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Two linear regression models predicting cumulative dynamic L5/S1 joint moment during a range of lifting tasks based on static postures

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Abstract

Previous studies have indicated that cumulative L5/S1 joint load is a potential risk factor for low back pain. The assessment of cumulative L5/S1 joint load during a field study is challenging due to the difficulty of continuously monitoring the dynamic joint load. This study proposes two regression models predicting cumulative dynamic L5/S1 joint moment based on the static L5/S1 joint moment of a lifting task at lift-off and set-down and the lift duration. Twelve men performed lifting tasks at varying lifting ranges and asymmetric angles in a laboratory environment. The cumulative L5/S1 joint moment was calculated from continuous dynamic L5/S1 moments as the reference for comparison. The static L5/S1 joint moments at lift-off and set-down were measured for the two regression models. The prediction error of the cumulative L5/S1 joint moment was 21±14 Nm × s (12% of the measured cumulative L5/S1 joint moment) and 14±9 Nm × s (8%) for the first and the second models, respectively.

Keywords

manual materials handling; low back pain; cumulative L5/S1 moment; static moment

1. Introduction

Lifting tasks have been identified as a risk factor for work-related low back pain (LBP) (Lotters *et al.* 2003, Kuiper *et al.* 2005). Previous literature has suggested that spinal load on the low back can contribute to LBP (Chaffin and Park 1973, Norman *et al.* 1998). From a biomechanical perspective, it is hypothesised that low back injury is developed when the spinal load exceeds the strength tolerance of the low back joint (McGill 1997). Therefore, the forces and moments of the lumbosacral (i.e. the L5/S1) joint in relation to tissue tolerance of the spinal joint have been frequently studied for various lifting activities (Plamondon *et al.* 1996, Marras *et al.* 2006, Faber *et al.* 2011). Among the studied spinal variables, the peak value of the L5/S1 joint loading for various lifting tasks has been widely investigated (Skotte 2001, Lavender *et al.* 2003, Shin and Mirka 2004, Jiang *et al.* 2005) as

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it is assumed that injuries occur once peak mechanical load exceeds the failure tolerance (McGill 1997).

Besides the peak load of the L5/S1 joint, several studies have focused on the relationship between LBP and estimated cumulative L5/S1 joint loads for different job tasks (Kumar 1990, Norman *et al.* 1998, Santaguida *et al.* 2005, Gregory *et al.* 2009). It has been found that cumulative compression and shear forces over a work shift were significantly higher in the group of institutional aides with back pain than in the group without back pain (Kumar 1990). In a study investigating workers in the automotive industry, it was found (Norman *et al.* 1998) that workers with increased cumulative L4/L5 moment over a work shift were more likely to report LBP (Odds Ratio: 1.6). In a review paper by Waters *et al.* (2006), the cumulative L5/S1 joint loading was summarised to be an important contributing factor for LBP. McGill (1997) hypothesised that sustained spinal loading for a long duration caused degraded tolerance of spinal tissues, which eventually reduced the margin of safety to zero.

One challenge of assessing the cumulative joint load during a field survey is that the joint load during the course of a lifting task varies. The varying joint loads at each time instant need to be identified in order to calculate the cumulative load accurately for the entire lifting task. This calculation procedure, however, may be laborious. In order to reduce the process time for calculating the cumulative joint load, Callaghan *et al.* (2001) investigated a few simplified methods and found that identifying the joint load at 5 frames/s in a video clip of the task preserved the time varying information and provided a good estimate of the cumulative joint load with 1.8% absolute error. With this frame rate, however, the authors indicated that a long processing time was still required (Callaghan *et al.* 2001). A recent study (Waters *et al.* 2011) made an untested hypothesis that the integrated cumulative dynamic low back joint load from lift-off to set-down may be approximated by the static joint load at the lift-off point multiplied by the time between the lift-off and set-down instants (i.e. the time for the course of a lifting task). This method can potentially simplify the assessment process of the cumulative low back joint load since the load can be easily estimated by identifying only the joint load at the lift-off point and the duration of the lift.

The goal of the current study was to evaluate two methods using the static L5/S1 joint moment at one or two time points to estimate the cumulative dynamic L5/S1 joint moments of lifting tasks for future field research. The first method was a regression model based on the mean of the static L5/S1 joint moments at both the lift-off and set-down points and the duration of the lifting task. The second method was based on the static L5/S1 joint moment only at the lift-off point and the duration of the lifting task. It was expected that, for both methods, the static L5/S1 joint moment would have a linear relationship with the cumulative dynamic L5/S1 joint moment during a lifting period from lift-off to set-down.

