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Toward a Quantitative Definition of Manual Lifting Postures

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Manual lifting techniques are commonly defined in terms of the postures adopted at the start of the lift. Quantitative definition is problematic, however, because the absolute joint angles adopted to lift an object are influenced by task parameters, such as the initial height of the load. We present an argument for the use of a postural index (the ratio of knee flexion from normal standing to the sum of ankle, hip, and lumbar vertebral flexion) to define the postures adopted at the start of lifting. Stooped postures adopted at the start of a lift correspond to postural indices close to 0, whereas full squat postures correspond to postural indices close to 1. We use angular kinematic data gathered from 71 individuals lifting loads of varying mass from a range of starting heights to illustrate the utility of this index. Although average absolute joint angles were influenced by load mass and initial load height, the average postural index remained unchanged. For example, changes in starting height from 9 cm to 63 cm accounted for between 19% and 67% of the variance in joint positions at the start of the lift but only 1% of the variance in average postural index. This suggests that the postural index provides a method of defining lifting posture that is independent of specific joint positions.

INTRODUCTION

Research on manual lifting has typically differentiated among lifting techniques on the basis of the posture adopted to lift a load. For example, Whitney (1958) described two lifting techniques as follows:

> Derrick action. Throughout the lifting operation the knee is kept fully extended, or even hyperextended, and the trunk is flexed forwards (lumbar spine and hip joint flexion) so that the grasp can be made.
>
> Knee action. The grasping point is reached by folding the legs as in squatting, the trunk being maintained quite erect. (P. 123)

Comparisons have frequently been made between these two techniques, variously defined as stoop, derrick, straight legs/bent back, back lift, torso lift, or high gear; and squat, crouch, bent legs/straight back, leg lift, or low gear, respectively (e.g., Andersson, Ortengren, & Nachemson, 1976; Davis, Troup, & Burnard, 1965; Grieve, 1974; Kumar, 1984; Leskinen, Stalhammar, & Kourinka, 1983; Lindbeck & Arborelius, 1991; Mairiaux & Malchaire, 1988; Mirka & Marras, 1990; Toussaint, van Baar, van Langen, de Looze, & van Dieen, 1992), although extreme positions are adopted relatively infrequently when people are allowed to select their own lifting technique. The typical posture adopted during self-selected lifting may be described as a semisquat (Burgess-Limerick, Abernethy, Neal, & Kippers, 1995; Gagnon & Smyth, 1992).

Despite the focus on the biomechanical consequences of different lifting techniques, the techniques prescribed have seldom been described

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in other than qualitative terms. For example, Lindbeck and Arborelius (1991) referred to back lift and leg lift styles, defining them as straight knees and bent back, and flexed knee and straight back respectively, whereas Pokorny, Fleiss, and Holzer (1987) defined a larger range of starting positions in similarly qualitative terms (straight leg/bent back, slightly bent knees/semibent back, knee bent at approximately 90°/nearly straight back, and maximal bent knee/mostly straight back).

Some measurements of absolute joint angles are available. For example, Troup (1977) recorded that the spine was flexed 25° farther at the start of a stoop lift than at a crouch lift; Garg and Herrin (1979) described the angle of the superior surface of the sacrum from the horizontal as being 9° and 77° during stooped and squat postures, respectively; and Nemeth and Ekholm (1985) reported straight knee lifts as involving 50° hip flexion and a femur/vertical angle of 23°, whereas a flexed knee position involved 85° hip flexion and a femur/vertical angle of 67°.

Definition of the posture adopted at the start of a lift in terms of the absolute angular position of joints is problematic. The characteristics of the task, and in particular changes in the initial position of the load, are logically associated with gradual changes in the posture adopted to lift a load when the posture is defined in terms of absolute joint positions. The aim of this paper is to provide a quantitative and empirically grounded definition of lifting posture that is robust in the face of changes in task parameters.

