionnaires to electromyography.

Field and laboratory studies evaluating the quantitative elements of physical exposure have found mixed results compared with the expectations of earlier research. Using biomechanical analysis to study motor variability between more and less experienced workers in meat processing, Madeleine and Madsen (2009) found that more discomfort was found in low variability, short-cycle activities of the more experienced workers. Their results suggest that efficient techniques developed through experience may not necessarily be of benefit to the musculoskeletal system of the worker. In a laboratory test, Wells et al. (2010) analyzed the functional similarity of three handgrips to determine the extent to which two sequential tasks might function as a working rest. The conclusion of their experiment suggested opportunities to extend the measurement to larger tasks but this is questionable due to the narrowness of scope in the experiment. Provided by the findings in these two papers is a basis for further research to evaluate changes in musculoskeletal activity within a task and between tasks for potential recovery to elements of the musculoskeletal system in the relative short term.

More recently, an apparent shift has occurred for research interested in physical exposure as a predictive analysis to new methods interested in defining the disparity between tasks and varying exposure of the tasks for the human. Early work in physical exposure evaluation suggested reduced levels of physical work under the assumption that lower physical demand for the human is beneficial to the musculoskeletal system. As research evolved, literature now identifies the need for broader consideration of the exposure problem by quantifying simultaneous elements of work activities to effectively assess physical exposure. This new branch of physical exposure research is interested in variation and diversity of exposure (Mathiassen, 2006) as well as effects of duration for musculoskeletal exposure (Wells et al., 2007). Though this research direction is somewhat unique from previous exposure studies, it would appear that it is interestingly closer aligned to the epidemiology findings related to the effects of physical exposure. These effects are specifically, where increased musculoskeletal risk identified by NIOSH (1997) found in the factors of frequency, duration, and intensity, present individually or in combination during work.

2.2 Ergonomic Assessment of Physical Work

The evaluation of physical work activities for associated risk of MSDs is appropriately supported by the ergonomic assessment of humans in industry to quantify the physical level of current conditions. This practice is a preliminary measure to further evaluation of work, including efforts to reduce physical exposure. The methods available for assessment of working conditions may be grouped into passive (review of injury records, discomfort survey) or active (direct or observational measure) surveillance techniques. Regardless of the chosen method, all techniques are generally interested in identifying the activities with the highest potential of contributing to a work-related musculoskeletal disorder.

For the engineer in industry, various assessment methods afford many options but selection will likely be influenced by the physical working conditions of interest and resources available to conduct a survey. As there is no known assessment method to date that can satisfy all requirements of any user, Winkel and Mathiassen (1994) in **Figure 2.1** on the following page, identify the unavoidable compromises associated with available techniques.

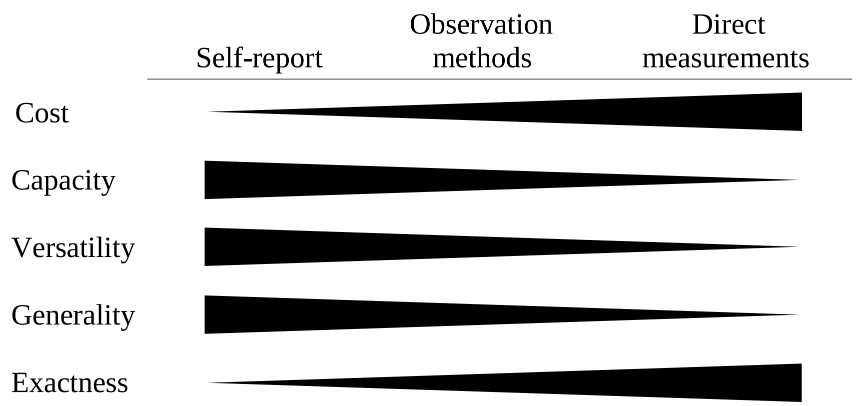

Figure 2.1: *Methods and associated compromise for ergonomic assessment of physical work from: Winkel and Mathiassen (1994).*

Therefore, while a direct measurement method such as the NIOSH Lifting Equation (Waters et al., 1993) is not relatively costly and provides a specific recommendation, it requires detailed measurements and is useful in limited conditions. Other direct measurement methods may deploy bioinstrumentation device accompanied techniques such as electromyography, accelerometry, photogrammetry or magnetic-based motion systems. However, these are costly options for obtaining reliable data found more often in laboratories than in field studies.

A convenient alternative to direct measurement methods for both the practitioner and researcher is the use of observational ergonomic assessment. Specifically, methods analyzing working postures are regarded as reliable tools through validation in research and practice. In one of the first formalized methods, Corlett and Bishop (1976) record perceived discomfort at locations of the body to indicate a precursor of disease or presence of damage in a technique evaluating worker comfort scores before and after work modification. Closely following this method, Karhu et al. (1977) presented the Ovako Working Posture Analysing System (OWAS) for sampling discomfort of work postures measured by frequency and duration to conclude with recommended corrective actions. These more recognized initial methods for assessing postural discomfort formed the basis for the next phase of postural assessment methods focusing on posture and work-related musculoskeletal risk.

When the combined elements of force and posture that deviate from normal are found in increasing instances, so too is the risk for musculoskeletal disorder to develop. Evaluating conditions such as these may take many forms but the end result must provide a context for identifying any physical conditions of potential harm. The Rapid Upper Limb Assessment (RULA) evaluates the potential for work-related upper limb disorders by recording working postures for upper extremities to obtain a score of associated action level to indicate the potential for MSD (McAtamney and Corlett, 1993). Continuing the focus on musculoskeletal exposure to repetitive movements of the upper extremities, Colombini (1998) provides the basis for a new assessment method described by Occhipinti (1998) as the concise exposure index (OCRA index) that mimics the structure of the 1993 NIOSH Lifting Equation but uses task frequency, duration, and multipliers such as force, posture, and recovery to recommend an appropriate number of activities as compared to current levels. In an expansion of the strengths of RULA, Hignett and McAtamney (2000) present the Rapid Entire Body Assessment (REBA) to record working postures for the primary segments of the entire body assigning a score of recommended action level according to the musculoskeletal risk potential of the activity assessed.

As noted earlier, compromises are necessary when choosing an assessment method and the previously reviewed methods offer useful advantages but carry associated limitations that are identified by Li and Buckle (1999b) accompanied by analysis of alternative posture-based assessment methods for identifying musculoskeletal risk. It is also beneficial to acknowledge the points of opposition to observational ergonomic assessment that generally point out the lack of specificity needed to appropriately identify and resolve musculoskeletal risk. However, this criticism is misguided in premise and is confronted by McAtamney and Corlett (1993): "if a comprehensive assessment of the workplace is to be made, RULA should be used as part of a larger ergonomics study covering epidemiological, physical, mental, environmental and organizational factors." Finally, studies evaluating the use of observational assessment have encountered variation among observer ratings but identified through the results that observers were still able to discriminate between levels of risk, supporting the usefulness of these assessment methods in practice (Winnemuller et al., 2004; Jones and Kumar, 2007).

2.3 Sequencing and Scheduling

Difficult to find in literature is the evaluation or discussion of the administrative activity of production scheduling and the potential for having a larger impact on human physical capacity to complete work than previously recognized. Therefore, it is necessary to consider the function of sequencing and scheduling as applied in literature to identify techniques that would support efforts to preserve this valuable human processing capacity.

Due to the prevalence in practice and contribution to research, the study of sequencing and scheduling problems remains a relevant topic in literature. Scheduling, as a decision-making function, has traditionally been interested in resource allocation and/or job sequencing (Baker, 1974). Whether explicitly known or implicitly understood, the production scheduler allocates the sequence of jobs and necessary resources based on a preferred or predefined performance measure. In scheduling models this performance measure is represented by the objective and may be complex or simple but shall serve as the criteria determining the success of the schedule (French, 1982). As a means for evaluating or demonstrating a sequencing technique, the single-machine sequencing problem or single processor model is often used. In this model, all jobs are routed through a single resource or machine independently and is considered the most simplified scheduling case.

Scheduling research motivated by production conditions in practice has expanded upon the single machine model by investigating levels of complexity. As a contribution to many production systems, single machine models may be used to address a bottleneck station or in combined effort, assist decomposition methods of more complicated systems (Pinedo, 2005). When addressing stochastic characteristics of single-machine sequencing problems, Van Oyen et al. (1999) discuss the opportunity to formulate the problem as deterministic to achieve an equivalent solution, suggesting this approach as a significant contribution to stochastic problems. Using of the single processor model in complex environments provides that the contribution of a simplified model is not necessarily limited to simplified environments.

Production systems are also often confronted with the challenge of managing product variations and batching requirements related to set-up times and cost. In Webster and Baker (1995), techniques for addressing such conditions found in practice are evaluated within the context of a single machine model. Therefore, whether functioning to directly represent conditions in a production system or partially assisting the solution for complex environments, the single processor model is an agile tool with applicability to a wide range of scheduling problems.

The contribution of research to the core of the single machine model is noteworthy, but this is only a sample of available opportunities this model might address in future research (Maxwell, 1964). At the root of all efforts is scheduling theory and the need to quantitatively represent conditions of interest through model construction. As an indication of effectiveness, schedule performance measures provide a quantitative assessment for a given schedule. While the resource in a production system or schedule model, whether it is machine or human, directly determines the system performance, there are few instances in literature where resource characteristics influence job allocation during schedule creation or receive representation in model construction. While such a practice is not uncommon in research, it highlights an opportunity to advance scheduling models with the incorporation of physical human characteristics. As a result, there is a unique opportunity to advance the interdisciplinary research of ergonomics and production scheduling to administratively preserve the productive capacity of human labor (Lodree et al., 2009).

2.4 Job Rotation Schedules and Work/Rest Scheduling

The most established instances of operations research techniques intersecting with ergonomic methods are found in the literature of job rotation and work/rest schedules. Unique from other resource allocation models, these methods include human characteristics in model performance measures. For the instances in literature where these methods address human labor, consideration is generally directed at human preservation as related to potential of developing a musculoskeletal disorder or physical or mental fatigue. By drawing from ergonomic research evaluating human response to working demands, these methods apply administrative controls through operations research formulation with the expectation of reducing the effect of potentially harmful working conditions. While these techniques are extended to conditions other than occupational risk, review will be limited to literature considering humans involved in labor-intensive working environments.

As a means for distributing humans across processing requirements in the workplace and aligning physical capacity with processing demands, job rotation schedule literature and applications in practice have demonstrated the extent of this method to manage exposure to musculoskeletal risk. Carnahan et al. (2000) develop job rotation schedules to distribute workloads using integer programming and genetic algorithm approaches where four gender capacity workers are allocated by a measure of Job Severity Index (JSI) to four operations involving lifting. Building upon the work of Carnahan et al. (2000), Tharmmaphornphilas and Norman (2004) use inter programming to find acceptable rotation intervals using measures of Job Severity Index for lifting tasks and Time-Weighted Average (TWA) for noise exposure to evaluate the quality of job rotation. As an evaluation of industrial manufacturers by survey, Jorgensen et al. (2005) found that the prevalence of job rotation as a strategy to manage work-related MSDs was reportedly higher than results of previous inquires, however, the structure (based on ergonomic assessment) of intervention strategies was not collected. Finally, as criteria for job rotation, the extent to which jobs differ is expected to affect the magnitude of relief available to the worker experiencing job rotation and was studied by Wells et al. (2010) testing isometric contractions of three handgrips in alternate combinations.