2. Methods

A lifting experiment was designed to provide reference cumulative dynamic L5/S1 joint moments during various lifting conditions (Figure 1). Because of the constraint of the experimental setup, only male participants were recruited and took part in the experiment (12 male participants, age: 47.5±11.3 years, height: 1.74±0.07 m, body mass: 84.5±12.7 kg).

The experimental protocol was approved by the relevant Institutional Review Board. Prior to the experiment, the testing procedures were explained to the participants and their informed consent was obtained. The participants lifted a plastic crate (10 kg, Width × Depth × Height=39 cm × 31 cm × 22 cm) in front of them and placed it on an adjustable shelf. The shelf height was set up for each participant to accommodate three levels of lifting ranges: from floor to knuckle height, floor to shoulder height, and knuckle to shoulder height. The lifting ranges were combined with three levels of asymmetric angles including 0 deg, 30 deg to the right, and 60 deg to the right, which resulted in a total of nine lifting conditions for each participant. These lifting conditions covered most lifting conditions in practice in terms of lifting range and asymmetric angle (Dempsey 2003). The weight of the plastic crate was set to 10 kg so that it would not exceed the National Institute for Occupational Safety and Health (NIOSH) recommended weight limit in tested lifting conditions (Waters *et al.* 1993). The participants were instructed to perform each lifting task using their choice of lifting style (i.e. free style method of lifting) and lifting speed, without moving their feet. The initial horizontal distance between the crate and the participants was not restricted. Before the experiment, the participants had five minutes to practice. For each lifting condition, two repetitions were performed. A total of 18 lifts (3 lifting heights × 3 asymmetric angles × 2 repetitions) were assigned to each participant in random order. A 15-second break was given between each lift.

The 3D spatial positions of the participants' body joints during the lifting tasks were measured at 100 Hz by an optoelectronic motion tracking system (Motion Analysis, Santa Rosa, CA). Reflective markers for the system were attached on the crate and over several anatomical landmarks of the participants' body segments including shanks (lateral and medial malleolus), thighs (lateral and medial femur epicondyle, trochanter), pelvis (left and right ASIS, midpoint between left and right PSIS,), trunk (navel, spine at 10th rib height, xyphion, T6, suprasternal, C7), head (left and right tragion, head vertex), forearm (radial and ulnar styoid), and upper arm (lateral and medial humeral epicondyle, acromion) (McConville *et al.* 1980). To minimise motion artefacts of the reflective markers during data collection, the participants wore only shorts and shoes during the experiment. In addition, the ground reaction forces were measured by two force plates (Model: 9286AA, Kistler, Switzerland), which were synchronised with the motion tracking system with a sampling frequency of 100 Hz. The raw kinematic and force plate data were filtered with a 4th order Butterworth low pass filter at 8 Hz. A trigger was mounted at the bottom of the crate to record the onset (lift-off) and cessation (set-down) of each lifting task.

For each individual lifting trial, the static L5/S1 joint moments were calculated by a top-down 3-D linked segment model which was based on the position of trunk, upper extremities, and load (Kingma *et al.* 1996; Plamondon *et al.* 1996). Ideally, for the purpose of comparisons, the dynamic L5/S1 joint moments should have been calculated using the same top-down method. However, using the top-down method for calculating dynamic body joints required monitoring real-time hand contact forces during the lifting task. Due to the limitations of the apparatus used in the study, real-time measurements of hand forces were not feasible. Alternatively, a bottom-up 3-D link segment model based on the movement of the lower extremities and ground reaction force was used in the current study to calculate the dynamic L5/S1 joint moments (Kingma *et al.* 1996, Plamondon *et al.* 1996). As the vector summation of the L5/S1 moments in 3-D has a high correlation with the L5/S1 compression force and a moderate correlation with the shear force during varying lifting tasks (van Dieen and Kingma 2005), both the static and dynamic L5/S1 moments were determined by the vector summation. The reference cumulative dynamic L5/S1 joint moment was calculated by a rectangular integration of the dynamic L5/S1 joint moments (the area under the thick solid curve in Figure 2).

