Trunk kinematic variability as a function of time during the early phase of a repetitive lifting task

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Abstract
Lift-to-lift variability occurs in repetitive lifting tasks due to alterations in the lifting techniques used by the lifter, resulting in variability in lower back tissue loading. Understanding how trunk variability changes with time in the initial phases of a lifting bout may provide insights into the risk of injury during work startup. The purpose of this study was to quantify the variation of lifting kinematics and kinetics during the initial phase of a lifting bout. Twenty participants performed a repetitive lifting task continuously for 30 min. The load was equivalent to 10% of each participant's body weight and lifting was done at a rate of six lifts/min. Kinematic variables (three-dimensional range of motion, angular velocity, and angular acceleration) of the trunk were measured using the Lumbar Motion Monitor and a dynamic biomechanical model estimated peak L5/S1 moment and spine compression. The variances of these variables were compared across 10-min intervals: 0–10 min, 10–20 min, and 20–30 min. Results indicate a significant reduction in the variance of the peak sagittal acceleration, the sagittal range of motion, the transverse range of motion, peak sagittal moment, and peak spine compression between the first and second time intervals, followed by no significant change in variance between the second and third intervals. The downward trend in variation of these kinematic and kinetic variables suggests an initial adjustment period as the lifters reach a steady state of their lifting technique. The reduced variance of spinal loading may reduce the probability that a tissue tolerance is exceeded.

Keywords
low back pain, repetitive lifting, trunk kinematics/kinetics, variability

1 | INTRODUCTION

Low back pain (LBP) is recognized as a significant and costly problem worldwide that particularly impacts workers involved in occupations which require repetitive lifting exertions. Guo et al. (1999) showed that LBP contributed to approximately 101.8 million days in lost productivity annually due to absenteeism from work. This lost productivity was shown to have contributed to an estimated revenue loss of $7.4 billion annually for employees aged 40–65 (Ricci et al., 2006). In addition to lost revenue, the cost of managing LBP is high, exceeding $100 billion per year in 2006 in the United States (Katz, 2006). In a review of the evidence of the work-relatedness of low
back disorders, Bernard and Fine (1997) stated that there was strong evidence of an association between low back disorders and work-related lifting and forceful movements and they found that there was evidence of a relationship between awkward trunk postures and low back disorders.

There is some intriguing evidence of a relationship between certain temporal aspects of work life and occupational injury. In a synthesis of data from the US Bureau of Labor Statistics, Brogmus (2007) showed that the lost time injury rate was greatest at the start of the work week, reached its nadir on Wednesday, and then increased again on Thursday and Friday. In contrast, Wigglesworth (2006) evaluated data from the Australian Bureau of Statistics which showed a continuous downward trend in the percent of occupational injuries by day, with Monday contributing approximately 23% of the weekly injuries and Friday contributing 17%, with a steady downward trend connecting these two endpoints. Exploring this data set from a different perspective, Wigglesworth (2006) also showed some interesting trends in the numbers of occupational injuries by time of day. He showed that the number of injuries peaked in the 8:30–9:30 a.m. timeframe, dropped sharply towards the middle of the work day and then increased into the middle of the afternoon before falling off again towards the end of the work day. While these studies did not focus exclusively on musculoskeletal disorders, but more generally on occupational injury, there appear to be some time-related mechanisms whereby musculoskeletal disorders might contribute to these trends. These mechanisms would include end-of-week and end-of-day effects such as muscular fatigue and cumulative trauma, as well a beginning-of-week and beginning-of-day effects such as warm-up effects (Woods et al., 2007), adjustment to working conditions, and so forth.

Interestingly, warm-up and stretching routines before task performance have been reported to reduce the likelihood of injury occurrence for a number or reasons. First, warm-ups/stretches reduce tissue viscosity and enhance flexibility which results in smoother contractions (Safran et al., 1989; Shellock & Prentice, 1985). In addition, the body heat generated during warm-ups increases dissociation of oxygen from hemoglobin for muscle contraction (Safran et al., 1989) and a one-degree rise in muscle temperature has been shown to increase length to failure in rabbit hindleg (Safran et al., 1988). These results highlight the importance of understanding the early phases of a physically demanding task.