With similar human preservation motivations, review of literature in work and rest provides for an expansive topic of research interested not only in rest pauses for production environments but also for the broader sense of work and off-work periods. Relevant to this review are those methods addressing human capacity during production periods by assigning periods of rest for physical recovery in the short-term. The study of work and rest typically considers variations in fatigue (general body, muscular, mental) and the subsequent recovery value of rest and is thoroughly reviewed in Konz (1998a,b).

As the human in a production system is influenced in varying degrees to conditions of scheduled work, so vary the suggestions of methods prescribing and evaluating rest periods in literature. Responding to the otherwise general statements of existing work regarding the value of rest schedules, Elion (1964) proposes an analytical model based on a production rate function to quantitatively determine the proper instances and duration of rest. In an industrial experiment measuring productivity and worker preference, Bhatia and Murrell (1969) find that the more frequent 10-minute rest break increased production from the baseline and was "unanimously preferred" to conclude: "rest pauses should operate to make work easier and not merely to make it possible". However, determining sufficient rest (fatigue) allowance is a larger problem than frequency and duration decisions where physiological, psychological, or environmental causes are the main factors but not yet fully understood as to the influence during production periods (Mital et al., 1991). The benefit of rest periods during physical work suggests viable relief for affected workers however; the inability to quantitatively support the contribution of relief continues to be a barrier for implementation.

In practice, the significance of job rotation or work/rest scheduling is difficult to ascertain due to limited supporting empirical evidence in literature. Both methods offer administrative controls for identified work-related musculoskeletal risks but stop short by contributing little motivation to pursue solutions addressing the root of risks through engineering controls.

The associated limitations for job rotation schedules receive minimal discussion in literature and are often omitted conversations in others. The conclusion of a job rotation study for refuse truck crews indicated, “job rotation might be less effective than expected,” where rotation between driver and collector reduced physical workload for the collector but increased physical workload for the driver as compared with driving or collecting only (Kuijer et al., 2004). A critical review of job rotation schedules suggests the supporting activity of cross-training necessarily occur prior to implementing most job rotation schedules, a requirement that cannot be avoided in practice. Observing that workers in production systems are inherently different, Wirojanagud et al. (2007) use mixed integer programming and General Cognitive Ability (GCA) to represent worker differences as a workforce management tool to minimize the often high associated cost of cross-training. Gel et al. (2007) stress the care that should be taken when implementing cross-training in Work-In-Process (WIP) constrained systems as hierarchical skill sets of workers make them more or less available to assist other stations.

The associated limitation of work/rest schedules is evident in the lack of consensus among literature related to recovery potential of rest and worker satisfaction or preference in studies. Literature in this area often prescribes the rest schedule be accompanied with supervised mandates to achieve compliance, a formula more often associated with failure than success. For some laboratory and semi-field studies in industry, rest breaks were not shown to convincingly reduce physiologic fatigue (Mathiassen, 2006). As the focus of modeling rest is devoted to construction of rest periods, work content between periods has not been considered in literature for harmful effects or opportunities to reorder the sequence of jobs (Lodree et al., 2009).

2.5 Summary

There is a tendency among literature and equally identifiable in the perceptions of practice that a response to identified work-related musculoskeletal risk may appropriately be satisfied by engineering control or administrative control but not efficiently through both or by a combination of complimentary elements from the strengths of individual controls. This may be partially attributed to the often cumbersome elements found in both engineering and administrative controls. An intuitive review of this condition does not find a basis for support and appeals for a risk management technique that is appropriately defined relative to the ability to preserve or protect humans from the identified risks.

The findings in epidemiology have benefited from retrospection and narrow scope, considering only specific body segments. This has served industry and literature well by defining the basis for motivating resolution of occupational risk. Based on this understanding is the need to further investigate and define the relationship of exposure-disorder during workplace activities. Related to this is the need to quantify the benefit or risk associated with processing successive jobs in production.

As the literature considering physical exposure of humans to workplace factors has developed, so too has the scope of this problem. With initial contributions to literature suggesting that instances of indentified risk and measured activity would benefit from reduced levels, methods following this work have yet to define acceptable limits for working conditions related to individual body segments or the entire body.

Similar to the challenge of measuring physical exposure are the various methods for ergonomic assessment of humans as identifiers of risk and predictors of work-related musculoskeletal disorder. Numerous alternatives may be found in literature; each recognized for strengths or useful qualities and associated limitations.

Though the challenges confronted by these research methods are easily identified, opportunities for advancement may be found in the instances where operations research discipline has intersected with the ergonomic study of humans in the workplace. The potential for this research is found in the flexible arrangements afforded by scheduling strategies and acceptance of human characteristics in model construction. The noteworthy instances of intersection receiving attention thus far are job rotation and work/rest schedules. However, the limits of these methods are partially related to the extent of quantification for humans in production systems by ergonomic and biomechanical research. Therefore, as the quantitative understanding of the human advances, it is expected that the consideration of causal relationships in developing work-related musculoskeletal disorders will follow. Such advances would directly contribute to scheduling research developments and likely lead to more rigorous models.

In this way, by strategically combining an ergonomic assessment of human activity to identify musculoskeletal risk with the administrative activity of production scheduling, an opportunity for a novel administrative control may be identified. The contribution of administrative controls should be directed at the stabilization of identified risks while promoting and assisting the long-term resolution by engineering controls. The challenge for effective administrative controls, but absent in existing methods, is therefore to find cohesion between the needs of production and the preservation of humans in the short-term. Such a method would be both aligned with the demands of production and the interests of the ergonomist.

As a method that has been validated in practice and is well regarded in literature, REBA offers a starting point assessment of working postures and forces for the entire body. Appealing as an “out-of-the-box” accessible and noninvasive observation method, the REBA assessment concludes with a score associated with a level of risk and a recommendation severity related to necessary action. By introducing the understanding gained by the REBA assessment into a sequencing strategy for the production schedule, potentially harmful exposures may be managed by the sequence. In this way, such a method would seek to arrange work activities or jobs about the human rather then allocating the human about workstations to avoid physical exposure as advocated in alternative methods.

Based on this identified opportunity, Chapter 3 will define a production setting as a foundation for ergonomic assessment of physical work that will then be used in subsequent job sequencing strategies to manage the cumulative element of physical exposure from successively scheduled jobs in the production period.

CHAPTER 3. ERGONOMIC DECISION RULES FOR JOB DISPATCHING

When confronted with a workstation and job processing requirements that potentially exceed human physical capacity, the risk to the musculoskeletal system is identified by NIOSH (1997) to be found in the factors of frequency, intensity, and duration of physical activity. For conditions of identified musculoskeletal risk, the production sequence affords the opportunity to allocate jobs in any fashion depending on characteristics of interest and their associated priority. Therefore, the purpose of this chapter is to first, construct a production problem setting where a human processor is the predominant resource at a single workstation. This will then provide the conditions to apply an ergonomic assessment of human musculoskeletal activity during job processing. Based on the defined problem setting and musculoskeletal activity level, decision rules for dispatching available jobs will be presented that are considerate of repeated instances, similar physical activities.

3.1 Problem Setting

The problem setting will consider a single workstation for the following evaluation where a human is the predominant resource and is exposed to dynamic physical activity for the processing requirements to complete jobs assigned in the production schedule. This human processor may be a specialist or generalist and is assumed to be in good physical condition but is exposed to the same general physical work content that differs according to product variation within and across production periods. The general activities within jobs processed at this workstation require lifting, orienting, and positioning, part transfer, pushing and pulling through postures under load and deviating from normal. For all jobs, the human is standing upright and engages the lower body for stability during physical exertions or to initiate movement with the product.

The processing activities for jobs at this workstation comprise multiple product types varying by component quantities and overall feature geometry. The processing steps required to complete jobs range from the relative basic products with fewer tasks than standard products followed by even more complex processing tasks in customized products. Therefore, the human is directed by the production schedule and ultimately by external demand in defining the set of jobs requiring processing within any given production period.

While there may be many independent products within the range of product offerings, it is acceptable to group jobs of similar processing requirements into product families for representation. Therefore, it is not uncommon for all product offerings experienced at a workstation to be represented by a much smaller number of distinct groups. For this problem setting, six product families will be described to provide a context for the production environment and use in subsequent dispatching methods. The first product family represents the relative smallest jobs according to dimension and mass of components with relative basic processing requirements. The second product family represents jobs of larger dimension and mass components but with basic processing requirements similar to the first product family. The jobs of the third product family are similar to those of the second product family in component dimensions and mass but involve more advanced processing requirements. The fourth product family contains jobs with similar component dimensionality and mass to jobs of the second and third product families but differs by requiring the most specialized processing for product customization. The fifth product family represents the relative largest jobs according to dimension and mass of components but involves basic processing requirements similar to jobs of the first and second product families. The final product family represents jobs similar to those of the fifth product family by component dimension and mass but differs by requiring highly specialized processing requirements for product customization similar to that of the fourth product family. These product families are provided in **Table 3.1** on the following page with corresponding average process time and distribution of external customer demand to provide a context for evaluation within a given production period.

Table 3.1: *Product family descriptions for single workstation with processing times and external customer demand distribution*

Product family, f_j, description	**Process Time**, p_j (*no units*)	**Demand** Triangular Distribution T_j (*min*, *mode*, *max*)
f_1 - small scale components, low processing complexity	4	T_1 (0, 12, 28)
f_2 - medium scale components, low processing complexity	4	T_2 (0, 8, 14)
f_3 - medium scale components, standard processing complexity	6	T_3 (0, 10, 25)
f_4 - medium scale components, high processing customization/complexity	8	T_4 (0, 6, 18)
f_5 - large scale components, low processing complexity	6	T_5 (0, 7, 15)
f_6 - large scale components, high processing customization/complexity	10	T_6 (0, 5, 12)

For the purposes of evaluating the behavior of the dispatching rules presented in this chapter within the context related to the conditions of dynamic customer demand, random samples were generated from the triangular distribution of **Table 3.1**. Therefore, provided in **Table B.1** of **APPENDIX A** are 30 samples from each of the product family demand distributions that represent the potential external customer demand within any given production period.

The processing requirements for jobs in each of the product families are associated with varying levels of musculoskeletal activity. For some product processing, high-level physical exertions are required and though this condition is not necessarily preferred it is considered unavoidable given component characteristics and the product design. To better define the physical factors of activities within product families, the Rapid Entire Body Assessment (REBA) contributes a score representing entire body activity level. As an active surveillance technique, this assessment method will identify any instances of potentially harmful musculoskeletal activity for the human at the workstation.