A preliminary data analysis showed that repetition did not have a significant effect on the outcome variables. Therefore, the mean of the two repetitions was calculated for each condition to build the entire dataset for reducing the sampling error. The entire dataset, including each trial and each participant, was then used for building the regression models. The first regression model (Equation (1)) was based on the static L5/S1 joint moment at lift-off multiplied by the time between lift-off and set-down (the area of the rectangle under the dash-dot line in Figure 2).

$$C=a_1 \cdot S_{\text{lift- off}} \cdot (t_{\text{set- down}} - t_{\text{lift- off}}) + b_1 + \varepsilon_1 \quad (1)$$

where *C* is the vector summation of the reference cumulative dynamic L5/S1 joint moment from lift-off to set-down (Nm × s),

$S_{\text{lift-off}}$ is the vector summation of the static L5/S1 joint moment at lift-off (Nm),

$t_{\text{lift-off}}$ is the time instant of lift-off (s),

$t_{\text{set-down}}$ is the time instant of set-down (s),

a_1 is the slope of the first linear regression model,

b_1 is the intercept of the first linear regression model,

and ε_1 is the error term (residual) of the second regression model.

The second regression model (Equation (2)) was based on the mean of the static L5/S1 joint moments at lift-off and set-down multiplied by the time between these two time instants (the area of the trapezoid under thεe dash line in Figure 2).

$$C=a_2 \cdot \frac{(S_{\text{lift- off}} + S_{\text{set- down}})}{2} \cdot (t_{\text{set- down}} - t_{\text{lift- off}}) + b_2 + \varepsilon_2 \quad (2)$$

where *C* is the vector summation of the reference cumulative dynamic L5/S1 joint moment from lift-off to set-down (Nm × s),

$S_{\text{set-down}}$ is the vector summation of the static L5/S1 joint moment at set-down (Nm),

a_2 is the slope of the second linear regression model,

b_2 is the intercept of the second linear regression model,

and ε_2 is the error term (residual) of the second regression model.

According to the shape of the areas, these two methods are referred to as the RECTANGLE method and TRAPEZOID method, respectively.

The null hypotheses that the slope was equal to one and the intercept was equal to zero were tested for the two regression models. A paired t-test was used to examine whether the absolute errors (absolute value of the residual) of the estimated cumulative dynamic L5/S1 joint moments of these two regression models were significantly different from each other. Within each regression model, a repeated-measures analysis of variance (ANOVA) was performed on the absolute error to test for the effects of the two independent variables (lifting range and asymmetric angle) and their two-way interaction term. The participants were treated as a block in the ANOVA. A *p*-value < 0.05 was considered to be statistically significant.

3. Results

The results indicated that the cumulative dynamic L5/S1 joint moment was linearly correlated to the area of both the RECTANGLE and the TRAPEZOID (Figure 3). The regression equation of the first model (RECTANGLE method) was

$$C=0.46 \cdot S_{\text{lift- off}} \cdot (t_{\text{set- down}} - t_{\text{lift- off}}) + 53.8 + \varepsilon_1. \quad (3)$$

The coefficient of determination (R-square) of the regression model was 0.83. The mean of absolute value of error term was 21±14 Nm × s, or 12% in terms of the percentage of the cumulative moment, with a skewness of 0.8. The root mean squared error term was 25.2 Nm × s.

The regression equation of the second model (TRAPEZOID method) was

$$C=0.72 \cdot \frac{(S_{\text{lift- off}} + S_{\text{set- down}})}{2} \cdot (t_{\text{set- down}} - t_{\text{lift- off}}) + 12.0 + \varepsilon_2. \quad (4)$$

The coefficient of determination (R-square) of the regression model was 0.93. The mean of absolute value of error term was 14±9 Nm × s, or 8% in terms of the percentage of the cumulative moment, with a skewness of 1.1. The root mean squared error term was 16.7 Nm × s.

For both regression models, the null hypotheses that the slope is equal to one and the intercept is equal to zero were rejected ($p < 0.001$). The result of the paired t-test indicated that the absolute error of the TRAPEZOID method was significantly smaller than that of the RECTANGLE method ($p < 0.001$). The ANOVA results indicated that lifting range was the only factor that significantly influenced the absolute error of the TRAPEZOID method and RECTANGLE method (Table 1 and Figure 4). Without using the model to correct, the area of RECTANGLE and TRAPEZOID overestimate the reference cumulative dynamic L5/S1 joint moment for all 9 lifting conditions (Table 2).

4. Discussion

Continuous 3D motion data are essential for the determination of the cumulative L5/S1 joint load over the course of a lifting task using a biomechanical model. Since using a traditional optoelectronic motion monitoring system is not feasible for most field surveys, many studies started focusing on using other technologies for measuring body movement, such as inertial measurement unit (Luinge and Veltink 2005, Faber *et al.* 2010) and ultrasound receiver (Marras *et al.* 2010). While those technologies offer great promise for quantifications of dynamic spinal loading in the field, applications of the technologies are still limited in some industrial settings (Marras *et al.* 2010, de Vries *et al.* 2010).