We devised a postural index based on the effect of joint flexion on trunk inclination to describe the posture adopted at the start of the lift independent of absolute joint angular positions. The rationale for such an index is as follows: Increases in knee flexion have the effect of rotating the trunk posteriorly, whereas dorsiflexion of the ankle and flexion of the hip and lumbar vertebral joints each rotates the trunk anteriorly. Consequently, the posture adopted at the start of extension is described in terms of the ratio between knee flexion (which causes posterior trunk rotation) and the sum of ankle, hip, and lumbar vertebral flexion (causing anterior trunk rotation; see equation in Figure 1).

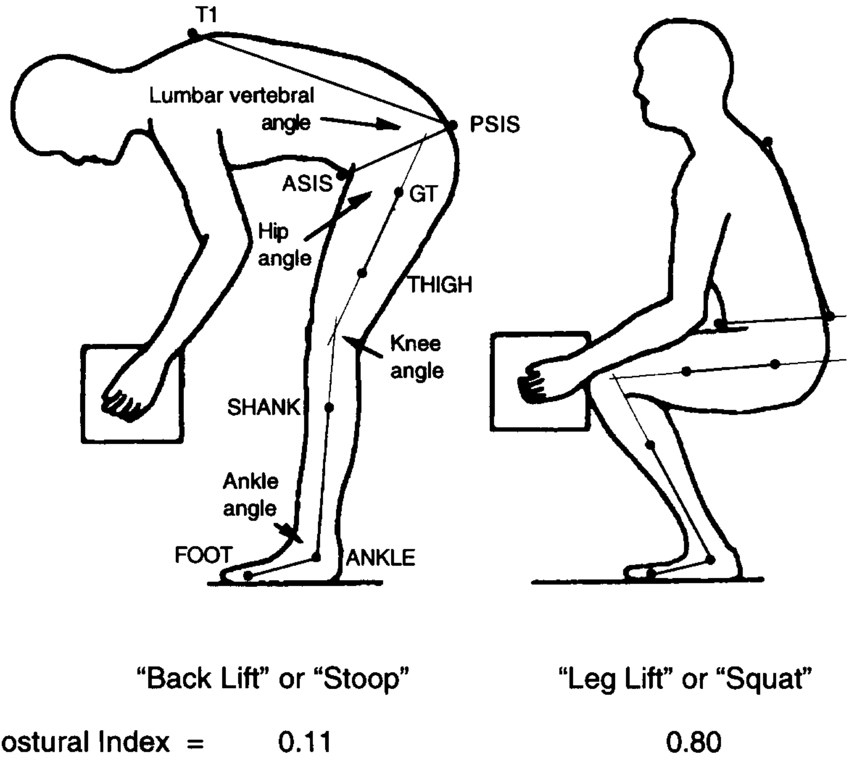
The postural index describes the posture adopted at the start of a lift in terms of a dimensionless ratio. This ratio indexes the extent to which the posture adopted at the start of extension deviates from a stooped posture. When knee flexion from normal standing is small relative to the flexion of ankle, hip, and lumbar vertebral joints, the postural index is small (indicating that the forward inclination of the trunk is relatively large and that the posture is closer to a stooped posture than to a full squat).

The reverse is true when knee flexion is large relative to the sum of ankle, hip, and lumbar vertebral flexion. For example, Figure 1 and Table 1 illustrate the calculation of postural index using angular measurements estimated from drawings presented by Toussaint et al. (1992, their Figure 2) of participants lifting with either the squat or stoop technique. When their participants were asked to lift while keeping their spine as erect as possible (a "leg lift" or "squat" technique), the posture they adopted corresponded to a postural index of about 0.8, whereas when minimal knee flexion was prescribed (a "back lift" or "stoop"), the posture adopted typically corresponded to a postural index of about 0.1. The experiments reported here investigate whether this method allows definition of lifting posture independent of load mass and initial height.