For each of the product families, a devised REBA score will represent the assumed musculoskeletal activity level required for processing respective jobs to completion. In this way, the activity in all product families involves degrees of trunk and neck extensions with neck twisting for jobs of the most specialized processing requirements. The lower extremities (legs) during processing are bilateral with flexion for the majority of processing periods but when more advanced processing requirement jobs are initiated, instances of unstable postures may be found with higher degrees of leg flexion. Postures for the upper arms, lower arms and wrists during processing involve varying degrees of flexion depending on component features and dimensions. The product mass ranges from 5-10 kg for the relative smallest component jobs increasing to greater than 10 kg components requiring moments of shock or rapid buildup of force during lifting or transfers. When handling components, coupling is good or acceptable when processing requirements are basic but as overall component geometry becomes increasingly complex with specialized processing, coupling becomes poor or unsafe. The overall activity of the human during processing is dynamic but instances of repeated small range actions are present in some jobs as well as instances with an unstable base and/or movements of rapid large changes in posture during pushing or pulling. The final REBA score for each product family is provided in **Table 3.2** on the following page along with the associated risk level and action recommendation for intervention. The detailed REBA assessment is provided in the REBA scoring sheets for each product family in **Figures A.1 - A.6** of **APPENDIX A**.

Table 3.2: *REBA postural analysis scores for dynamic musculoskeletal activity within product families*

Product family, f_j	Product family postural asessment, $REBA_j$	$REBA_j$ Score	Risk Level	Action Level	Action
f_1	$REBA_1$	4	Medium	2	Necessary
f_2	$REBA_2$	5	Medium	2	Necessary
f_3	$REBA_3$	7	Medium	2	Necessary
f_4	$REBA_4$	10	High	3	Necessary soon
f_5	$REBA_5$	12	Very High	4	Necessary *NOW*
f_6	$REBA_6$	14	Very High	4	Necessary *NOW*

With the insight gained from the results of the REBA assessment, activities with high potential of contributing to musculoskeletal disorder have been identified. For the activities of high levels of risk it is critically important that ergonomic interventions be pursued. The deployment of interventions as engineering controls offer the best long-term solutions, however, this may not be immediately available. The current state in this problem setting is therefore in need of alternatives for risk reduction. Affording the most timely response without significant supporting requirements and able to limit the human physical exposure to repetitive high risk jobs to reduce the otherwise potential musculoskeletal effect is the production schedule using a strategic and ergonomic job sequence.

It is here that the divergence from previous sequencing and scheduling strategies may be presented. For the traditional scheduling problem, the single processor model has been used to evaluate job allocation decisions related to productivity related performance measures. The possible consequence of job dispatching decisions has for long been overlooked but is represented in this problem setting by musculoskeletal activity level and associated musculoskeletal risk level for the human processor. The sequence determined in the production schedule defines the musculoskeletal exposure pattern from jobs that the human will process. The potential risk associated with the schedule is found in the cumulative effect from successive jobs of similar physical demand. Therefore, with awareness of the musculoskeletal activity level associated with available jobs to be scheduled, the sequence is able to manage the risk factor of frequency related to cumulative physical exposure. The risk factors of intensity and duration are not assumed to be influenced by the production sequence as they are inherent requirements related to product features and defined work instruction.

For the workstation described in the problem setting, the single processor model will be applied to represent the processing activities and will use the following notation. Each job j corresponds directly with a product family f_j representing the group of jobs with similar processing requirements. In this problem it is assumed that $f > 1$ at all times. For any production period, there are n of jobs j $\{j_1, j_2, j_3, \ldots, j_n\}$ to be processed through a single workstation by a human resource designated as M_1. The length of time that job j requires at M_1 is defined as the processing time, p_j. Jobs in the schedule become available for processing at their ready time or release date, r_j. The time at which job j must complete processing at M_1 is defined in the schedule as the due date, d_j.

The following assumptions are applied to the problem setting and commonly associated with the single processor model:

1. At time zero, *n*, independent single-operation jobs are available for processing.
2. Setup time for each job *j* is considered inherent to the processing time and is not affected by the job sequence.
3. Job attributes (process time; p_j, ready time; r_j, due date; d_j) are known in advance and do not change.
4. A single workstation with a single human resource is continuously available and is never idle when jobs are available for processing.
5. When the human begins processing job *j*, processing continues through completion without interruption.
6. Only one job may be processed at a time.
7. The due date, d_j is considered to be ∞ for all jobs available for processing.

With a full description of the product options, demand in a production period and the physical factors required for job processing, the following dispatching rules will present alternative sequencing strategies to develop feasible heuristic production schedules. The purpose of the following dispatching rules is to minimize the instances of consecutive high-risk jobs being successively scheduled as otherwise assumed to be contributors of cumulative musculoskeletal disorders attributed to the sequence of the production schedule.

3.2 Sequencing to Maximize Change in Musculoskeletal Activity Level

If work activity followed by rest where no musculoskeletal activity occurs affords the greatest recovery potential, then work at a high physical activity level followed by work at a lower activity level or vice versa is expected to provide partial musculoskeletal recovery. Therefore, when two consecutively scheduled jobs differ by entire body muscle level, portions of the body may be allowed partial or full recovery through changes in musculoskeletal activity. This sequencing method is achieved by a dispatching rule that seeks to find the maximum available difference between successive $REBA_j$ scores. For the stakeholders involved, this dispatching rule is expected to be the preferred administrative control of the ergonomist as compared with the production scheduler. The conditions for this dispatching method are provided in **Table 3.3** below followed by the notation and algorithm to define a feasible heuristic sequence.

Table 3.3: *Production period product options with $REBA_j$ score and associated demand.*

Jobs	**1**	**2**	**3**	**4**	**5**	**6**
p_j	4	4	6	8	6	10
$REBA_j$	4	5	7	10	12	14
n_j	1	1	1	1	1	1

At the beginning of the scheduling period, a set of J jobs is released for scheduling with known $REBA_j$ scores. For the following heuristic, define for job j a priority index I_j that is a function of contiguous $REBA_j$ job scores, i.e.,

$$I_j = \left| REBA_{[k-1]} - REBA_j \right|$$

Select as J_1, the job that satisfies $J_1 = \{ j \in : REBA_{[j]} \geq REBA_{[i]} \;\; \forall \;\; i \in J \}$. Thus, the set of jobs previously dispatched will be denoted as J_k. This is followed by evaluation of all remaining unscheduled jobs by the priority index to find $\hat{j}$ equal to the argument that maximizes I_j for $j \in J \setminus J_{k-1}$. For all remaining jobs yet to be dispatched;

$$J_k = J_{k-1} \cup \{ j : \left| REBA_{[k-1]} - REBA_j \right| \geq \left| REBA_{[k-1]} - REBA_i \right| \;\; \forall \;\; i \in J \setminus J_{k-1} \}.$$

This heuristic may therefore be summarized as follows.

Algorithm 3.2.1 (Maximize Change in Musculoskeletal Activity Level)

Step 1.

Select as the first job j to be dispatched, the available job with the highest $REBA_j$ score.

Step 2.

Priority should then be given to the job of those remaining in J that maximizes the difference between $REBA_j$ scores (according to I_j) from the previously dispatched job.

Step 3.

If all remaining jobs $i \in J$ have been dispatched, then STOP;

otherwise go to Step 2.

This dispatching rule is displayed as a Gantt chart in **Figure 3.1** below with respect to the basic conditions provided in **Table 3.3**.

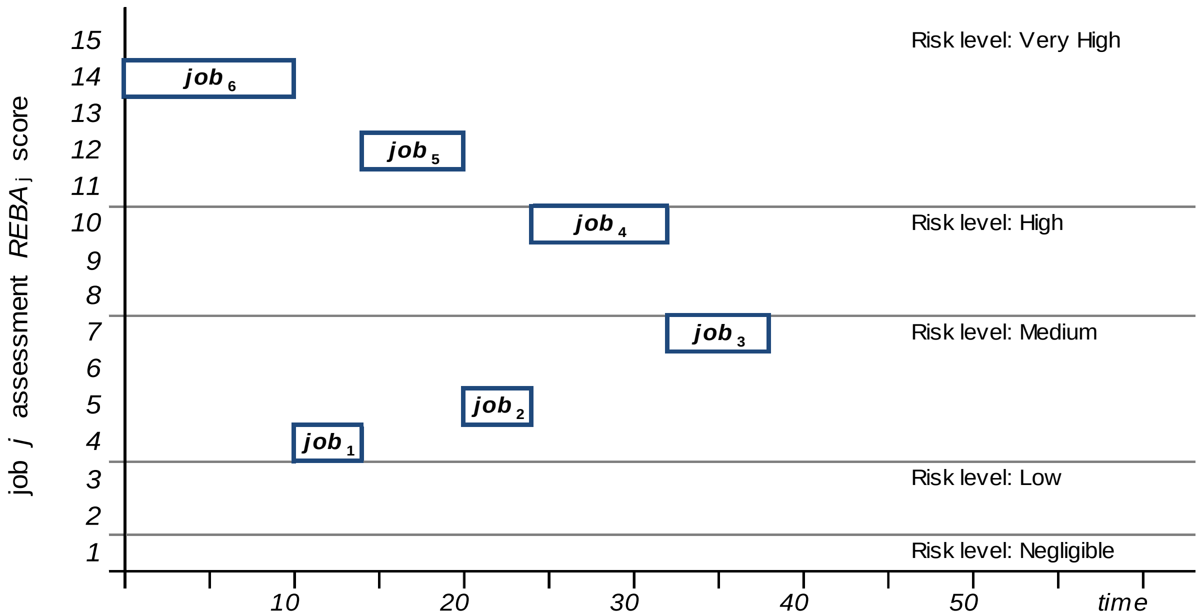

Figure 3.1: *Gantt chart for sequencing to maximize change in musculoskeletal activity level.*

This defined method of sequencing is expected to offer the highest potential for musculoskeletal recovery during work and therefore perform as the favored ergonomic sequence to reduce the risk of musculoskeletal disorder attributed to cumulative physical exposures that may otherwise have been assigned in the production schedule. By allocating jobs in this fashion, relief from high risk jobs, indicated by high REBA score, is provided by the subsequent processing of a lower REBA scoring job of lower musculoskeletal risk level. This dispatching rule also functions to minimize the instances of two high risk jobs being processed consecutively. To better understand the behavior of this dispatching rule, each of the production period demand distribution random samples, provided in **Table B.1** of **APPENDIX B**, for each of the product families defined in **Table 3.1** were hand-scheduled according to Algorithm 3.2.1.