Variability in a lifting technique employed by a manual material handler could be one potential source for increased injury risk. Epidemiological studies have showed that trunk kinematics contribute to LBP development (Marras et al., 1993). Perhaps information on this variability trend will explain the increased risk of occupational injuries at the onset of the work day and the work week reported in the epidemiological data, and also influence our approach to injury risk assessment in manual task performance. Variability in these important trunk kinematic variables during repetitive lifting exertions will generate distributions of joint (i.e., spine) reaction forces leading to a scenario where an appreciable percentage of the lifts may create forces and moments that exceed the threshold level within the spine tissues (Granata et al., 1999). Furthermore, there has been some published evidence of a relationship between some of these temporal effects (specifically fatigue) and an increase in the variability of motions (Bauer et al., 2017; Sedighi & Nussbaum, 2017) intuitively agreeing with the previously cited epidemiologic findings (Brogmus, 2007; Wigglesworth, 2006). Moreover, a comprehensive review by Srinivasan and Mathiassen (2012) highlighted the importance of understanding the concept of motor variability in work task performance and injury prevention. One specific recommendation from this study was a recognition of the importance of the study of the temporal aspects of work task performance. For these reasons, focusing on trunk kinematic and trunk kinetic variability could provide insight to LBP development that results from repetitive lifting.

While increasing kinematic variability as a function of fatigue has been established in the literature, much less is known about trunk kinematic and kinetic variability during the early stages of a repetitive lifting task, as might be seen as a worker begins their work day. Hence, the objective of the current study was to investigate the effect of time on the variability of trunk kinematics and kinetics during the early phase of a repetitive lifting task. Trunk motion and loading variability was hypothesized to be high at the onset of task performance, followed by a gradual reduction in this variability as the lifter settles into their natural lifting rhythm.

## METHODS

### 2.1 Participants

Twenty college students (10 males and 10 females, aged 25 ± 3 years, height 171.6 ± 10.2 cm, and body mass 71.5 ± 19.2 kg), were recruited for this study. None of the participants had a history of low back pain or any chronic hip, shoulders or leg pain. Furthermore, none was currently experiencing pain in these areas of their body. Participants had no professional experience in manual materials handling. Before participating in the study, each participant provided written informed consent (document approved by the Institutional Review Board of Iowa State University).

### 2.2 Apparatus

#### 2.2.1 Data collection apparatus

The Lumbar Motion Monitor (LMM; Chattanooga Group Inc., TN; Marras et al., 1992) was used to measure and record trunk kinematic data as shown in the Figure 1. The LMM was mounted on the upper torso and lumbar region of each participant and moved with the trunk. This device captures the angular position of the lumbar spine in the three cardinal planes of human movement (sagittal flexion/extension, transverse rotation, and coronal tilt about the L5/S1 joint) at a frequency of 60 Hz. These angular data are then used to...
calculate the angular velocity and angular acceleration in the sagittal, coronal, and transverse planes of motion. In this study, only the sagittal and transverse plane variables were considered.

2.2.2 | Experimental task apparatus

The load used in the repetitive lifting task was a crate (33 cm [width] × 33 cm [length] × 29 cm [height]) with handles for good coupling. It was filled with a stable load corresponding to 10% (7.1 ± 1.9 kg) of the whole-body mass of each participant. Body weight was used as a normalization parameter because it was readily available data and has been shown to be effective at scaling for muscle strength (Hurd et al., 2011). Two sets of roller conveyors were used in this study to provide the beginning and end point of the lift. These conveyors were height adjustable enabling the starting and ending heights to be set relative to participant anthropometry. The height of the conveyor at the start of the lift was adjusted so that the crate handles were at the knee height of each participant, while the height of the destination conveyor was set so that the crate handles were at elbow height. The experimenter was stationed at the other end of these conveyors and would replace the load on the conveyors at the designated frequency. Finally, a visual analog scale (VAS; 16 cm long) with no fatigue (0 cm) and extreme fatigue (16 cm), was used to capture the subjective assessment of the participants.