METHOD

The methods employed have been previously described (Burgess-Limerick, Abernethy, & Neal, 1993; Burgess-Limerick et al., 1995). Angular motion in the sagittal plane of the ankle, knee, hip, and lumbar vertebral joints was estimated in two experiments in which a total of 71 untrained participants each performed 100 symmetric bimanual lifts using a self-selected technique.

Participants were given a brief, standardized explanation of the purpose of the experiment, and no deception was involved. The standardized instructions given to the participants emphasized that they were to lift the load in "the way you



$$\text{postural index} = \frac{\text{knee flexion from normal standing } (^\circ)}{\text{ankle + hip + lumbar vertebral flexion from normal standing } (^\circ)}$$

Figure 1. Illustration of marker placement and definition of joint angles used in the present study (see text for details) and an example of the calculation of postural index using angular measurements estimated from drawings presented by Toussaint et al. (1992; their Figure 2) of participants lifting with either the squat or stoop technique.

would normally do the task, that is, the most comfortable way for you." They were instructed to adopt a normal standing posture facing the load, with feet approximately parallel and an equal distance from the load. The distance of the feet from the load was self-selected, and participants were allowed to vary this distance between trials as desired with the proviso that their feet remain stationary during each lift. Participants were not instructed to purposely replicate either stooped or squat postures.

Ten spherical reflective markers (30 mm

TABLE 1

Data Used to Calculate the Postural Index for Lifting Techniques Illustrated by Toussaint et al. (1992; see Figure 1)

Angle	Average Normal Standing	Position in "Back Lift"/Flexion from Normal Standing	Position in "Leg Lift"/Flexion from Normal Standing
Ankle	107°	110°/-3°	75°/32°
Knee	170°	160°/10°	65°/105°
Hip	80°	40°/40°	0°/80°
Lumbar vertebral	95°	45°/50°	75°/20°

diameter) were placed on the right side of each participant on the following anatomical locations: (a) head of the fifth metatarsal (FOOT in Figure 1), (b) lateral malleolus (ANKLE), (c) lateral surface of the shank on a line joining the lateral malleolus with the knee joint center (SHANK), (d) lateral surface of the thigh on a line joining the knee joint center with the greater trochanter (THIGH), (e) superior point of the greater trochanter (GT), (f) posterosuperior iliac spine (PSIS), (g) anterosuperior iliac spine (ASIS), (h) spinous process of the first thoracic vertebra (T1), (i) head of the radius, and (j) dorsal surface of the hand.

These markers defined lumbar vertebral, hip, knee, and ankle angles as illustrated in Figure 1. All were defined as included angles that increased when the joint extended or, in the case of the ankle, plantar flexed. Lumbar vertebral angle was defined as the anterior angle subtended by lines joining the first thoracic vertebra, posterosuperior iliac spine, and anterosuperior iliac spine markers. The use of these markers to estimate lumbar vertebral movements has been radiographically verified (Kippers & Parker, 1989). Hip angle was defined as the anterior angle subtended between the line joining the posterosuperior iliac spine and anterosuperior iliac spine and the extrapolated line of the femur (as defined by thigh and greater trochanter markers). This angle became negative in extreme hip flexion. Knee angle was defined as the posterior angle subtended by the extrapolated line of the femur and the extrapolated line of the shank (as defined by shank and ankle markers). The ankle angle was defined as the anterior angle subtended by the shank, ankle, and foot markers.

In Experiment 1, 39 volunteers (20 women, 19 men; ages 18–26 years; mass 47.7–93.5 kg, mean = 67.7 kg; height 158.5–191.0 cm, mean = 174.1 cm) performed a task that involved flexing from a normal standing position to lift a load from 9 cm above floor height and placing it on a shelf at about shoulder height. The mass of the load varied from 2.5 to 10.5 kg in 2-kg increments. Participants performed 100 trials in blocks of five lifts of each mass in ascending series. Five seconds elapsed between trials and 30 s between blocks. The 25-trial series was repeated four times. Ratings of perceived exertion were obtained after each trial. Data were collected at 100 Hz using an NAC video camera and recorder. Data gathered in Experiment 1 have been previously reported in terms of absolute joint angles (Burgess-Limerick et al., 1995).