The results of the current study indicate that the area of RECTANGLE and the area of TRAPEZOID had an approximate linear relationship to the reference cumulative dynamic L5/S1 joint. This finding may provide an alternative method for estimating cumulative L5/S1 joint moments based on the static L5/S1 moment at lift-off and at set-down, and the time duration from lift-off to set-down. The required static moment and time duration data could be estimated from posture analysis using video clips frames combined with a biomechanical model.

The TRAPEZOID method had a better estimate compared with the RECTANGLE method since the TRAPEZOID method included the static L5/S1 joint moment at both lift-off and set-down while the RECTANGLE method only employed the static moment at lift-off. However, inclusion of one more static moment as input data in the TRAPEZOID method would require collecting additional posture data at the set-down during the field survey. Processing the extra data would generally double the analysis time that would be required for the RECTANGLE method. Therefore, the choice of these two methods depends on the availability of resources and the accuracy required for a field survey.

The area of the RECTANGLE in RECTANGLE method in the current study was similar to the ‘work only’ method examined in Callaghan *et al.* (2001) for estimating the cumulative moment of the L4/L5 joint during lifting tasks. In their study, the cumulative spinal moment, calculated by the load held by hands multiplied by the time period for the hand loading, was termed ‘work-only’ method. It was compared with the reference data which was the integration of the static L4/L5 joint moment for the entire lifting cycle, including the time before lift-off and the time after set-down. Their results showed that the ‘work only’ method underestimated the cumulative L4/L5 joint moment by approximately 15–25% when compared to their reference. In the current study, the area of the RECTANGLE was 49% greater than our reference cumulative L5/S1 joint moment on average (Table 2). The discrepancy in the results between these two studies was primarily attributed to the following two main reasons. First, the reference of the cumulative L5/S1 joint moment in the current study was integrated from lift-off to set-down, which did not include the preparation duration before the lift-off and finishing duration after set-down. A further analysis indicated that, on average, this partial cumulative L5/S1 moment accounted for 52% of the cumulative moment of the entire lifting course in the current study. By including the data for the preparation and finishing durations for comparisons, the RECTANGLE method underestimated the total cumulative L5/S1 moment by an average 32.0% which was comparable to results reported in Callaghan *et al.* (2001). Second, the tested lifting tasks in the current study involved moving a crate from a low position to a high position but not vice versa. The static moment at lift-off used for estimating the cumulative moment was larger than the reference L5/S1 moment for most of the time from lift-off to set-down (Figure 2).

In the study in Callaghan *et al.* (2001), one lifting task involved lowering a weight from a high to a low position. Such a lifting task would have a lower static L5/S1 moment at the lift-off point to offset the overestimation.

In general, the more time frames used as input, the more precise the estimated cumulative moment (Andrews and Callaghan 2003). Therefore, adding additional frames between lift-off and set-down can improve the accuracy of the estimate. However, it should be noted that the selection of the time frames can vary the error. For example, selecting four frames capturing lift-off, closest-to-body, highest point, and set-down would yield less error on the estimated body segment angular trajectories for a lifting task compared with four equal time interval frames (Hsiang *et al.* 1998). In the present study, if a third time frame was added, choosing the time frame where the local minimum occurred between lift-off and set-down seems to yield a better estimate than choosing the middle time frame (Figure 2). A further analysis showed that this would yield the following regression model

$$C=0.93\cdot\left[\frac{(S_{\text{lift- off}}+S_{min})}{2}\cdot(t_{min}-t_{\text{lift- off}})+\frac{(S_{min}+S_{\text{set- down}})}{2}\cdot(t_{\text{set- down}}-t_{min})\right]+11.7+\varepsilon \quad (5)$$

where S_{min} is the vector summation of the static L5/S1 joint moment when the local minimum occurs (Nm),

t_{min} is the time instant when the local minimum occurs (s),

The coefficient of determination (R-square) of the regression model was 0.99. The mean of absolute value of error term was 7±6 Nm × s, or 4% in terms of the percentage of the cumulative moment, with a skewness of 1.0. The root mean squared error term was 9.2 Nm × s. This result indicated that choosing the time when the local minimum occurred as the third frame could improve the estimate of the cumulative L5/S1 moment for the tested lifting tasks in the experiment. However, unlike lift-off and set-down, identifying this time frame from a video clip of a field survey could be challenging as the body posture in this frame may lack identifying characteristics. Therefore, the selection of the additional frame is likely to be task-dependent since the identification of body posture is in relation to a task. In comparison, equal time interval frames have a better accessibility since they can be easily extracted from a video clip by computer.

