DYNAMIC VERSUS STATIC ANALYSES OF LIFTING A BOX FROM THE FLOOR

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Ergonomics, Biomechanics, Low-Back, Posture, Floor Slope, L5/S1

ABSTRACT

Lifting objects from below knee height has been implicated as a source of low back pain and injury. Static models have often been used to assess forces produced in the lumbar region by lifting; however, inertial forces generated by acceleration may be significant. Therefore, the goal of this investigation was to assess differences between static and dynamic analysis methods. Sagittal plane kinematics were collected on 21 men and 22 women of college age while lifting a milk crate (men = 25 kg, women = 15 kg) from the floor to standing knuckle height on level as well as sloped (facing uphill and downhill at 10° and 20°) ground conditions. Both static and dynamic top-down inverse models were utilized to assess net muscular moments at L5/S1 as well as the posture of the person at the time of static max (TSM) and dynamic max (TDM) moments. The TDM moment was significantly later than the TSM in the level through uphill conditions ($p<0.001$). The dynamic max moment was significantly greater than the static max moment in all conditions ($p<0.001$). Torso angles at TSM exhibited a significantly greater forward lean (by < 2°) in the level through uphill conditions ($p<0.001$). Overall low-back curvature, hip angles, knee angles, and ankle angles were not affected by the type of model ($p>0.05$), though several minor differences occurred at conditions other than the level (most dramatic in the downhill 20° condition). Therefore, if moments are of interest, a dynamic model should be utilized. However, body position is very similar at TSM and TDM.

INTRODUCTION

Pain and injury suffered in the lower back is a significant problem in the United States. Out of the 1.4 million occupational injuries reported by the Bureau of Labor Statistics [1] that caused lost days from work in 2002, 11.7% involved the lumbar region of the back. Of these low-back injuries, 38.8% were caused by overexertion in lifting. Therefore, it is important to find the modalities that will most likely cause an injury so that they might be avoided.

Since it is difficult/impossible to measure the forces in the lower back directly, musculoskeletal models have been utilized to estimate the forces in the muscles and spine. Because of the relatively slow nature of many occupational lifting tasks, dynamic variables such as acceleration are often assumed to have no significant effect on the force distribution in the lumbar region of the back. Therefore, static models are commonly used since they are relatively simplistic and much easier to implement. However, Shin and Mirka [2] recently observed significant differences in a comparison of static and dynamic results when lifting with an altered foot orientation. An altered foot orientation is similar to lifting from a sloped floor; however, it does not include the additional component of the box also being on this slope. Therefore, the goal of this investigation was to assess the differences in low-back net muscular moments when using both a static and dynamic model and posture differences at the time of each max moment when the lifting occurs with the box initially on the same slope as the lifter.

METHODS

Subjects were selected from the general college population, limiting age from 18-24 yrs so that a relatively homogeneous group could be analyzed in an age range that would normally be employed in

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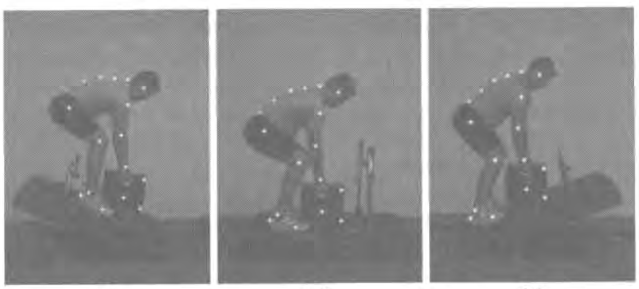
manual labor intensive jobs. Though not required to be employed in a job that had a substantial lifting component, subjects were required to be familiar and comfortable with lifting a box from the ground to standing knuckle height. An equal representation of each gender was included in the sample population with women lifting 15 kg and men 25 kg due to strength differences between genders [3]. Prior to participation, a health-history questionnaire and university-approved informed consent form were completed by each person.

All lifting was performed in the center of a 1.23 x 1.23 m wooden platform hinged at one end and outfitted with screw jacks on the other to alter floor slope (Figure 1). Latex paint and granular non-slip adhesive on the surface of the platform helped to increase traction. A standard cubic milk crate with padded handles was lifted. The 3D motion of retro-reflective markers was captured with a six-camera (60 fps) optical capture motion analysis system (Motus 7.0, Peak Performance Technologies Inc., Englewood, CO). The coordinate data was low-pass filtered at 5 Hz (4^{th}-order recursive Butterworth).



(a) (b) (c)

Figure 1: Demonstration of lifting conditions: (a) -20° (b) LVL, and (c) +20°.

All data was collected from each subject in a single visit lasting ~1.5 hrs. A 30 min warm up and familiarization session was followed by data collection. Subjects wore their preferred shoe and sock and a dark-colored, tight-fitting spandex type short. Men wore no shirt and women an exercise bra.