2.3 | Experimental tasks

When participants arrived at the laboratory, a research assistant provided a concise description of the task and written informed consent was obtained. Anthropometric data (weight, height, elbow height, and knee height) were measured and recorded. Each participant was then guided through a short warmup session which consisted a set of standardized upper extremity and back muscle movement routines to prepare him/her for the lifting task. The LMM was then fitted on the participant as shown in Figure 1. After which they were allowed to select a comfortable position on the stable platform, which would be maintained throughout duration of the repetitive lifting task. For reference, those positions were marked with tapes. Before actual task performance, each participant was familiarized to the lifting task by letting him/her stand in their chosen foot position while lifting the load from the start to the end point in Figure 1 (left and right). This was repeated until the participant was comfortable with the task. The lifting task required the participant to lift the crate (load 10% of whole-body mass) from knee height and then set the crate on the take-away conveyor 90° to their right. Participants performed six lifts per minute continuously (Norasi et al., 2019) for 30 min, leading to a total of 180 lifts. Participants were not instructed to use any specific lifting technique. At the end of each 10-min segment the participants were asked to place a check mark on the VAS to rate their level of fatigue. At the end of the 30-min trial, the LMM was doffed and the participant was led through a short cool-down session.

2.4 | Independent and dependent variables

The independent variable in this study, was TIME, which was divided into three levels corresponding to the 1st, 2nd, and 3rd 10-min intervals of the 30-min lifting task (Segment 1: 0–10 min; Segment 2: 10–20 min; Segment 3: 20–30 min). The dependent variables were
the variances across the observations of the six kinematic variables obtained directly from the LMM in the sagittal and transverse plane during the concentric range of motion. These are: Variance of the Sagittal Range of Motion (sROM), Variance of the Mean Sagittal Velocity (sVEL), Variance of the Variance of the Maximum Sagittal Acceleration (sMACC), Variance of the Transverse Range of Motion (tROM), Variance of the Mean Transverse Velocity (tVEL), and Variance of the Maximum Transverse Acceleration (tMACC). The other two dependent variables were the Variance of the Peak Sagittal Plane Moment about the L5/S1 joint (sMOMmax) and Peak Spine Compression (COMP). Finally, the subjective level of fatigue was captured using the visual analog scale before task performance and at the end of the first, second, and third 10 min of lifting.

2.5 | Data processing

A custom-developed script in MATLAB was used to extract the dependent variables of interest extracted from the concentric range of lifting motion. The concentric range of lifting motion was defined as a vector of values between the time of the greatest sagittal flexion angle to the time of the maximum (rightward) transverse angle. Each of the kinematic variables were found within this range of the lifting motion. To explore the kinetics of this concentric lifting motion, a simple, dynamic biomechanical model (Appendix) utilized these kinematic variables to estimate the peak dynamic moment about L5/S1 and the resulting spine compression. To control for the large interindividual variability in all of these dependent variables, a centering technique was employed that shifted an individual’s data by a constant value so that the mean value of each participant’s data matched the overall mean (across participants) for that condition. This allowed the subsequent analysis to essentially explore the effects of the independent variable on the intra-participant variability response. After centering was completed, the variance ($s^2$) was computed across each 10-min segment.

2.6 | Statistical analysis

All statistical analyses were conducted using R (Version 4.0.2). Statistically significant differences between the variances of trunk

| Dependent variable          | Level | Mean   | Standard deviation | Variance  | F-value | p-value |
|----------------------------|-------|--------|--------------------|-----------|---------|---------|
| Sagittal range of motion   | 1     | 45.91  | 4.51               | 20.34 (A) | 7.10    | <.0008  |
|                            | 2     | 44.14  | 3.93               | 15.44 (B) |         |         |
|                            | 3     | 44.09  | 3.92               | 15.37 (B) |         |         |
| Sagittal mean velocity     | 1     | 23.40  | 6.18               | 13.90     | 4.32    | .013    |
|                            | 2     | 23.30  | 3.22               | 10.40     |         |         |
|                            | 3     | 24.10  | 3.39               | 11.5      |         |         |
| Maximum sagittal acceleration | 1     | 420.58 | 72.68              | 5282.38 (A) | 39.04  | <.0001  |
|                            | 2     | 394.04 | 54.52              | 2972.43 (B) |        |         |
|                            | 3     | 389.33 | 54.21              | 2938.72 (B) |        |         |
| Transverse range of motion | 1     | 20.37  | 2.57               | 6.60 (A)  | 11.82   | <.0001  |
|                            | 2     | 19.98  | 2.26               | 5.11 (B)  |         |         |
|                            | 3     | 20.28  | 2.22               | 4.93 (B)  |         |         |
| Transverse mean velocity   | 1     | 9.37   | 2.24               | 5.02      | 1.72    | .1798   |
|                            | 2     | 9.34   | 2.11               | 4.45      |         |         |
|                            | 3     | 9.83   | 2.08               | 4.33      |         |         |
| Maximum transverse         | 1     | 131.08 | 33.00              | 1089.00   | 0.08    | .9265   |
| acceleration               | 2     | 140.42 | 32.54              | 1058.85   |         |         |
|                            | 3     | 146.82 | 32.88              | 1081.09   |         |         |
| Maximum moment around      | 1     | 234.1  | 20.50              | 420.1 (A) | 24.99   | <.0001  |
| L5/S1 joint (Nm)           | 2     | 229.8  | 16.29              | 265.3 (B) |         |         |
|                            | 3     | 228.5  | 16.49              | 271.9 (B) |         |         |
| Maximum spine compression  | 1     | 4199.6 | 379.36             | 91671.9 (A) | 22.11  | <.0001  |
| force (N)                  | 2     | 4100.9 | 302.99             | 59338.3 (B) |        |         |
|                            | 3     | 4076.2 | 308.23             | 61445.1 (B) |        |         |