In the current study, the dynamic L5/S1 joint moment was calculated by the bottom-up method while the static L5/S1 joint moment was calculated by the top-down method. The top-down method seems to be more practical than the bottom-up method for field use because it does not require measurements of the ground reaction force for calculating the static L5/S1 moment. However, it requires continuous measurements of hand contact force for calculating the dynamic L5/S1 moment required, which was limited by our data collection instrumentation. Although alternatively the hand contact force can be estimated by calculating the acceleration of the plastic crate, the exact force transitions to the hands at lift-off and set-down would still be difficult to derive. Without accurate force transitions, the L5/S1 moment would contain unrealistic sudden jumps at lift-off and set-down. Previous research showed that the difference in calculating the dynamic L5/S1 joint moment between the top-down and bottom-up method was about 3.9% (Kingma *et al.* 1996). Therefore, it should be noted that there is an error source in calculating the L5/S1 joint moment introduced by using different biomechanical models. However, the validity of the study results is unlikely to be significantly affected by errors inherent in the methodology difference since this error is much smaller than the variation of the measured L5/S1 joint moment.

A few study limitations should be noted. First, as the participants were free to choose their own lifting speed, this lifting speed can be categorised as ‘normal’ (Tsuang *et al.* 1992, Lin *et al.* 1999). Compared with fast lifting, the resultant dynamic component of the L5/S1 joint moment with normal lifting speed was relatively small. This makes the area representing overestimation larger than the area representing underestimation during the lifting course from lift-off to set-down (Figure 2), which results in overestimations of the cumulative dynamic moments by the area of RECTANGLE and TRAPEZOID. If the lifting speed were instructed to be faster, the dynamic moment from lift-off to set-down would have deviated from the static moment more (de Looze *et al.* 1994, Lavender *et al.* 2003). A previous study showed that when the dynamic component of the L5/S1 joint moment during a faster lifting speed was added to the static moment, the estimated peak L5/S1 moment was 1.25 times higher (Tsuang *et al.* 1992). Thus, it is speculated that the current regression equations might underestimate the cumulative dynamic L5/S1 joint moment for highly dynamic lifting tasks.

Second, only one 10 kg weight was used for the lifting tasks. A hand-held weight more than 10 kg was not tested due to the NIOSH recommended weight limit for protecting human subjects from potential lifting-related injuries. Previous research indicates that the hand-held weight had a significant effect on the L5/S1 joint moment during lifting tasks, accounting for about 25% of the variance in the peak moment (Lavender *et al.* 2003). However, the effects of lifted weights on cumulative load or moment remain unclear. Generally, a heavy weight requires an increased force exertion for lifting and placing the weight, resulting in an increased static moment at the lift-off and set-down points. On the other hand, heavy weights may lead lifters to choose a slower lifting speed to reduce the dynamic component of the L5/S1 joint moment for protecting themselves (Lavender *et al.* 2003). Since both the static and the dynamic moments can be influenced by the weight, the coefficients of the regression equation could be altered as the weight load changes. In addition, only using a 10 kg weight during the experiment may have limited the observation of intra-participant variability. Previous studies showed that intra-participant variability of L5/S1 moments increased with increasing external load and accounted for up to 24% of the total trunk moment variability during varying lifting conditions (Mirka and Baker 1993, Granata *et al.* 1999). With an increased intra-participant variability, the derived predicted errors in this study will be inflated.

Third, the effect of the lifting technique was not examined in the current study as the participants were instructed to use a free style technique for the lifting trials. A further analysis showed that the extreme knee angle was close to 90 degree for all the participants when they lifted the weight from the ground. Such a lifting technique can be considered a semi-squat (Faber *et al.* 2010). Lifting techniques can be altered by training and experiences (Schibye *et al.* 2003, Keir and MacDonell 2004) and have a potential for changing the static and dynamic L5/S1 moments (van Dieen *et al.* 1999). Therefore, lifting techniques may affect the validity of the results of the current study. Investigation into effects of different lifting techniques such as stoop vs. squat is recommended.