A group of 32 volunteers (13 women, 19 men; ages 18–35 years; mass 50.3–106 kg, mean = 69.7 kg; height 163.8–190.0 cm, mean = 176 cm) participated in Experiment 2. None had participated in the previous experiment. These participants lifted 2.5 or 6.5 kg from five starting heights (9, 22, 36, 50 and 63 cm above floor level) and were randomly assigned to one of four protocols. Each protocol involved two practice trials from the 9 cm height followed by 100 trials in which the load mass remained constant (either 2.5 or 6.5 kg). The load starting height varied (in blocks of five trials) in either ascending or descending order. This 25-trial series (five heights × five trials) was repeated four times. Kinematic data collection procedures were identical to those in Experiment 1, except that an NEC TI-23A CCD camera was used to record the movement of markers on a Panasonic AG-6300 VHS recorder, and the data were collected at 60 Hz.

In both experiments we determined the range of ankle, knee, hip, and lumbar vertebral flexion from normal standing at the start of each lift for each of the last 75 trials performed by each participant (15 trials in each of five load mass or initial height conditions) and calculated the postural index. The start of the lift was defined for each trial as the time at which the hand marker reached minimum vertical displacement. We sought evidence of reliable effects of task characteristics on each dependent variable by submitting the mean data for each load mass condition to separate one-way repeated-measures analyses of variance (ANOVAs) for each dependent variable. (Multiple ANOVA with appropriate Bonferroni correction to maintain experiment-wise Type I error rate at the desired level is preferable in this situation to multiple analysis of variance [MANOVA] because Type I error rate is not fully controlled by MANOVA; Schutz & Gessaroli, 1987.) Probability values were Greenhouse-Geisser-corrected for deviations from sphericity (Schutz & Gessaroli, 1987), and a Bonferroni correction was employed to maintain alpha below .05. Only those effects of load mass yielding adjusted p values less than .005 were considered reliable as a consequence. The coefficient of determination (r^2) was calculated as a measure of effect size.

RESULTS

The average postural index across all participants was 0.58 ($SD = 0.16$) in Experiment 1 and 0.59 (0.17) in Experiment 2. These values correspond to a posture intermediate between the extremes of stoop and full squat (see Figure 1). Changes in load mass (Experiment 1) and initial load height (Experiment 2) were associated with reliable changes in absolute joint position at the start of the lift (Table 2). Increases in load mass were associated with significant increases in hip and lumbar vertebral flexion at the start of the lift, whereas increases in starting height were associated with significant decreases in flexion of ankle, knee, hip, and lumbar vertebral joints at the start of the lift. However, neither task parameter had a significant effect on average postural index at the start of the lift (Table 2).

Although statistically significant, the effect of load mass on joint position at the start of the lift was relatively small (see Table 2 in Burgess-Limerick et al., 1995). In contrast, the initial height of the load had a large effect on the absolute joint angles adopted at the start of lifting (Figure 2 and Table 3). Coefficients of determination revealed that initial load height accounted for 19% of the variance in ankle position at the start of the lift, 45% of knee position variance, 67% of hip position variance, and 39% of lumbar vertebral angle variance. In contrast, changes in initial load height accounted for only 1% of the variance in average postural index.

Examination of the ratings of perceived exertion revealed no significant effects of fatigue. Neither the posture adopted at the start of extension nor the within-subjects variability of this posture was significantly influenced by the number of previous trials performed. In Experiment 1, for example, the mean range of knee flexion from normal standing at the start of the first block of 25 trials was 95.7°. The average value for the last 25 trials was 92.6°, but the effect of blocks was nonsignificant, $F(3, 114) = 2.25$, corrected $p > .1$.