Note: Bold denotes statistically significant differences between levels at $\alpha = .008$ and variance values noted with the same letter were not statistically significant.
kinematic variables at the 1st, 2nd, and 3rd 10-min segments were explored using the Levene’s test of homogeneity of variance. The Bonferroni correction was applied by dividing the initial p value of .05 by the number of dependent variables to reduce the probability of occurrence of Type 1 error. Pairwise comparisons of the variances between levels of TIME were performed to further explore the nature of the significant differences in the values of the variance. The residuals of the subjective fatigue measurement violated the normality assumption thus, the non-parametric Friedman’s test was used to test for any statistical differences between back muscle subjective fatigue for the three levels of the independent variable. The post hoc Nemenyi method was used to explore the pairwise differences between the initial subjective fatigue and the end of each 10-min segment of lifting.

3 | RESULTS

These results of the analysis of trunk kinematics illustrate that the peak sagittal acceleration, sagittal and transverse range of motion were the trunk kinematic variables that were significantly influenced by TIME (Table 1 and Figures 2 and 3). Exploring these kinematic data a bit further, the present results indicated that there was significantly greater variance in the peak sagittal acceleration in the first 10 min as compared with the second and third 10 min of the task performance. The kinetic data (Table 1 and Figures 4 and 5), likewise, demonstrated that the variability in the moments about L5/S1 were significantly greater in the first ten-minute bout as compared with the other two bouts. The kinetics of the task were further explored by the calculation of the peak spine compression and the distributions of this spine compression force as a function of TIME are shown in Figures 5-7. Note how the spread of the distribution from the first 10-min period is greater than that of the following periods.

The analysis of the subjective fatigue showed a significant effect of time on subjective muscle fatigue (p < .05; Table 2). These post hoc analysis showed that significant increments were only present between Segment 0 (before task performance) and Segment 2, Segment 0 and Segment 3, and Segment 1 and Segment 3.

4 | DISCUSSION

The results of this study provide data that supports the hypothesis that variability in lifting kinematics/kinetics is greater in the early phases of a repetitive lifting task than those seen just ten minutes into the task. These changes may point to a dynamic level of physical flexibility and warm-up effects that changes within these early stages of lifting. While in this experiment there was a period of warm-up and familiarization provided, once the experiment began, the participants may have still been getting into their lifting rhythm and gaining task-specific flexibility that would lead to a steady state lifting style over the first 10 min of lifting. The kinematic and kinetic response observed in this study both point to this type of modification in this initial 10-min period.

This result is important because these lifting kinematics and kinetics have a direct impact on the loading of the tissues of the low back, and variability in these parameters will create variability in the loading of the internal structures of the spine. Considering peak sagittal acceleration, for example, research has shown that these accelerations directly impact the required trunk extensor muscle activation (Marras & Mirka, 1990), and the biomechanical impacts of an increased level of variance of this sagittal acceleration in the early phases of the lifting bout has direct impact on peak loading of the spine across lifts (Figure 5a). A previous study by Granata et al. (1999) of a repetitive lifting task similar to the one described in this

FIGURE 2  Plot of variance of sagittal and transverse range of motion against time

FIGURE 3  Plot of variance of maximum sagittal acceleration against time during concentric range of motion

FIGURE 4  Plot of variance of maximum moment around L5/S1 against time during concentric range of motion
FIGURE 5  Distribution of spine compression force during the first 10 min of lifting