Applying this sequencing technique to the random samples of **Table B.1** provided insight into the priority index I_j allocation of available jobs. By alternating the highest REBA score jobs with the available lowest REBA score jobs, the dispatching rule is generally found to effectively prevent successive and therefore cumulative exposures of high risk musculoskeletal activity. The cost associated with this method is identified by the median REBA score jobs being generally withheld from being dispatched until the end of the sequence after the higher priority jobs have been scheduled. This method deployed in a production environment may require supportive modifications to the supply or depletion of products required to complete jobs as defined by the sequence.

3.3 Sequencing by Descending Change in Musculoskeletal Activity Level

If job processing at a high level of musculoskeletal activity depletes the physical capacity of the human processor, then there is a descending available output of physical exertion as the production period advances. Therefore, when consecutive jobs require reduced levels of muscle activity, physical expenditure available from the human processor is aligned with the descending musculoskeletal levels required in the production sequence. This sequencing method is achieved by a dispatching rule that seeks to dispatch available jobs in descending subsets to the schedule in a similar trend. For the stakeholders involved, this dispatching rule is expected to be the preferred administrative control of the production scheduler but may also be favored by the ergonomist. The conditions for this dispatching method are provided in **Table 3.4** below followed by the notation and algorithm to define a feasible heuristic sequence.

Table 3.4: *Production period product options with* $REBA_j$ *score and associated demand.*

Jobs	**1**	**2**	**3**	**4**	**5**	**6**
p_j	4	4	6	8	6	10
$REBA_j$	4	5	7	10	12	14
n_j	1	1	1	1	1	1

At the beginning of the scheduling period, a set of J jobs is released for scheduling with known $REBA_j$ scores. For the following heuristic, the first phase is to form a subset of jobs with a single job from each of the available product families selected from the unscheduled jobs in set J. Thus, denote $J^{[1]}$ as the first subset of J where for all k = 1, … , n, $J^{[1]} = \{ j \in :$ $\mathrm{REBA}_{[j]} \ \forall \ j \in J^{[k]} \}$. The set of jobs to be scheduled is defined as $J = J^{[1]} \cup J^{[2]} \cup \ldots \cup J^{[n]}$. The second phase is to select from the group of jobs in the subset $J^{[1]}$ the job to be dispatched according to the priority index $I_j^{[k]}$ that is a function of descending $REBA_j$ job scores, i.e.,

$$I_j^{[k]} = REBA_j$$

For the jobs in $J^{[k]}$, dispatch the job ĵ to the schedule equal to the argument that maximizes $I_j^{[k]}$ for j $J^{[k]} \setminus J^{[k-1]}$. For all remaining jobs i in the set J to be allocated to subsets and dispatched, $J^{[k]} = J^{[k-1]} \cup \{ j : REBA_j \ \forall \ i \in J \setminus J^{[k-1]} \}$. This heuristic may therefore be summarized as follows.

Algorithm 3.3.1 (Descending Change in Musculoskeletal Activity)

Step 1.

Select from the set of jobs to be scheduled, a single job from each of the available product families to form a subset as the first scheduling phase.

Step 2.

From the jobs selected for the subset in Step 1, give priority to the job with the highest $REBA_j$ *score and dispatch this job to the schedule sequence as the second scheduling phase.*

Step 3.

For the remaining jobs in the subset, give priority to the job with the highest $REBA_j$ *score and dispatch this job to the schedule sequence.*

Step 4.

If all remaining jobs in the subset have been scheduled, proceed to Step 5;

otherwise go to Step 3.

Step 5.

If all remaining jobs $i \in J$ *have been dispatched, then STOP;*

otherwise go to Step 1.

This dispatching rule is displayed as a Gantt chart in **Figure 3.2** on the following page with respect to the basic conditions provided in **Table 3.4**.

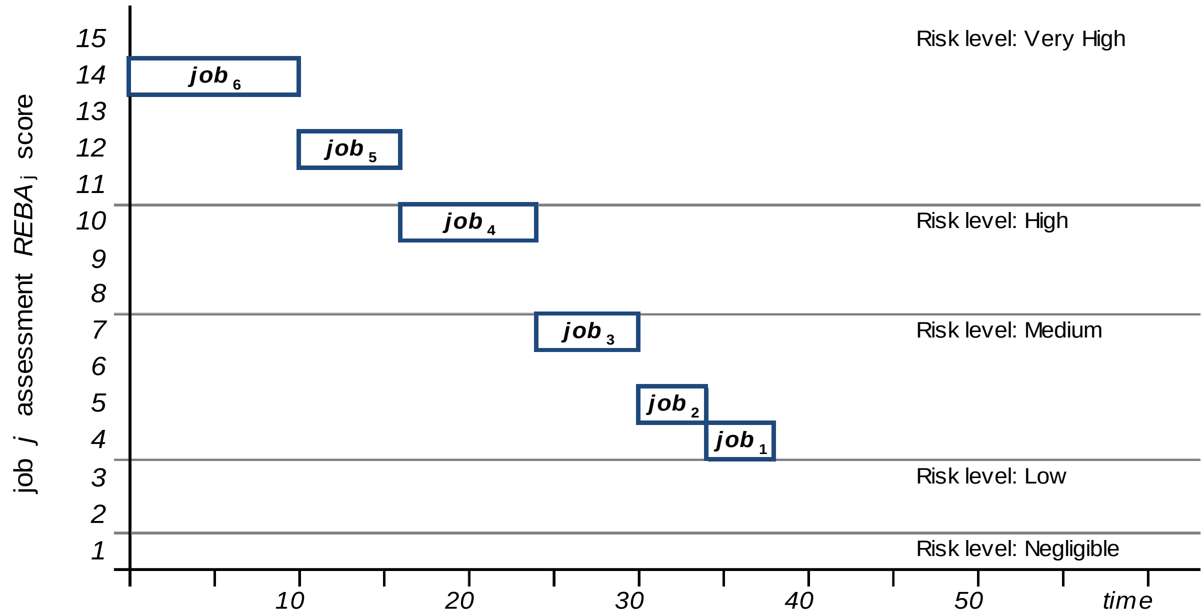

Figure 3.2: *Gantt chart for sequencing by descending change in musculoskeletal activity level.*

This defined method of sequencing described is expected to provide the human processor with a gradual change in musculoskeletal activity level between successively dispatched jobs as indicated by the entire body REBA score. By allocating jobs this fashion, relief from high risk jobs, indicated by high REBA score, is provided through descending muscle activity levels for subsequent processing of lower REBA scoring jobs associated with lower musculoskeletal risk. This dispatching rule also functions to minimize the instances of two high risk jobs being processed consecutively and provides greater relief periods between two exposures of high REBA scoring jobs. To better understand the behavior of this dispatching rule, each of the production period demand distribution random samples, provided in **Table B.1** of **APPENDIX B**, for each of the product families defined in **Table 3.2** were hand-scheduled according to Algorithm 3.3.1.

Appling this sequencing technique to the random samples of **Table B.1** provided insight into the priority index $I_j^{[k]}$ allocating jobs within each subgroup $J^{[k]}$. By sequencing jobs according to descending REBA score, the dispatching rule is generally found to effectively distribute high REBA scoring jobs among lower REBA scoring jobs at the expense of jobs with higher proportional demand not being fully dispatched until the distribution of all other jobs is satisfied in the sequence. This method deployed in a production environment will likely be favorable to a production scheduler as the descending arrangement of jobs is also aligned with the scheduling interest of level-loading for more uniform component usage and depletion.

3.4 Sequencing to Minimize Repetitive Musculoskeletal Activities

Recognizing that the scheduling function in practice is often a dynamic activity, the purpose of this section is to provide a dispatching rule as a compromise between the human preservation interests of the ergonomist and the practical needs of the production scheduler while maintaining focus on musculoskeletal risk. As the schedule sequence affords the opportunity to limit repetitive instances of equal REBA scoring jobs, this shall be the sole interest of the dispatching rule in this section. Therefore, this sequencing method is achieved by seeking to limit the instances of consecutively scheduled jobs of equal REBA score while still offering scheduling flexibility. For the stakeholders involved, this dispatching rule is expected to allocate jobs to avoid cumulative effects of high risk activities but by doing so in a less rigidly defined method. This should assist the scheduler in addressing multiple objectives or productivity related performance measures. The conditions for this dispatching method are provided in **Table 3.5** below followed by an algorithm to define a feasible heuristic sequence.

Table 3.5: *Production period product options with $REBA_j$ score and associated demand.*

Jobs	**1**	**2**	**3**	**4**	**5**	**6**
p_j	4	4	6	8	6	10
$REBA_j$	4	5	7	10	12	14
n_j	1	1	1	1	1	1

At the beginning of the scheduling period, a set of *J* jobs is released for scheduling with known $REBA_j$ scores. This heuristic may therefore be generally defined as follows.

Algorithm 3.4.1 (Minimize Repetitive Musculoskeletal Activities)

Step 1.

Select as the first job j to be dispatched, the available job with the highest $REBA_j$ *score; otherwise, select any job j to be dispatched from the set J jobs.*

Step 2.

Priority should then be given to the job i of those remaining in J with a REBAj score that is less than or greater than the previously dispatched job;

otherwise, select any of the jobs remaining to be given priority.

Step 3.

If all remaining jobs $i \in J$ *have been dispatched, then STOP;*

otherwise go to Step 2.

This dispatching rule is displayed as a Gantt chart in **Figure 3.3** on the following page with respect to the basic conditions provided in **Table 3.5**.

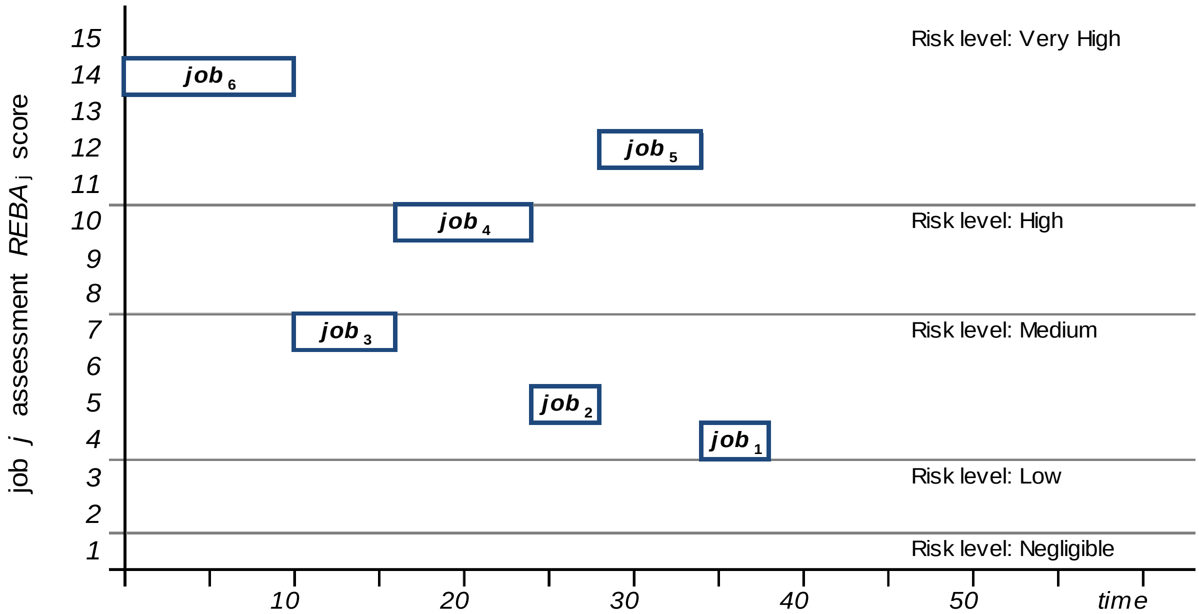

Figure 3.3: *Gantt chart for sequencing to minimize repetitive musculoskeletal activities.*

This generally defined method of sequencing may take many forms but stresses the importance of avoiding the dispatching of two successive, identical jobs that when associated with high risk musculoskeletal activity will likely contribute to cumulative physical exposure and risks of musculoskeletal disorder. Similar to this, an alternative but more restrictive dispatching method may suggest the scheduler avoid dispatching two contiguous jobs of the same $REBA_j$ risk level (0-5) rather than by $REBA_j$ score (1-15). Regardless of the job arrangement resulting from this method, the scheduler should focus efforts at the minimization of repetitive instances of equal muscle activity level jobs in the sequence. This decision rule also functions to minimize the instances of two high risk jobs being processed consecutively while distributing median REBA score jobs earlier in the sequence.