TABLE 2

Means (and Standard Deviations) for Extreme Conditions and ANOVA Statistics Describing Effect of Load Mass and Starting Height on Posture Adopted at the Start of the Lift

Dependent Variable	Condition	Condition	*F*	*p*
Experiment 1				
(load mass varied)	2.5 kg	10.5 kg		
Ankle position	24.2° (9.9)	25.1° (7.6)	1.7	.24
Knee position	88.7° (26.1)	93.7° (23.8)	4.9	.015
Hip position	85.8° (9.6)	88.1° (9.0)	12.2	<.001
Lumbar vertebral position	44.1° (9.8)	46.4° (9.9)	18.0	<.001
Postural index	0.57 (.16)	0.59 (.15)	1.82	.127
Experiment 2				
(initial load height varied)	9 cm	63 cm		
Ankle position	26.7° (9.6)	13.4° (9.1)	53.2	<.001
Knee position	95.1° (22.4)	42.9° (18.5)	172.7	<.001
Hip position	87.7° (10.9)	40.4° (9.8)	422	<.001
Lumbar vertebral position	40.8° (10.2)	18.9° (7.5)	182.8	<.001
Postural index	0.61 (.13)	0.57 (.22)	3.029	.072

Note: All probability values are Greenhouse-Geisser adjusted to correct for deviations from sphericity. Degrees of freedom for Experiment 1 and Experiment 2 were 4 152 and 4 124, respectively.

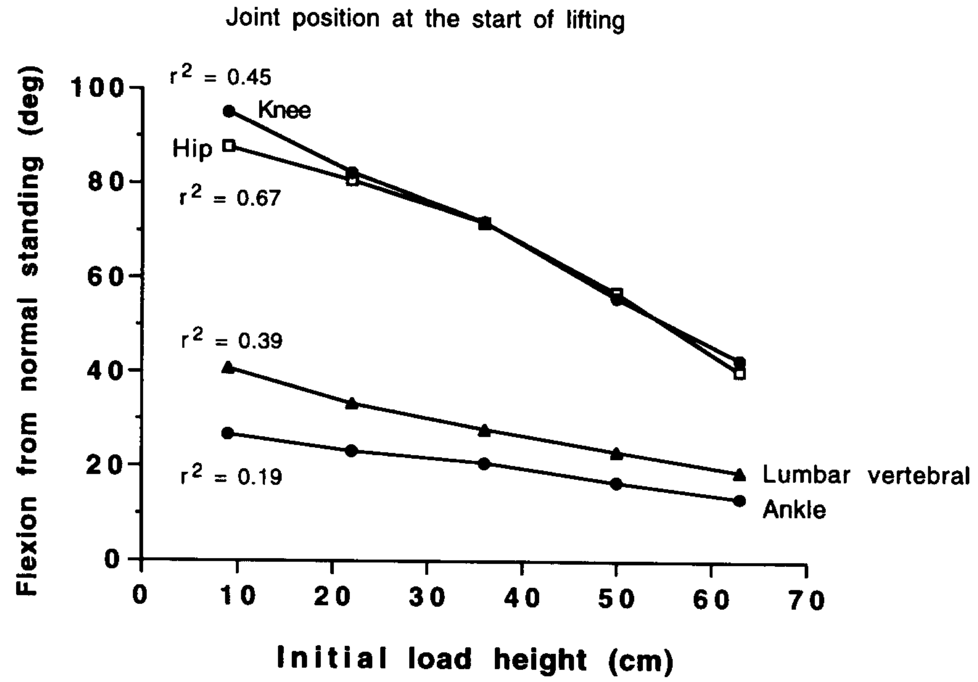


Figure 2. Posture adopted at the start of self-selected lifting as a function of initial load height (Experiment 2).