Reflective markers were placed on the skin/clothing over the right temple (approximating head center of mass), joint centers of the shoulder, elbow, wrist, hip, knee, ankle, and toe (base of 5^{th} metatarsal), and heel as viewed from the sagittal plane. Five reflective markers were also placed on the back at L5/S1, C7, and ¼, ½, and ¾ the distance between L5/S1 and C7. The box was tracked by placing markers on the right side at an estimated center of mass, and on both the top and bottom of the leading vertical edge to show orientation (Figure 1).

Lifting conditions of facing down the slope at 20° (-20°) and 10° (-10°) , level (LVL), and up the slope at 10° (+10°) and 20° (+20°) were presented to each subject in a randomized order. A restricted "freestyle" lifting technique was required of the subjects. A symmetric, non-staggered stance, with feet wider than the box, was required. The subject counter-moved bending at the hip, knee, and ankle and in a fluid motion grabbed both handles of the crate and picked it up, returning to a motionless erect standing position with arms extended and crate resting in front of the their hips (knuckle height). After settling on foot placement to ensure comfort, six lifts for record were performed with one minute rest between lifts. Before moving to the next lifting condition three minutes rest were required.

Torso angle was calculated from the shoulder and hip relative to vertical such that 0° was upright. Hip and knee angles were defined as the included angles between the shoulder, hip, and knee and hip, knee, and ankle, respectively, such that 180° was full extension. Ankle angle was the included angle between the lines created by the ankle to the knee and the heel to the toe such that 180° was full plantar-flexion. Lower back curvature of the spine was defined as the angle produced by three reflective markers outlining the lumbar region of the back. The angle was defined such that a value lass than 180° was lordotic in nature.

A four segment model (head and neck, trunk (without pelvis), upper arm, and forearm and hand) based on the reflective markers was constructed. Motion of the left side of the body was assumed identical to that of the right and incorporated into the mass distribution of segments. Gender specific anthropometric values were utilized based on the work of Plagenhoef *et al.* [4].

The L5/S1 joint location was calculated using the procedure outlined by Chaffin *et al.* [5]. For the static model, the net muscular moment about L5/S1 was calculated by summing the torque created by the weight of each body segment superior to L5/S1 and that of the box. The dynamic model was based on the static model. However, the inertial forces and moments were included from the linear and angular acceleration of the body segments and box.

Since the force acting on the box from the ground was not measured, it was assumed that no force was acting on the hand from the crate until the center of mass of the person reached its lowest point in the countermovement. At this time the full weight of the mass was instantly applied marking the transition from the countermovement phase to the lifting phase of activity (Figure 2). While in reality there is a gradual increase in the force on the hand due to the box as its support is transitioned from the floor to the person, it was found that the box begins to move several frames after the minimum in the subject's center of mass. Therefore, the entire weight of the box was virtually in their hands at the start of the lifting phase where analysis of low-back forces began and limited error would be incurred by this method of load transition. This was supported in the results since the majority of the maximum static and dynamic moments occurred not at the start of the lifting phase, but slightly after when accelerations were highest.

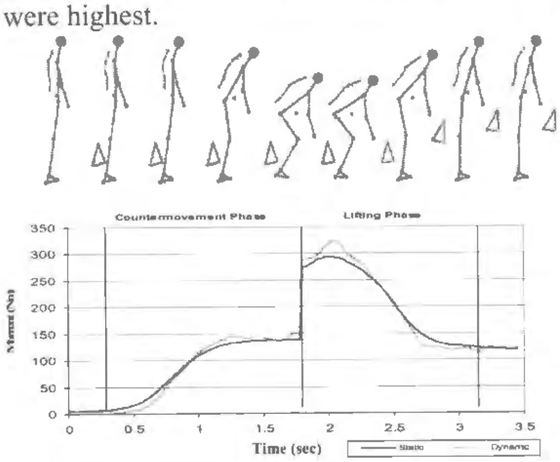


Figure 2: Exemplar net muscular moment profile of an 80.5 kg male subject lifting in the +20° condition from both the static and dynamic model.

The last three lifts of each subject in each condition were averaged and analyzed to create a representative lift for each condition for further comparison across condition. Before combining the men and women into one single group, analyses were performed to ensure that trends across conditions were not significantly different between genders ($p>0.05$).

Instantaneous parameter values were extracted at the time of dynamically calculated maximum net muscular moment (TDM) and time of statically calculated maximum net muscular moment (TSM). Parameters included the torso, hip, knee, ankle, and low-back curvature angles. TDM and SDM relative to the start of the lift phase were also retained.