When this sequencing technique is applied to the random demand distribution samples of **Table B.1** of **APPENDIX B** for each of the product families, performance is generally found to effectively alternate high REBA score jobs with all other available REBA score jobs where the cost associated with this method is identified by the time required to effectively distribute all jobs in the production period to minimize cumulative musculoskeletal exposures.

Finally, as dispatching rules and sequencing techniques afford many alternative methods for arranging jobs, there are likely many yet to be defined strategies available for evaluation. The purpose of this chapter was to identify, demonstrate and promote sequencing methods at a single workstation for jobs of potentially harmful physical activity or postures to provide the best expected preservation of the human processor exposed to the physical effects associated with the production schedule. Perspective for the contribution of methods presented in this chapter may be found in the consideration of contrasting and more advanced production environments and is the subject of Chapter 4.

CHAPTER 4. EXTENSIONS TO COMPLEX ENVIRONMENTS

The potential risk for humans to develop a work-related musculoskeletal disorder is present in many arrangements of production environments and not limited to single processor production settings. As production environments become more complicated or require additional human laborers, it is recognized that decision rules for dispatching available jobs may offer inconsistent relief as compared to the single processor setting of Chapter 3. Therefore, conjecture as to the effect of applying the suggested dispatching rules in contrasting production settings will allow for discussion related to the potential for musculoskeletal relief. Though the suggested decision rules may not fully be deployable for all instances in practice, portions of the defined method may still prove valuable as contribution to larger efforts for reducing risk. Therefore, the following sections will provide a discussion of the decision rules for dispatching available jobs, as presented in Chapter 3, in light of the opportunity or restrictions associated with extending these techniques to more complex production environments.

4.1 Sequencing by Entire Body Ergonomic Assessment of Work

The opportunity for extension of REBA and job sequencing to complex production environments will likely be largely influenced by product processing requirements and the associated change in musculoskeletal activity level across identified product families and related to the levels of individual body segments. It must also be recognized that there is an unavoidable element of compromise associated with any method assessing human physical activity during work. For direct measurement methods, only specific and limited body segments are investigated. With an expanded scope, assessment methods evaluate additional body segments or the entire body but at the expense of reduced specificity in measurement. As REBA was selected as the method to quantitatively represent human physical activity in this research it is necessary to consider the compromise of this decision and the implication related to the stated long-term goal.

The decision rules of §3.2 - §3.4 for dispatching available jobs are motivated by the potential to afford recovery and/or limit the cumulatively degenerative effects for repetitive activities. When two consecutively processed jobs provide a shift in musculoskeletal activity, the muscle groups not in use during the subsequent activity are allowed partial or full recovery. Additionally, when no change in musculoskeletal activity is afforded the associated risk for humans is prolonged exposure and cumulative musculoskeletal risk. Therefore, when these instances are repeated in the short-term and over production periods in the long-term requiring force and intensity for job processing, there is potential for degeneration of soft tissues due to cumulative effects from successive exposures. It might therefore be reasonable to expect the greatest relief available from sequencing techniques be realized from the dispatching method of §3.2 and to a reduced extent as fewer dispatching options are available to the scheduler. While portions of this problem have been defined in previous research, the quantification of individual human physical exposure and consequential internal effect has yet to be defined. Though it is not yet possible to quantify the magnitude of relief from sequencing toward reducing musculoskeletal risk, discussion will therefore focus on dispatching rules based on the entire body and the exposure pattern for individual body segments.

By considering the dynamic conditions of production environments and potential for disorders in the workplace among other factors, it is the entire body activity during work that contributes to the manifestation of trauma within a specific body segment. In this way, the REBA assessment is appropriately aligned to assess preliminary conditions by identifying instances involving risk through body segment posture and activity intensity, determining the final REBA score. The accepted challenge addressed in this research was not only to identify risk but also to reduce the potential for development of a disorder due to physical exposure to high risk musculoskeletal activities. However, while REBA is a reputable method for identifying this risk, dispatching jobs by entire body score is only a partial representation of the successive physical exposures experienced at the individual body segment level.

If the assumption is appropriate that considering the entire body activity for assessment and as the basis for job dispatching provides sufficient relief, the subsequent expectation would likely be that similar relief is afforded to the individual body segments during the production sequence. Therefore, an equally important consideration for job dispatching decisions is the relief afforded to the body segments between scheduled jobs and across the production period. To understand this interaction between entire body and body segment activity for the dispatching rules of Chapter 3, it is necessary to compare the changes in musculoskeletal level for these components as related to the respective sequencing strategies.

In the following three figures, the job sequence as presented in the basic strategies of **Figure 3.1**, **3.2**, and **3.3** of **§**3.2, **§**3.3, and **§**3.4 respectfully will be combined with added elements to allow comparison between changes in entire body activity level and the corresponding change in activity level for each body segment. These figures are constructed with six vertical bars to represent the REBA job score (vertical $axis_2$) where the width of each bar represents processing time (horizontal axis) given for the single workstation problem setting. The sequence of bars in each figure is determined by the respective dispatching rule of **§**3.2 **-** **§**3.4. Finally, each figure contains nine horizontal rows (vertical $axis_1$) representing each of the body segments and condition values that contribute to the final REBA score for each product family. The REBA score tables with devised segment and condition values for each job type may be referenced in **Figures A.1 - A.6** of **APPENDIX A**.

The first of the three dispatching rule figures, **Figure 4.1**, is presented on the following page and is consistent with the job sequence of **Figure 3.1** for the method defined in **§**3.2 for sequencing to maximize the change in musculoskeletal level between jobs. This sequence, when n = 1 for all jobs j is: $j_6 \rightarrow j_1 \rightarrow j_5 \rightarrow j_2 \rightarrow j_4 \rightarrow j_3$.

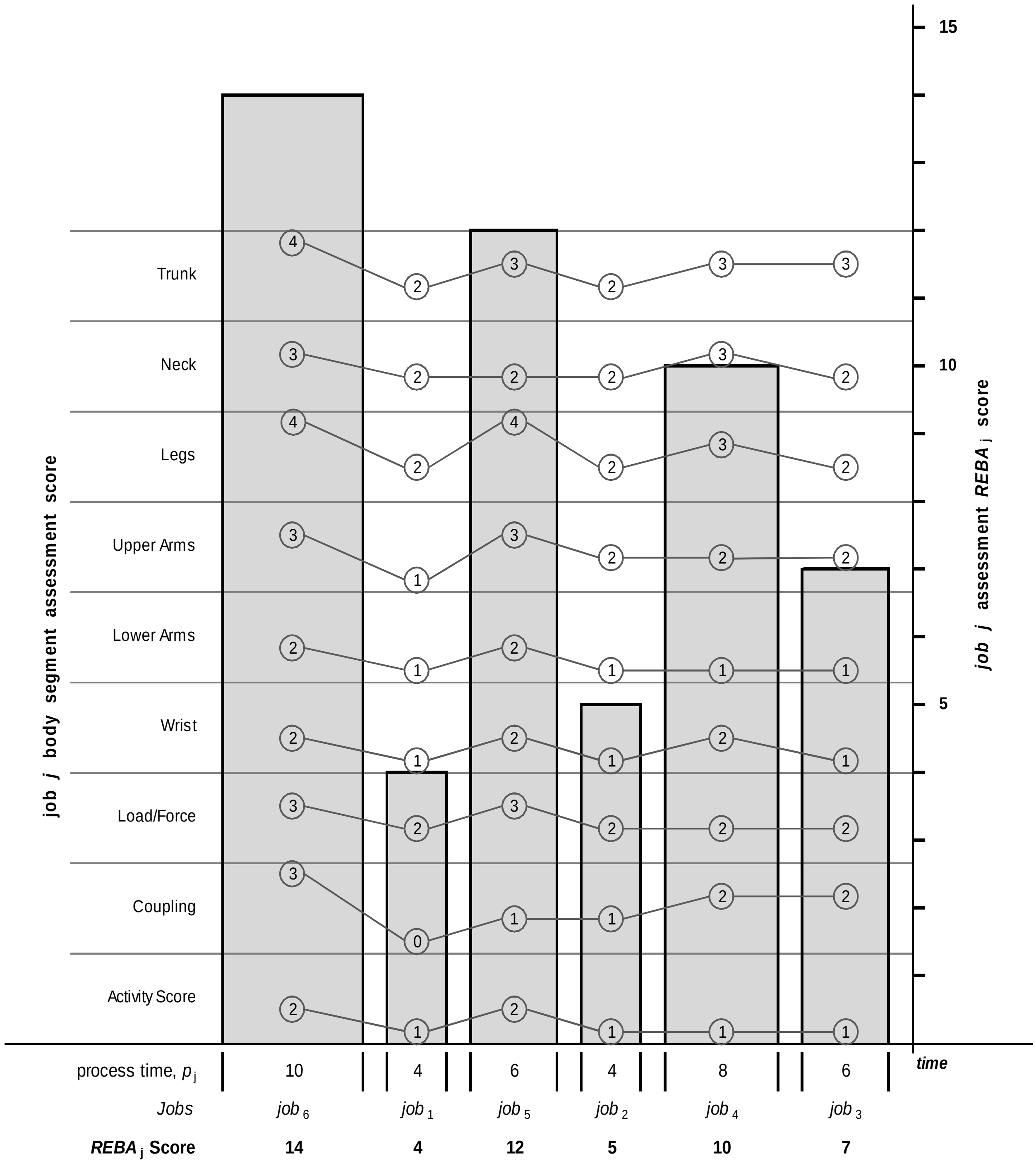

Figure 4.1: *Dispatching rule of §3.2 with job processing times and change in body segment and condition levels compared with the change in entire body musculoskeletal activity level.*

The sequence of jobs displayed in **Figure 4.1** on the previous page demonstrates that when the change in REBA score between two jobs is large, reference $job_6 \rightarrow job_1$, there are comparable reductions observed for each of the body segment and condition level scores. However, this is not always true, reference the Neck for $job_1 \rightarrow job_5$. When the difference between successive REBA job score narrows, reference $job_4 \rightarrow job_3$, there are fewer body segment and condition levels that decrease. In general, for the majority of successive jobs in the sequence, the body segment and condition levels follow the pattern of change for the entire body levels.