At the same time, the average within-subjects standard deviation of this measure increased from 3.9° to 4.2°, but this difference was similarly nonsignificant, $F(3, 114) = 0.293$, corrected $p > .1$.

DISCUSSION

The posture adopted at the start of lifting has previously been defined only in qualitative terms, usually involving some reference to the extent of knee flexion in the posture adopted at the start of extension. For example, Davis and Troup (1965) defined a stooped posture as one in which the "legs are relatively straight and the trunk horizontal" (p. 323). Although quantification of what is meant by "relatively straight" may be desirable, the difficulty with defining postures in terms of the absolute position of the knee is that, as demonstrated in Experiment 2, differences in environmental parameters such as initial load height have a large influence on the knee position adopted at the start of extension.

The ratio of knee flexion from normal standing at the start of the lift to the sum of ankle, hip, and lumbar vertebral flexion was devised in an attempt to provide a method of defining lifting posture that is not affected by changes on task characteristics. The data presented here illustrate that

TABLE 3

Effect of Initial Load Height on Posture Adopted at the Start of the Lift (Experiment 2)

Dependent Variable	Regression Equation	*r*	r^2
Ankle flexion from normal standing (°)	−0.243 x ht (cm) + 28.9	−.44	.19
Knee flexion from normal standing (°)	−0.96 x ht (cm) + 104.2	−.67	.45
Hip flexion from normal standing (°)	−0.87 x ht (cm) + 98.8	−.82	.67
Lumbar vertebral flexion from normal standing (°)	−0.397 x ht (cm) + 43.1	−.63	.39
Trunk inclination from normal standing (°)	−0.59 x ht (cm) + 71.5	−.69	.47
Postural index	−0.0009 x ht (cm) + 0.619	−.10	.01

this postural index does provide an appropriate method of defining lifting posture.

Examination of previous research (e.g., Anderson & Chaffin, 1986; Hagan, Sorhagen, & Harms-Ringdahl, 1995; Nemeth & Ekholm, 1985; Park & Chaffin, 1974; Toussaint et al., 1992) indicates that stooped postures—in which the range of knee flexion from normal standing is small relative to the flexion of ankle, hip, and lumbar vertebral joints—are described by postural indices below about 0.3. In some cases hyperextension of the knee occurs, leading to a negative postural index. At the other extreme, full squat postures correspond to postural indices above about .8. Postures intermediate between these extremes (semisquat postures) are more commonly observed (Burgess-Limerick et al., 1995; Gagnon & Smyth, 1992) and correspond to intermediate values of the postural index. The proposed postural index is sensitive to qualitative differences in lifting posture (Figure 1 and Table 1), allowing quantitative differentiation of postures that might previously have been described in qualitative terms as "stooped" or "squat."

At the same time, the index is insensitive to changes in load mass and starting height. Although we found that both load mass and initial load height altered the absolute joint angles adopted at the start of the lift (during freestyle lifting at least), no significant effect of task characteristics on posture existed when expressed in terms of postural index. The postural index thus provides an appropriate method of defining lifting posture independently of task characteristics and specific joint positions.

The finding that postural index during self-selected manual lifting remains relatively invariant across changes in load mass and starting height may have implications for understanding the control of lifting and whole body movements in general. It should be noted, however, that all possible lifting conditions have not been explored, and it may well be that heavier loads or larger horizontal distances will influence the postural index. The utility of the postural index as a method of defining lifting posture has also been examined only under sagittally symmetric conditions, and its utility in asymmetric situations has not been determined.

Although the postural index does not indicate a risk level for injury to any joint or, on its own, speak to the question of which postures are less likely to contribute to injury, its use is advantageous because it permits lifting posture to be defined independently of absolute joint position. In particular, the use of this index to define lifting postures has the potential to facilitate biomechanical comparisons of different lifting techniques by providing a quantitative definition of lifting postures that is independent of task characteristics.

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