Statistical analysis was conducted with SPSS 12.0 (Statistical Package for the Social Sciences, Chicago, IL) with $p < 0.05$ set for determination of significant differences. A 2 x 5 within subjects repeated measures ANOVA was utilized to compare the static and dynamic model results.

RESULTS

Forty-three healthy men (n=21) and women (n=22) successfully completed the research protocol. While age was not significantly different between the men and women ($p=0.517$), the men were significantly heavier ($p<0.001$) and taller ($p<0.001$) than the women. The average combined age, height and mass of the subjects was 22.3 ± 1.6 years, 173.2 ± 8.2 cm, and 67.5 ± 10.2 kg, respectively.

After an instantaneous increase due to the onset of the load in the subject's hands, the moment generally increased slightly to the maximum value shortly after initiating the lifting phase (Figure 2), though in some cases the maximum net moment occurred at the start of the lift phase. The greatest differences between the static and dynamic models were near the beginning of the lift phase with the models converging and the moments declining through the remainder of the lift.

Across the lifting conditions (slope) there was a significant change in both the TDM ($p=0.003$) as well as the TSM ($p<0.001$) relative to the start of the lift (Table 1). However, there was a significant difference in the time trends across lifting condition between TDM and TSM ($p<0.001$). The TSM was significantly shorter than the TDM by approximately 38% in the LVL condition, 47% in the +10° condition, and 49% in the +20° condition ($p<0.001$ each condition).

Table 1: Comparison across the -20° through +20° lifting conditions for each parameter using the dynamic model and time of dynamic max (TDM) and the static model and time of static max (TSM) moments.

	Dynamic					Static				
Parameter	**-20°**	**-10°**	**LVL**	**+10°**	**+20°**	**-20°**	**-10°**	**LVL**	**+10°**	**+20°**
L5/S1 Moment	*246	*240	*244	*243	*244	209	205	208	212	220
	(69)	(69)	(70)	(67)	(64)	(57)	(56)	(58)	(57)	(57)
Time	0.295	0.321	*0.321	*0.268	*0.252	0.341	0.295	0.199	0.141	0.129
	(0.130)	(0.114)	(0.122)	(0.092)	(0.141)	(0.230)	(0.225)	(0.194)	(0.166)	(0.156)
Torso Angle	60.2	57.5	*56.1	*54.8	*57.8	59.6	57.5	57.1	56.3	59.7
	(14.4)	(14.6)	(13.0)	(12.8)	(13.4)	(16.1)	(15.8)	(13.6)	(13.1)	(13.6)
Lower Back	181.2	176.8	175.4	173.9	173.7	180.1	177.3	175.4	173.8	173.8
	(8.0)	(9.8)	(7.7)	(7.7)	(7.8)	(8.8)	(9.1)	(7.6)	(7.7)	(7.8)
Hip Angle	*56.1	*65.4	73.4	*79.3	*84.5	64.0	69.4	71.3	76.3	81.5
	(10.5)	(10.9)	(9.2)	(9.8)	(9.6)	(21.0)	(19.0)	(14.4)	(13.5)	(11.1)
Knee Angle	*89.8	*94.8	101.5	107.5	120.8	100.9	100.8	100.2	104.9	118.6
	(15.9)	(15.1)	(13.5)	(12.6)	(13.9)	(15.7)	(16.8)	(12.7)	(14.0)	(16.0)
Ankle Angle	*94.2	82.8	75.1	*68.4	*62.9	97.2	83.6	73.1	66.1	61.4
	(7.4)	(7.6)	(8.1)	(8.6)	(9.4)	(8.5)	(10.4)	(12.2)	(9.5)	(9.8)

Units: Moments in Newton-meters; Time in seconds; Angles in degrees
* ($p<0.050$) between static and dynamic models (same lifting condition)

Similar to the TDM and TSM, there was also a significant interaction between the max L5/S1 moments ($p<0.001$) (Table 1). While the dynamic max moment exhibited no effect for lifting condition ($p=0.340$), the static max moment significantly increased as floor slope increased ($p<0.001$). Even with this slight increase in the static max moment as slope increased, the dynamic moment was significantly greater than the static max moment in all lifting conditions ($p<0.001$).

Since the time of maximum L5/S1 moments were affected by model, joint angles were also affected (Table 1). There was a significant change in torso angles across lifting condition at both the TDM ($p<0.001$) and TSM ($p=0.006$). However, trends across condition were different ($p<0.001$). A slight reduction in forward lean across conditions of -20° through +10° existed in both models with a rebound at the +20° condition; however, TSM values were significantly greater than TDM values ($p<0.001$) in the LVL and uphill conditions.

Trends across lifting condition were similar for back curvature angles at both TSM and TDM ($p=0.450$) with no differences between TSM and TDM. Both back curvatures exhibited a decrease in curvature (more lordotic) from the -20° through +20° lifting condition producing a significant effect for condition ($p<0.001$) in each model.