The second figure in the group of dispatching rule figures, **Figure 4.2**, is presented on the following page and is consistent with the job sequence of **Figure 3.2** for the method defined in **§**3.3 for sequencing jobs by descending change in musculoskeletal activity level between jobs. This sequence, when n = 1 for all jobs j is: $j_6 \rightarrow j_5 \rightarrow j_4 \rightarrow j_3 \rightarrow j_2 \rightarrow j_1$.

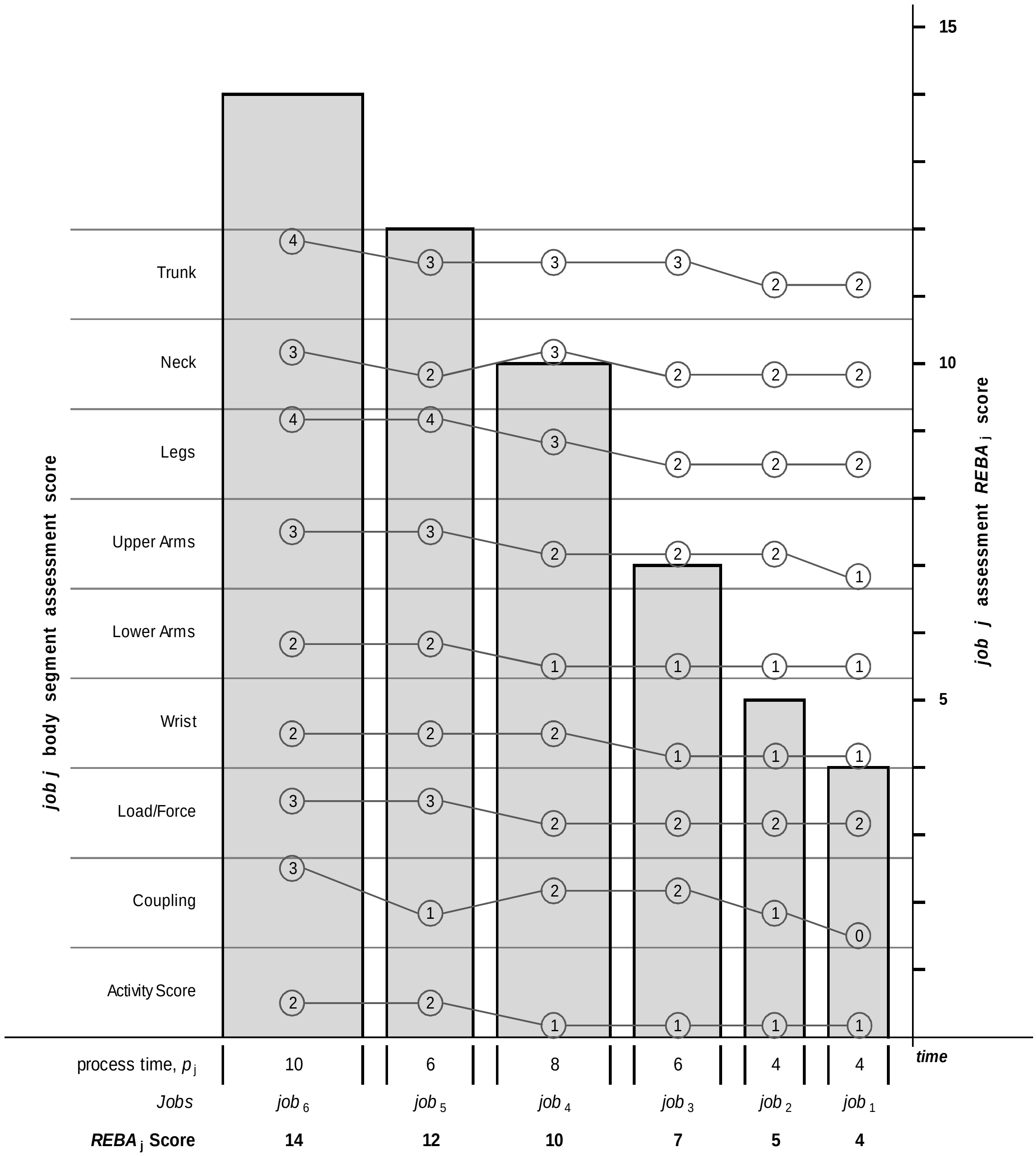

Figure 4.2: *Dispatching rule of §3.3 with job processing times and change in body segment and condition levels compared with the change in entire body musculoskeletal activity level.*

The sequence of jobs displayed in **Figure 4.2** on the previous page demonstrates that when the successive change in REBA score between two jobs is slightly less as compared with **Figure 4.1**, there are fewer associated reductions observed for each of the body segment and condition level scores. In two noteworthy instances, reference the Neck and Coupling for $job_5 \rightarrow job_4$, the reduction in entire body level is associated with increased level changes for these elements. In general, for the majority of successive changes, the body segment and condition levels follow the pattern of descending change for the entire body levels.

The third dispatching rule figure, **Figure 4.3**, is presented on the following page and is represents the job sequence of **Figure 3.3** for the method defined in §3.4 for sequencing jobs to minimize repetitive instances of musculoskeletal activity between jobs. This sequence, when $n = 1$ for all jobs j is: $j_6 \rightarrow j_3 \rightarrow j_4 \rightarrow j_2 \rightarrow j_5 \rightarrow j_1$.

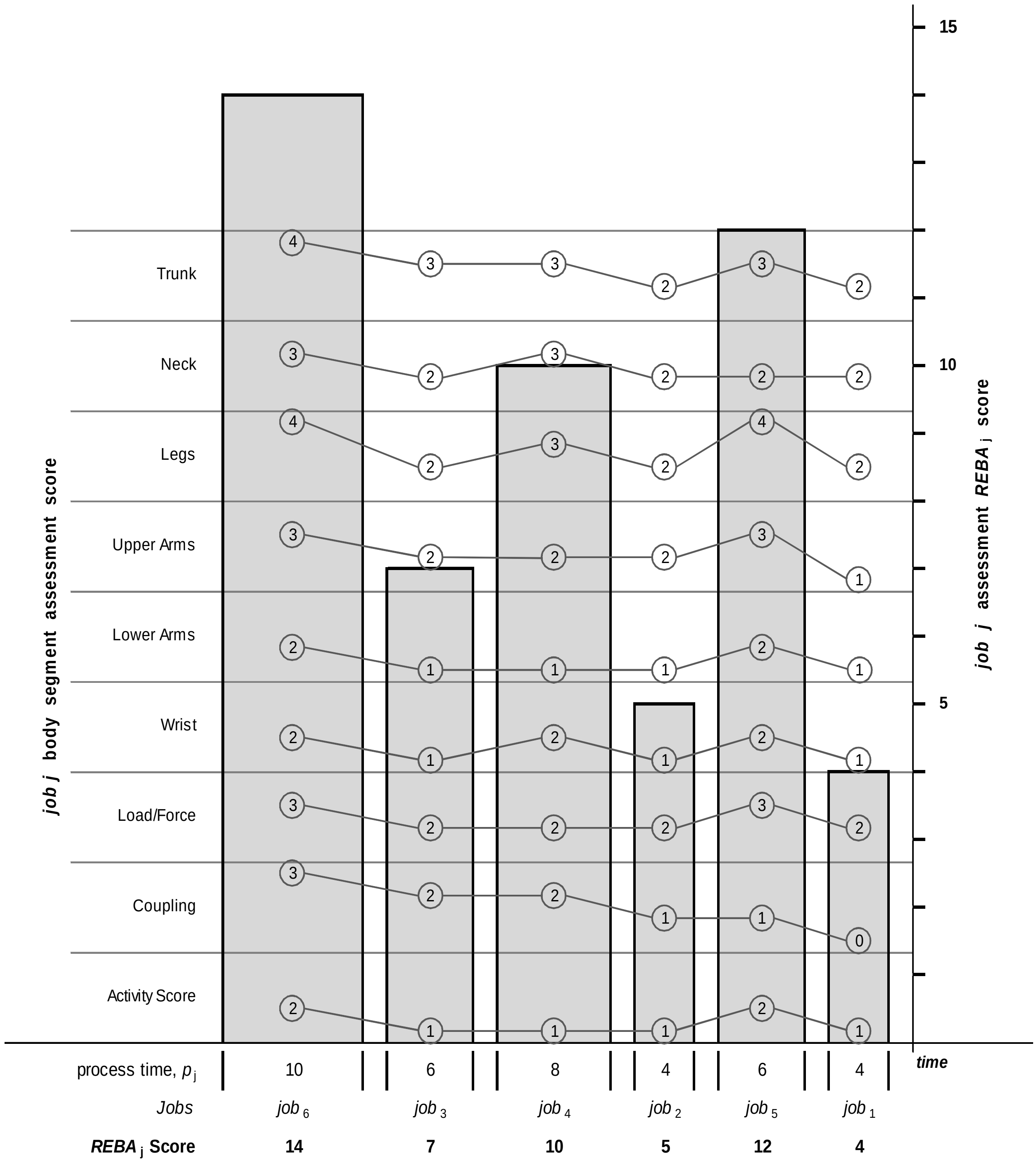

Figure 4.3: *Dispatching rule of §3.4 with job processing times and change in body segment and condition levels compared with the change in entire body musculoskeletal activity level.*

The sequence of jobs displayed in **Figure 4.3** on the previous page demonstrates again that when the change in REBA score between two jobs is large, reference $job_6 \rightarrow job_3$, there are comparable reductions observed for each of the body segment and condition levels. Unique to **Figure 4.3** are the instances where entire body level increases for $job_3 \rightarrow job_4$ but a potion of the segment or condition level scores remain unchanged within these two jobs. This condition, while not consistent with the change for entire body activity is considered desirable due to consecutive equal levels of physical activity within a body segment during an otherwise increased level for entire body physical activity. In general and consistent with patterns of **Figure 4.1** and **Figure 4.2**, during the majority of successive changes, the body segment and condition levels follow the trend of change for the entire body levels.