Fourth, it should be noted that only male participants were recruited in the current study due to the experimental setup. Based on the biomechanical models used in the study, the same anthropometric and motion data of different genders would not yield a significant difference in the calculated spinal moments. Therefore, the validity of the study findings would not be significantly compromised by the absence of female participants. One can argue that there is some evidence that male and female workers have different lifting techniques (Jager *et al.* 1991, Lindback and Kjellberg 2001), which may impact the spinal loading for the same lifting task. In our opinion, the effect of gender is likely to be confounded within the effect of the lifting technique.

Lastly, the feet of the participants were fixed in the experiment to accommodate the limitations of the force plates used in the study. In reality, people tend to move their feet forward when placing the load to reduce the moment arm for the lifting task, resulting in reduced spinal moments. By restricting the participants' feet during the testing, the study may have artificially increased the spinal moments at the set-down points of the lifting trials. This artificial increase, however, would have similar effects on both static and dynamic spinal moments because of the equally reduced moment arms. Therefore, feet position may not have a significant effect on the validity of the two proposed methods for estimating cumulative spinal moments.

In summary, caution should be exercised while applying the regression models to estimate cumulative spinal moments because several other variables that were not evaluated in the study may have a potential for affecting the validity of the models. If variations in the lifting technique are small and the lifting speeds are not very high, the proposed methods for estimating cumulative spinal moments should have practical applications for field surveillance.

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Practitioner Summary

The proposed regression models may provide a practical approach for predicting the cumulative dynamic L5/S1 joint loading of a lifting task for field studies since it requires only the lifting duration and the static moments at the lift-off and/or set-down instants of the lift.