FIGURE 6  Distribution of spine compression force during the second 10 min of lifting

FIGURE 7  Distribution of spine compression force during the third 10 min of lifting
study showed that performing the exact same exertion does not produce similar kinetics. Using an EMG-assisted biomechanical model to estimate spinal loading, their study showed that this inconsistency in kinematics resulted in approximately 20% of the lifts producing spinal compression loads that exceeded the 6400 N threshold; a condition which pre-disposes the task performer to back injuries. Our analysis of the variability of maximum moments supports this perspective and our results further show that this variability appears to vary depending on the time into the lifting bout. This is particularly interesting as it underscores the results from Marras et al. (1993) who's study reported maximum sagittal moment to be one of the key kinematic parameters that influence the development of low back injuries. The distributions of spinal compression forces align well with the results from (Granata et al., 1999). However, the load in this study was standardized to 10% of each participant’s body weight (maximum weight = 11.4 kg), while the load used in the previous study was 13.6 kg and 27.3 kg. In addition, our study required 6 lifts/min without controlling how fast the participants performed each lift while the previous study had a "faster than preferred lifting speed" as an independent level, and this could have significantly increased trunk acceleration which could subsequently increase trunk extensor moment and compression forces.

Interpretation of these kinematic results may be attributed to motor variability (MV)—an inherent characteristic of the neuromuscular system to explore and refine movement patterns while interacting with the environment (Krakauer & Mazzoni, 2011). In this regard, the neuromuscular system actively alters its structure, that is, muscle recruitment pattern, and so forth in an effort learn the task for optimum performance. This is associated with increased variability at the on-set of task performance (Wu et al., 2014), hence the increased variability in the variables observed during the first 10 min as compared with the second and third 10 min. While it is conceivable that the initial stretching and lifting practice session might have played a role in the variability trend, the authors do not believe this was the case. The practice session was intended to familiarize the participant with the start and end point of the lifting task, and not the technique to complete the task.

The variability of transverse plane acceleration was found to be insignificant and this could be ascribed to the nature of the lifting task. The task was setup to have a starting height at the knee level and end height at standing elbow height. Given that the participants would be focused on getting the load up to approximately neutral posture before twisting to set load down, the sagittal plane trunk extension was the most difficult and time-consuming part of each lift and study participants may have used a combination of the two studied lifting techniques to bring the load to neutral trunk posture (Bazrgari et al., 2004). Thus, the participants were much more variable with their lifting technique in during the time-consuming trunk extension phase, compared to the significantly shorter trunk twisting phase. This was evident in the significant variability observed in the sagittal trunk acceleration, compared with the transverse plane acceleration.

The findings of this study support previously established general recommendations for the start-up of the work day and may have implications for the use of existing risk assessment tools employed by ergonomists in industry. One general recommendation that is often promoted for work day start up, is the use of muscular warmup and stretching routines before task performance to increase joint range of motion as well as reduce the likelihood of injury occurrence (Mahieu et al., 2007). As such, consideration should be given to providing manual material handling workers a time for warmup and stretching as well as a period of lowered productivity expectations as they gain their rhythm and consistency in their lifting technique. This will enable material handlers to gradually warm up, which enhances blood flow to muscles and tendons for efficient performance and injury prevention (Nakamura et al., 2015). These recommendations are not new, or the result of the current study, but are sound advice that is supported by the results of the current study. Our results shown in Figure 5 indicate that the probability of high spine compression level (right-hand tail of distribution) is increased during the early phases of the lifting bout and preparing the body through warm-ups could be particularly important. In terms of the implications of these results relative to risk assessment tools, the results of this study can be influential in two ways. First, this study has demonstrated that there is variability in the kinematics of trunk motions, even during very simple, consistent lifting tasks, and this kinematic variability results in significant variability in spine reaction forces. Risk assessment tools such as the Revised NIOSH lifting equation (NLE; Waters et al., 1993) do not account for performance characteristics such as variability in trunk kinematics and may not fully reflect the risk of back injury, particularly in those rarely occurring scenarios where the spine reaction forces are considerably higher than the average. Second, given the time-dependency of this variability shown in the current study, risk assessment tools might be enhanced by recognizing the time-varying, probabilistic low back injury risk present in the repetitive lifting tasks. The interaction between the impact of warmup/stretching and the variability as it should be represented in risk assessment tools is an area for future research.