Based on this comparison, the use of sequencing to manage cumulative elements of musculoskeletal risk, similar to most administrative controls, is expected to afford the greatest relief to the human when scheduling flexibility for available jobs is high. Thus, as external customer demand changes to require processing of disproportionately high quantities of jobs with REBA score greater than 10 relative to lower risk jobs, scheduling flexibility will likely be reduced. Similarly, when resulting REBA scores for product families outside of the problem setting in Chapter 3 identify only minor differences between body segment activities or when there are few identified product families at a given workstation, this is also expected to reduce scheduling flexibility and potential contribution of dispatching methods.

Finally, it is worth mentioning that sequencing according to a REBA job score or any other measurement or assessment of human physical activity is an administrative control at best that may offer potential reductions for the musculoskeletal effect of physically demanding work. This is indicated in the entire body and body segment comparisons of Figures 4.1 - 4.3 displaying inconsistency in change within the sequencing techniques. The contribution and associated value for ergonomic considerate job sequencing is identified in the ability to limit the cumulative effects due to frequency of repetitive activities for entire body musculoskeletal activity but is available to a lesser extent when considering the musculoskeletal activity of body segments as defined by the REBA assessment. A better understanding of this relationship would likely be provided from subsequent detailed measurements for body segments of interest. Such a desire must be considered within the perspective of associated compromise with ergonomic assessments provided in **Figure 2.1** and the increased cost for direct measurement. It would therefore fall under the discretion of the engineer as to what compromises are made when applying the method of Chapter 3.

4.2 Mixed Model Production and Batch Model Production

The function of mixed model production in the problem setting of Chapter 3 may appropriately be described as a relaxation of many production systems in practice. Use of this production model framework allowed for dedicated focus on the defined dispatching techniques in order to demonstrate the characteristics and behavior of a novel method rather than rigorously represent a complex production environment. While for the single processor there are instances of mixed model production found in practice where set-up times and changeovers are negligible it is not believed that these are representative of the majority of production systems. Often necessitated due to multiple product variations produced within the same workstation are unavoidable set-up activities when changing between product options. This requirement will typically contribute to the need for producing products in batches in order to distribute the non value added time of the changeover across multiple products to reduce the effect of the disruption to production.

The use of batching for production systems in practice is a natural response that while receiving almost absent representative discussion in literature may be found in many instances of practice. However, as related to sequencing and the need to limit repetitive instances of high physical activity, the batch model production environment is a constraint that is unavoidable in practice. For any of the random demand samples provided in **Table B.1** of **Appendix B**, if a set-up was required between processing changes in product type, this condition would necessarily influence the processing of all like jobs before selecting the next product family batch of like jobs. Under this condition, and in keeping with the problem setting of Chapter 3, the human exposed to job processing will inevitably be exposed without relief to all jobs j within the set J before being allowed to initiate processing of the next product family.

The risk of developing a work-related musculoskeletal disorder is therefore expected to be notably higher in a batch model production environment as compared to mixed model settings. For the human processor, being unable to avoid known activities of high associated risk is a hazardous condition that would benefit from the assistance of ergonomic intervention larger than an administrative control can provide, specifically, immediate engineering control deployment. However, even with the identified severity and established need, engineering controls may still be sluggish to provide sufficient relief from extreme conditions. The recommendation in this case, related to the contribution of sequencing is therefore to sequence the set-up constrained groups of jobs according to the first or third dispatching rules defined in **§**3.2 and **§**3.4 for independent jobs. While it is not yet understood as to the extent of relief afforded to such a condition, it is expected to be a preferable alternative to the processing requirements from all high risk batches as would be prescribed in the dispatching rule of **§**3.3 or any other alternative arrangement.

4.3 Flow Lines with Multiple Workstations

The use of humans as processors in production environments extends beyond the single workstation setting in many cases. While many production configurations may be identified here, of interest to this thesis is the flow line with multiple workstations in series. To address the possible variations, consideration will include connected and disconnected flow lines. Additionally, these arrangements may be found in practice as paced or unpaced configurations. When evaluation is directed at the physical human activity in any of these arrangements it is of less importance to consider the system structure within the environment as compared to the REBA score resulting from assessment of all humans (assuming the configuration requires human processors > 1) processing jobs within the cell. The challenge related to sequencing jobs in these systems relative to ergonomic assessment of human activity is of questionable benefit afforded as the number of humans at within the production system of interest increases.

Therefore, the recommendation in this case is to follow through with REBA scoring for all product families and for each human laborer within the system to evaluate the associated changes in musculoskeletal activity experienced by each human for the series of workstations during processing of product variations. From an optimistic view, there may be potential to apply sequencing strategies to a production flow line and realize levels of relief for all humans through the production schedule. More likely, the reverse will be found in that little or no relief is provided to the humans in the system. It is important to note that as the methods defined in Chapter 3 assesses the musculoskeletal activity for current conditions where there is likely no prior consideration given to human demand or capacity due to the sequence of jobs, the risk associated with an alternative sequencing method if even as a trial for evaluation should introduce no greater detriment to the humans affected as compared with doing nothing.

Finally, the discussion provided in this chapter has recognized the challenges found in practice and need for further understanding through application of the associated dispatching methods defined in Chapter 3. Based on this discussion and provided for complex environments, are opportunities to deploy partial or entire portions of the administrative control using an observational ergonomic assessment and or jobs sequencing are available. This deployment in complex environments may still contribute to risk reduction while investigating alternatives as engineering controls. Even though this administrative control contributes assistance by managing risks, if only in part to larger problems, it may arguably be credited as a more rigorous and flexible intervention strategy than many of the competing administrative controls available to date. Therefore, from the previous review of extensions to complex environments, the practicing engineer or ergonomist may recognize the most opportune conditions for dispatching methods to be deployed. While for more complicated environments, applying suggested elements from the defined methods or as motivation to develop a conditional administrative control based on alternative assessment methods are equally interesting opportunities provided by this thesis.

CHAPTER 5. SUMMARY AND DISCUSSION

This thesis has identified a unique opportunity to introduce human characteristics into the administrative activity of job sequencing in the production schedule for the reduction of work-related musculoskeletal disorders. The novelty of defined dispatching methods is found in contribution of the production sequence to provide physical recovery and assist in the musculoskeletal preservation of human laborers. While the long-tem goal of this thesis is supported by the proposed dispatching rules, validation is needed from empirical studies to further demonstrate the contribution of sequencing in musculoskeletal risk reduction for human processors.

As previously identified, the quantitative introduction of human characteristics into scheduling problems is a challenge further complicated by attempts to reduce the risk associated with labor-intensive job processing. As the first part in achieving the overall objective, REBA was selected as the ergonomic assessment method to quantitatively represent the level of musculoskeletal activity for a human during job processing in a production setting. Subsequently, the REBA job scores were used as an influence to define alternative decision rules for dispatching available jobs to the production sequence. The expected result from applying any one of the suggested techniques from Chapter 3 is that the cumulative element of musculoskeletal risk associated with physically demanding activity may be reduced. The methods of §3.2, §3.3, and §3.4 established the opportunity for risk reduction and relief to be provided for the entire body through changes in musculoskeletal activity levels within the job sequence.

Though the production environments considered in Chapter 4 were associated with expected challenges for implementation in practice, they also supported the basis of rationale related to the need of dispatching methods provided in Chapter 3. The significance of the entire body assessment using REBA was indicated through a comparison between the changes in entire body musculoskeletal activity level and the associated changes in musculoskeletal activity level within individual body segments. The basis for this comparison is motivated by the indiscriminate nature of work-related musculoskeletal disorders that may develop in any body segment due to the unique individual internal response to cumulative physical exposures. As the entire body physical exposure to work influences the internal musculoskeletal response, it is recommended that no less than the entire body during dynamic physical activity be considered for similar subsequent evaluations. Directly related to this is importance for the inclusion in the evaluation of entire job processing durations. Without full consideration by assessment of job processing requirements for a given product family, proper insight cannot be achieved regarding the potential musculoskeletal effect within a job used for subsequent scheduling decisions.

Sequencing strategies related to ergonomic assessments arguably still hold the strongest potential for becoming a new class of applied ergonomic administrative controls. The basis for this statement is supported by the following conditions. The first is due to the acceptance by scheduling models of any human characteristics of interest. Therefore, if the production setting of interest would benefit in understanding from an alternative ergonomic assessment, the practitioner may choose any assessment that satisfies their needs from those available.

The dispatching rules presented in Chapter 3 would subsequently perform in the same fashion and change only by the assessment measures representing the activities of interest. The second is related to the still developing measurement of humans in production systems. Future methods will likely be found in “sophisticated evaluations of both the biomechanical requirements of jobs and the mechanical work capacity of workers” (Chaffin et al., 2006). Were a more comprehensive ergonomic assessment method be developed, a schedule performance measure could follow to quantify the magnitude of relief from risk contributed by the dispatching methods of this thesis.

Finally, as challenging scheduling conditions are still being encountered in practice and humans are expected to long be deployed as production resources, the direction of future research may find an interesting potential in this subject area. The complexity of scheduling problems in practice would likely benefit from established algorithms and models to advance scheduling theory (Lee et al., 1997). In determining the health of scheduling systems, Graves (1981) promotes the “need to be able to diagnose and evaluate an operating production scheduling system to determine whether the system is effective and whether the system can be improved.” While this statement still holds true, consideration should also be devoted in higher proportion to the health of humans as related to their working capacity and the associated cost of work-related musculoskeletal disorders. Some of the strongest examples of research in this area are credited to Carnahan et al. (2000) for safe job rotation schedules, Mathiassen (2006) investigating diversity and variation in biomechanical exposure, Lodree et al. (2009) promoting the integration of scheduling theory and human factors, and Lodree and Geiger (2010) for identifying the potential for rate modifying activities in the sequence of jobs related to human fatigue.

This thesis has accepted, recognized, and addressed the challenges faced by engineers and ergonomists in practice assigned with responsibility for improving working conditions for human laborers by contributing a method appropriately aligned with their expected needs. There is still exciting potential to be investigated in the quantification of human activity during work supported by accessible and easily deployed administrative controls functioning to reduce the potential risk of developing work-related musculoskeletal disorders in labor-intensive production systems.