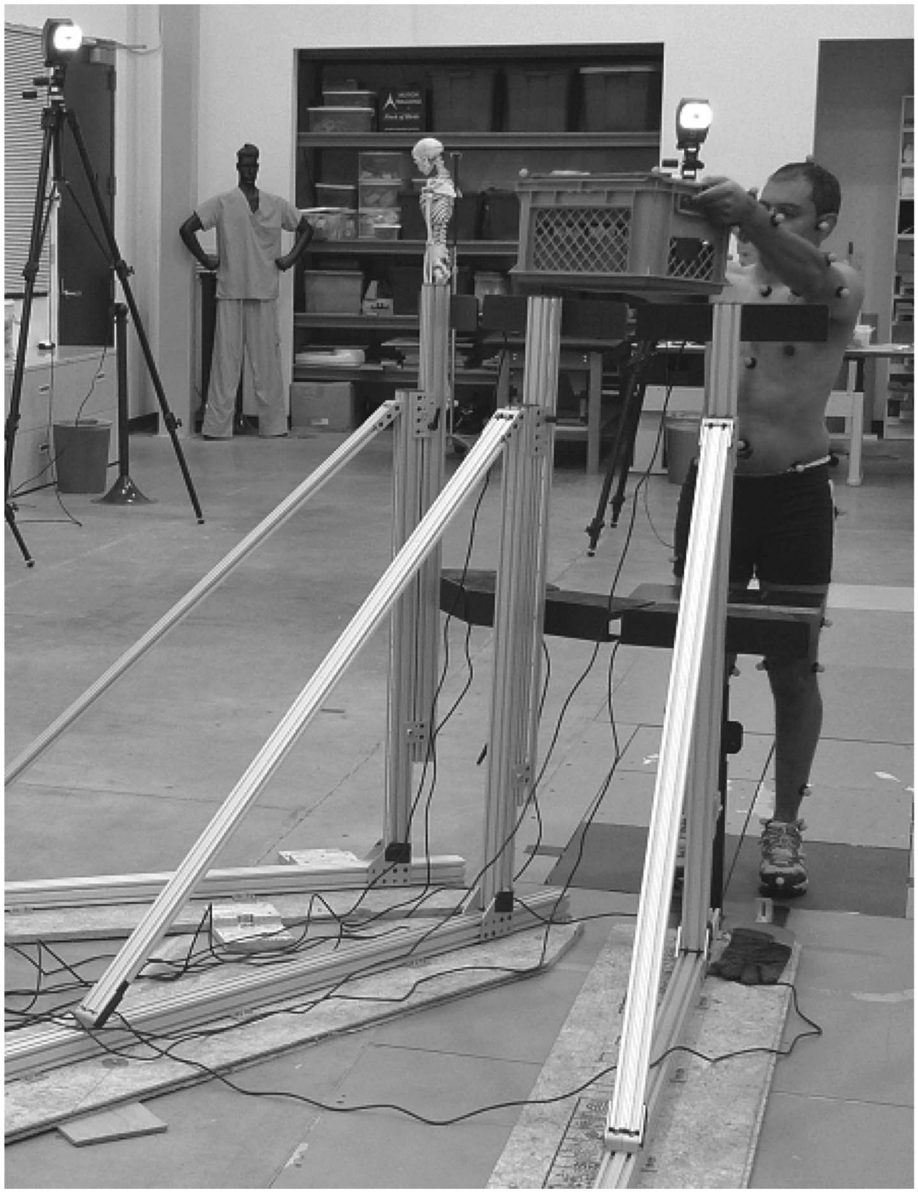

Figure 1.
Experimental setup for the lifting tasks. There were three lifting ranges (from floor to knuckle height, floor to shoulder height, knuckle to shoulder height) and three lifting asymmetric angles (0 deg, 30 deg and 60 deg to the right).

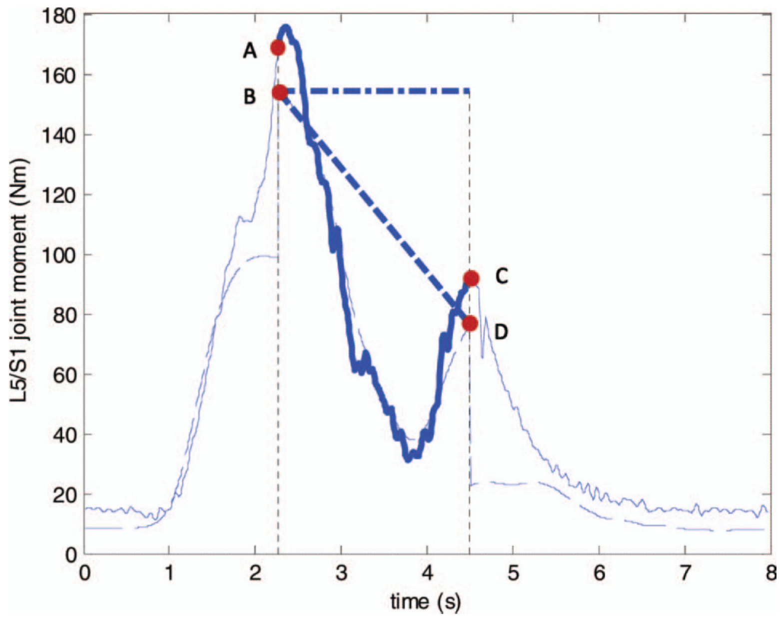

Figure 2.

Y-axis is the total L5/S1 moment. X-axis is the time of the lifting course. The thin solid curve is the dynamic L5/S1 joint moment during a lifting task (floor to shoulder height, 60 degree to the right). The thin dash line is the static L5/S1 joint moment. The bold solid curve is the reference L5/S1 joint moment from lift-off to set-down. The area under the bold dash line represents the TRAPEZOID method. The area under the bold dash-dot line represents the RECTANGLE method. Points A and C are the dynamic L5/S1 joint moment at lift-off and set-down, respectively. Points B and D are the static L5/S1 joint moment at lift-off and set-down, respectively.

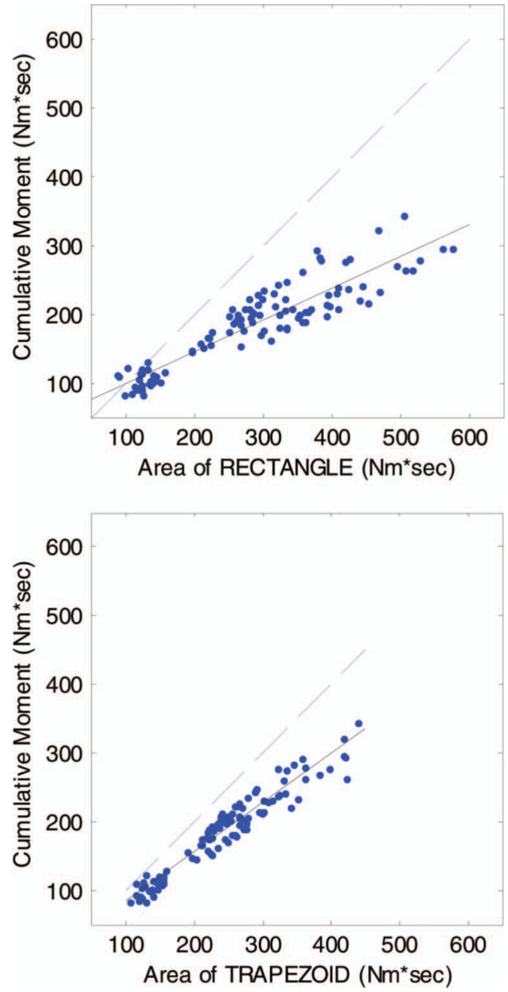

Figure 3.
Upper chart: The relation between the area of the TRAPEZOID and the reference cumulative dynamic L5/S1 joint moment. Lower chart: The relation between the area of the RECTANGLE and the reference cumulative dynamic L5/S1 joint moment. The solid line is the linear regression line. The dash line is the diagonal line. The dataset consists of the means across the replication.