There are a few limitations to the generalizability of these results that need to be considered. First, this study employed college students, not practiced manual materials handlers. The skill that experienced manual materials handlers possess may allow them to be a bit more focused/consistent in their lifting technique, even in the early phases of each day's MMH activities. This is a skill which novel MMH might not possess. Thus, future studies may focus on understanding this variability response in experienced manual

| TABLE 2  | Nemenyi pairwise comparisons for subjective fatigue |
|------------------------|------------------------|
| Before task performance | After 10 min | After 20 min |
| After 10 min | .159                  |
| After 20 min | <.001                 | .122         |
| After 30 min | <.001                 | <.001        | .159         |

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material handlers. Second, the lifting task chosen for this study was very controlled in terms of the starting and ending points for each lift. This was done deliberately to create a precise lifting task that would most easily highlight the changes in the variance of the dependent measures. Individuals performing MMH activities on the job, certainly have much more variability in the characteristics of the lifting task and this type of variability would provide another layer of complexity in the assessment of variability in biomechanical loading.

5 | CONCLUSIONS

The results from this study suggests a temporal impact to the intra-individual variability in manual materials handling tasks. Further exploration of the effects of time, as well as other lifting parameters, on the variability of lifting kinematics and kinetics, may provide a deeper understanding of injury risk and may offer potential avenues for appropriate ergonomic interventions to prevent low back injuries.

CONFLICT OF INTERESTS

The authors declare that there are no conflict of interests.

PEER REVIEW

The peer review history for this article is available at https://publons.com/publon/10.1002/hfm.20888.

DATA AVAILABILITY STATEMENT

The data that supports the results of this study and all the tables and figures in this article are available upon reasonable request from the corresponding author.

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**APPENDIX: DYNAMIC BIOMECHANICAL MODEL**

The net external moment about the L5/S1 joint consisted of five components:

\[
M_{L5/S1} = \text{Static torso moment} + \text{Inertial torso moment} + \text{Tangential torso moment} + \text{Static handload moment} + \text{Dynamic handload moment}
\]

\[
M_{L5/S1} = (F_{BW} \times \sin(\theta) \times r) + (I_{CM} \times \dot{\theta}) + (F_T \times r) + (m_L \times g \times \sin(\theta) \times R) + (m_L \times a \times \sin(\theta) \times R)
\]

Where:

- \(m\) = mass of torso, calculated as 0.55 \times whole body mass (kg) \(^*\)
- \(m_L\) = mass of load calculated as 0.10 \times whole body mass (kg)
- \(\theta\) = trunk sagittal angle measured from vertical (radians)
- \(\dot{\theta}\) = instantaneous angular velocity (radians/sec)
- \(\ddot{\theta}\) = instantaneous sagittal acceleration (radians/sec/sec)
- \(g\) = acceleration due to gravity (9.81 m/sec/sec)
- \(R\) = distance of shoulder joint from L5/S1, calculated as 0.23 \times stature (m) \(^*\)
- \(r\) = distance of center of mass of the torso from L5/S1, calculated as 0.2 \times stature (m) \(^*\)
- \(a\) = instantaneous vertical, linear acceleration of load (m/sec/sec)
- \(F_{BW}\) = gravitational force on center of mass of torso, calculated as \(m \times g\) (N)
- \(A\) = moment arm of the extensor muscle about the L5/S1 fulcrum (0.06m) \(^*\)
- \(I_{CM}\) = moment of inertia, calculated as \(m \times (0.497 \times 0.5 \times \text{stature})^2\) (kgm\(^2\))
- \(F_T\) = tangential force due to trunk rotation, calculated as \(m \times r \times \dot{\theta}\)
- \(F_C\) = centripetal force away from the L5/S1 joint, calculated as \(m \times r \times \ddot{\theta}\) (N)

The spinal compression is estimated as the net downward force along the axis of the spine: (Kumar, 1988)(Kumar, 1988)

\[
F_{comp} = (F_M) - (F_C) + (F_{BW} \cos(\theta)) + (m_L \times g \times \cos(\theta)) + (m_L \times a \times \cos(\theta))
\]

Where:

\[
F_M = \frac{M_{L5/S1}}{A} = \text{compression force due to extensor muscle force (N)}
\]

\(^*\)Derived from data and regression equations found in Webb Associates (1978).

\(^*\)Derived from data found in Chaffin et al. (2006).

\(^*\)Derived from (Kumar, 1988).