APPENDIX A. REBA Scoring Sheets for Product Families

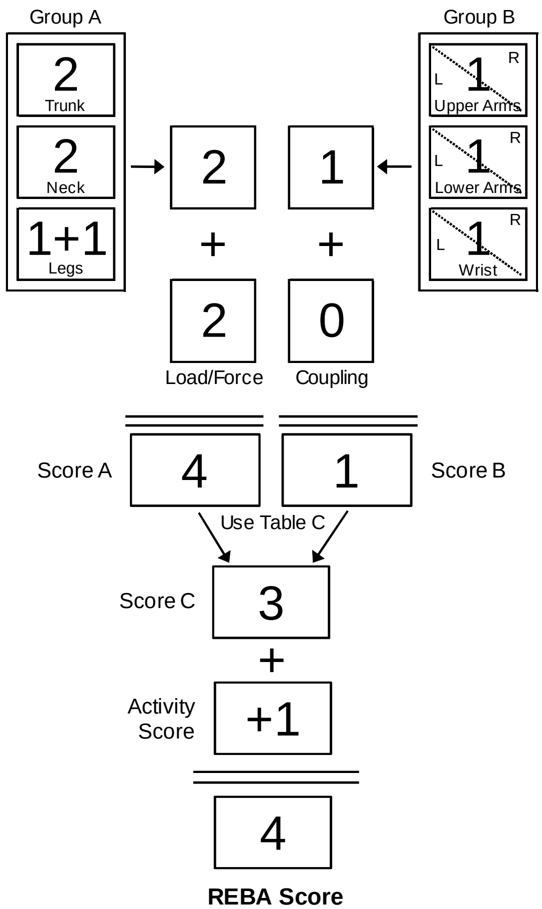

Figure A.1: *Detailed REBA assessment scoring sheet for the first product family, f_1*

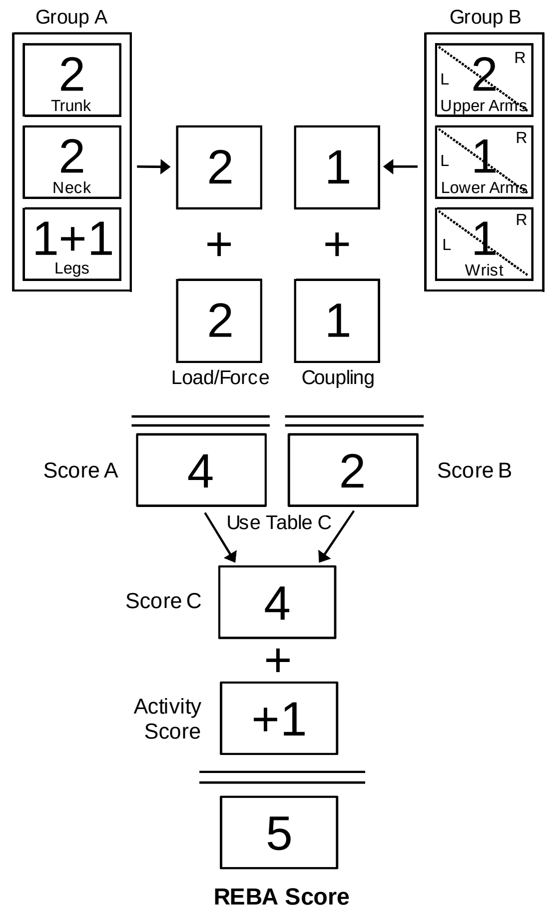

Figure A.2: *Detailed REBA assessment scoring sheet for the second product family, f_2*

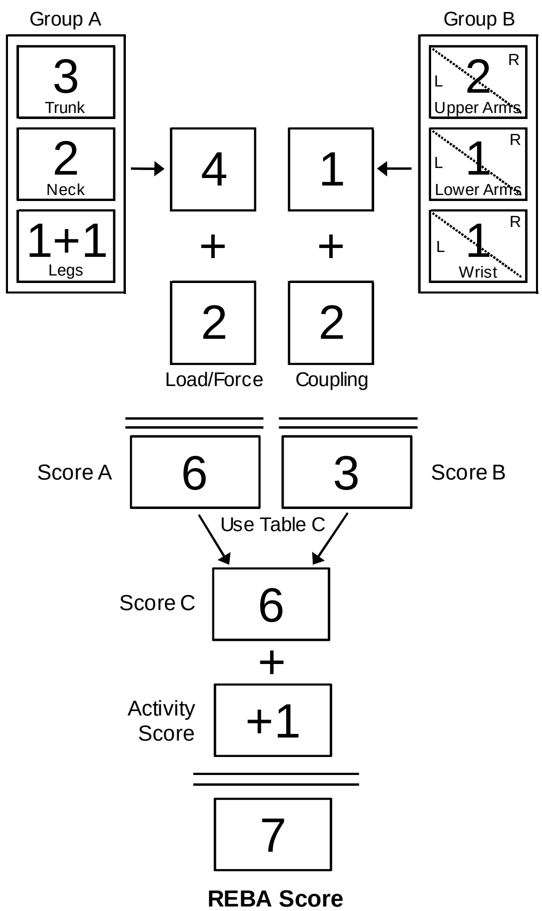

Figure A.3: *Detailed REBA assessment scoring sheet for the third product family, f_3*

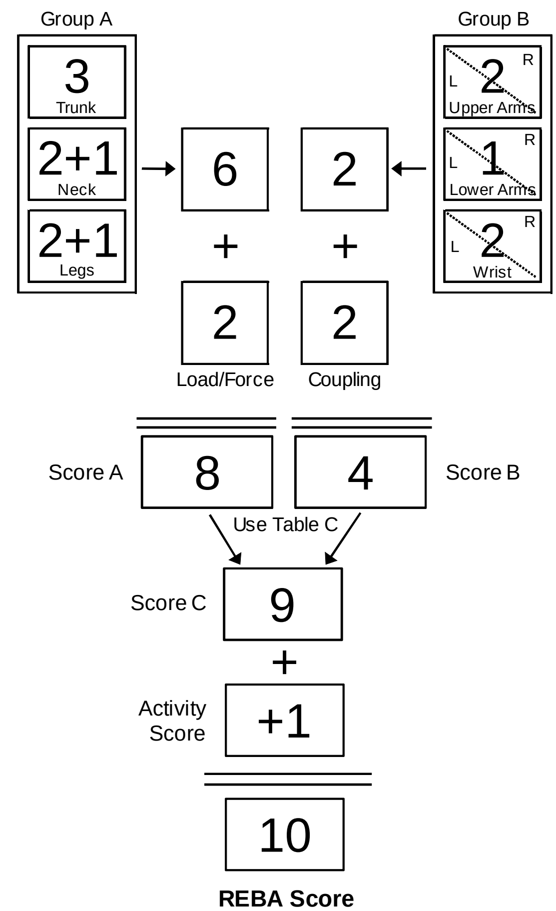

Figure A.4: *Detailed REBA assessment scoring sheet for the fourth product family, f_4*

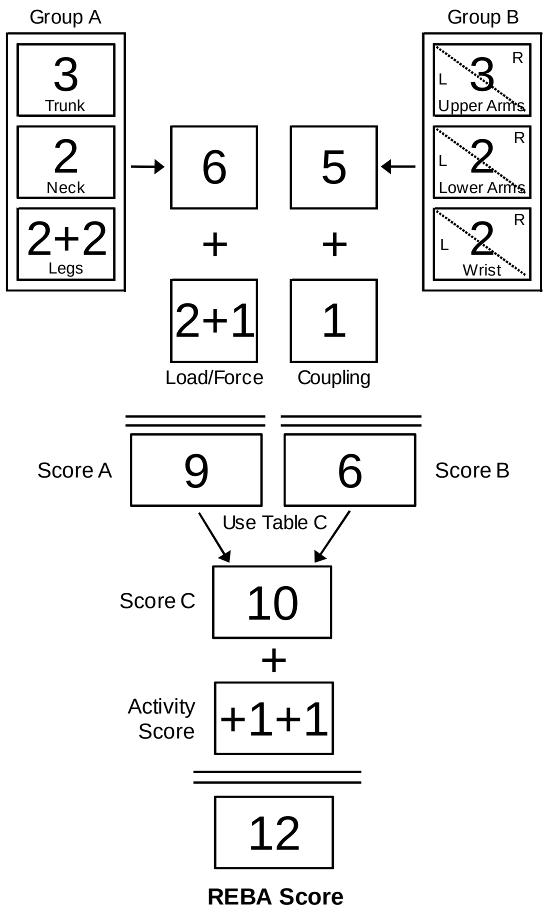

Figure A.5: *Detailed REBA assessment scoring sheet for the fifth product family, f_5*

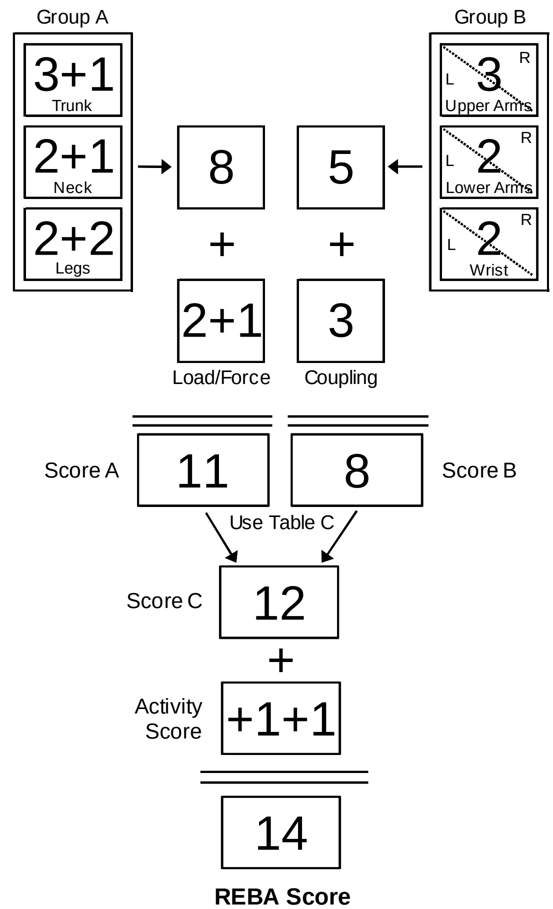

Figure A.6: *Detailed REBA assessment scoring sheet for the sixth product family, f_6*

APPENDIX B. Random Samples from Product Family Demand Distributions

Table B.1: *Random demand samples from product family distribution of Table 3.1*

Production Period Demand Distribution, T_j, Random Samples	number of jobs, n_j, per product family, f_j					
	n_1	n_2	n_3	n_4	n_5	n_6
1	1	8	6	4	14	2
2	6	10	20	9	12	11
3	10	8	12	3	2	7
4	16	5	12	6	4	5
5	5	5	10	5	7	7
6	22	6	18	4	5	5
7	16	1	20	5	7	9
8	7	10	11	16	1	3
9	17	11	15	10	2	2
10	12	5	8	7	11	7
11	18	5	14	8	11	5
12	20	7	14	13	12	6
13	14	12	17	4	10	4
14	10	10	11	4	5	9
15	12	8	15	11	7	4
16	12	1	7	10	6	5
17	4	5	5	7	7	12
18	13	8	8	4	4	7
19	9	5	16	5	8	7
20	20	13	11	10	9	10
21	14	8	11	11	8	6
22	7	9	22	8	4	6
23	4	10	10	1	6	2
24	18	5	18	16	10	2
25	24	8	7	7	7	6
26	17	8	7	17	6	8
27	10	12	3	11	11	6
28	14	6	9	3	5	11
29	11	8	10	5	11	8
30	27	9	17	1	6	4

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