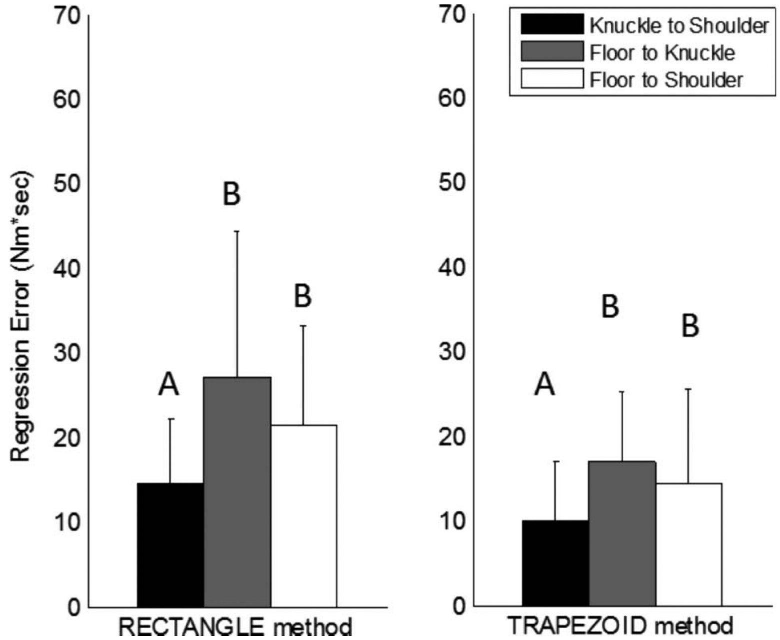

Figure 4.
The effect of lifting range on the absolute error.

Table 1

Summary of ANOVA for the absolute error of the regression models.

	RECTANGLE method		TRAPEZOID method	
	F value	***p*-value**	***F*-value**	***p*-value**
Participants	1.72	0.182	1.31	0.223
Lifting range	14.26	< .0001	17.06	< .0001
Asymmetric angle	1.23	0.300	0.75	0.47
Lifting range × asymmetric angle	1.18	0.316	0.96	0.432

Table 2

Mean value and standard deviation of the reference cumulative dynamic L5/S1 joint moment, estimated moment based on RECTANGLE and TRAPEZOID methods, area of RECTANGLE and TRAPEZOID, and the lifting duration for nine lifting conditions.

Lifting range	Asymmetric angle (°)	Reference cumulative L5/S1 joint moment from lift-off to set down (Nm × s)	Estimated cumulative moment based on RECTANGLE method (Nm × s)	Estimated cumulative moment based on TRAPEZOID method (Nm × s)	Area of RECTANGLE (Nm × s)	Area of TRAPEZOID (Nm × s)	Time from lift-off to set-down (sec)
Floor to knuckle height	0	221 (47)	190 (33)	206 (46)	295 (71)	270 (63)	1.6 (0.2)
	30	228 (49)	198 (35)	210 (47)	314 (75)	276 (66)	1.7 (0.3)
	60	220 (42)	200 (31)	201 (39)	317 (67)	263 (55)	1.7 (0.3)
Knuckle height to shoulder height	0	110 (27)	118 (18)	121 (27)	139 (38)	151 (38)	1.6 (0.3)
	30	111 (23)	116 (16)	115 (23)	134 (34)	144 (33)	1.7 (0.3)
	60	116 (30)	123 (21)	121 (29)	150 (45)	152 (41)	1.8 (0.3)
Floor to shoulder height	0	213 (41)	230 (41)	226 (49)	384 (89)	298 (68)	2.1 (0.4)
	30	214 (38)	234 (36)	226 (42)	392 (78)	298 (58)	2.1 (0.3)
	60	217 (37)	241 (38)	224 (43)	406 (82)	295 (60)	2.2 (0.3)