Hip angles became more extended in both TSM and TDM from the -20° through +20° lifting conditions producing a significant effect for condition ($p<0.001$). A significant difference in trend existed ($p<0.001$) since the TSM hip angles were more extended in the -20° ($p=0.001$) and -10° ($p=0.050$) conditions while the TDM hip angles were more extended in the +10° ($p=0.004$) and +20° ($p=0.001$) uphill conditions. There was no significant difference between TSM and TDM hip angles in the LVL condition ($p=0.103$).

Knee angle trends were similar to hip angles trends across lifting conditions and between TSM and TDM models. Knee angles became more extended from the -20° through +20° lifting condition and a significant interaction was present between the two models ($p<0.001$). TSM values were significantly more extended in the -20° ($p<0.001$) and -10° ($p=0.026$) conditions, while TDM values were more extended in the LVL and uphill conditions. Differences between TSM and TDM knee angles in the LVL and uphill conditions were not significant ($p>0.05$).

Trends in the ankle angles were opposite of hip and knee angle trends. Both TSM and TDM ankle angles became less plantar-flexed from the -20° through +20° lifting condition. A significant difference in trend existed ($p<0.001$) with the TSM significantly more plantar-flexed in the -20° condition ($p=0.010$), and the TDM ankle angles significantly less plantar-flexed in the uphill conditions ($p<0.001$ each condition).

While many of these angles were significantly different between the TSM and TDM moments, the magnitude of these differences were relatively small. The differences in torso angles and lower back curvature angles were less than 2°. Hip angles differed by 7.9° in the -20° lifting condition, 4° in the -10° condition, and less than 3° in the LVL and uphill lifting conditions. Differences in knee angles were similar to the hip angle differences differing by 11.1° in the -20° condition, 6° in the -10° condition, and less than 3° in the LVL and uphill conditions. Ankle angles were 3° or less in all lifting conditions.

DISCUSSION

The subjects that participated in this study portrayed similar characteristics to the general population [6]. However, neither gender represented specific occupations where lifting is a substantial component of work. Though this has been refuted as a requirement in some lifting assessment applications [7], it does not rule out the possibility that those who lift from a sloped surface on a regular basis may adopt slightly different techniques than those observed here.

Extensor moments at TDM were significantly greater than TSM moments in all conditions. This was expected since the TDM moment includes both static and inertial contributions and the inertial contribution at the start of the lift phase would be positive in direction. Though the TDM was significantly different than TSM in 3 of 5 lifting conditions (level through uphill), the magnitude of the time difference was relatively small, such that the person was still experiencing a static component that was near the TSM value. These findings are in support of those by Shin and Mirka [2], where it was concluded that the inertial component may be significant and, therefore, a dynamic model should be incorporated. However, Shin and Mirka [2] did not assess possible postural differences that would be observed if a static model were utilized instead of a dynamic model.

The magnitude was not the only difference in the moments between static and dynamic models. A difference in trend was also evident across floor slope lifting conditions. The static model suggested that the max extensor moment increases as floor slope increases from a level floor to one where a person is facing uphill at 20°. However, a dynamic model shows no difference in max extensor moment across floor slope. While it was difficult to speculate why the TSM moment increased with floor slope from the data analyzed here, it was not surprising that the TDM moment did not. In the uphill conditions the person does not need to lift the box as far, so most likely, accelerations do not need to be as high in order to comfortably perform the task. Therefore, a greater static contribution combined with a lesser inertial component might yield the same peak moment regardless of floor slope.

Since the TDM occurred slightly later than TSM in the level and uphill lifting conditions, it was not surprising that the hip, knee, and ankle angles were slightly more extended, and the torso angle slightly more erect when comparing the TDM to the TSM values. However, this did not appear to influence low back curvature angles when analyzing the position of the person at TSM or TDM.

It was interesting to see that even though the TDM and TSM were not significantly different in the downhill conditions, there might be a slight switch in the downhill 20° lifting condition where the TDM actually occurred before the TSM. In the downhill conditions the person had to lift the box further, so it was not surprising that the TDM moment might be higher and occur slightly sooner, placing the peak TDM moment earlier in the lift relative to the other conditions. However, this was only speculative since the TSM and TDM were not significantly different in the downhill conditions.

CONCLUSIONS

Depending on the purpose of the analysis, either a static or dynamic model may be acceptable. A static model may be suitable for applications where body position is of interest (except when facing downhill where postural differences approached 10° at the hip and knee). A dynamic model, however, is necessary when examining the extensor moments. L5/S1 peak extensor moments are significantly greater due to the inertial contribution. Trend across floor slope is also differs from a static model.

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