International Journal of Industrial Ergonomics, 10 (1992) 207–215
Elsevier

Quantification of velocity coupling during asymmetric lifting

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(Received April 3, 1992; accepted in revised form July 8, 1992)

Abstract

The objective of this study was to quantify velocity coupling, which was operationally defined as simultaneous trunk motion in two or three planes of the body. Velocity coupling was measured as the percentage of time the velocity was above a given percentage of maximum voluntary velocity in two or three planes. Four types of velocity coupling were quantified: sagittal/transverse (S/T), sagittal/frontal (S/F), transverse/frontal (T/F), and sagittal/transverse/frontal (S/T/F). These types of velocity coupling were quantified as a function of seven task asymmetries and two task weights. The results showed that the three types of two-way velocity coupling had different response patterns to increased task asymmetries. The total percentage of two-way velocity coupling significantly increased as task asymmetry increased from 0 to 30 degrees. The percentage of S/T velocity coupling decreased as task weight increased. It was also found that twice as much velocity coupling occurred at lifting task asymmetries beyond 120 degrees as compared to symmetric lifts. The effects of velocity coupling on strength and spinal loading are discussed.

Relevance to industry

The current lifting guides assume sagittally symmetric and static work postures. This work quantifies the influences of velocity coupling patterns under realistic circumstances, thus pointing out the limitations of static sagittal plane models.

Keywords

Velocity coupling; asymmetric lifting; biomechanics.

Introduction

Eighty percent of the population will suffer from low back pain (LBP) during their lifetime (Andersson, 1981). Back injuries not only afflict the elderly, but also young adults. Among the population under age 45, low back injuries are estimated to be the number one disabling injury in the United States (Bigos et al., 1986). Bigos and associates also found that once a person has sustained an initial back injury there is often reccurrence of the injury within two years.

In order to help control musculo-skeletal back injuries in the workplace the National Institute for Occupational Safety and Health (NIOSH) published the *Work Practices Guide for Manual Lifting* in 1981. The NIOSH guide was based on a static 2-dimensional model, which assumes the worker performs a slow smooth lift in the sagittal plane. The dynamic and 3-dimensional aspects of the workplace were not addressed in the NIOSH guide. However, we now know that 3-dimensional dynamic factors are important since epidemiological studies have cited that occupational factors such as frequent bending and twisting, lifting and

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forceful movement; and repetitive work contribute to low back disorder (LBD) risk in the workplace (Andersson, 1981; Frymoyer et al., 1980; and Bigos et al., 1986).

Effects on the spine

In biomechanical terms, changes in these occupational factors affect the forces acting on the spine by changing the back motion characteristics (i.e. position, velocity, and acceleration). It has been established that symmetric and asymmetric static trunk posture as well as static external moment arm length significantly effect spinal loading (Chaffin and Parks, 1973, Bendix and Eid, 1983, Seroussi and Pope, 1987, Zetterberg et al., 1987, Ladin et al., 1989). However, during a manual material handling task the trunk moves dynamically in all three planes. Thus, the forces acting on the spine would change due to trunk velocity in all three planes of the body, as well as the position of the object and trunk posture. In fact, increased isokinetic velocity has been found to decrease trunk strength (Kumar et al., 1988; Marras and Mirka, 1989). Marras and Mirka (1991) also found that EMG levels increase as isokinetic velocity increases. This increase in EMG under controlled isokinetic conditions may indicate that the muscle is producing more force due to the increase in velocity.

There are also theoretical reasons to believe that an increase in trunk motion increases spinal loading. Newton's second law states that force is equal to mass times acceleration. If the mass of the trunk remained the same then one would expect that an increase in back motion would increase the magnitude of the forces acting on the spine. Hence, it is hypothesized that simultaneously increasing the trunk motion characteristics in two or three planes of the body would increase the loading on the spine and therefore increase the risk of occupationally-related low back disorders.

From a spinal unit viewpoint, it has been established that coupling in a spinal segment does occur (White and Panjabi, 1990). The degree and direction of the coupling depends on the spinal segment level (i.e. L1-L2, L2-L3, L3-L4, L4-L5 or L5-S1, Pearcy et al., 1984, Panjabi et al., 1989). Thus, occupational tasks that require simultaneous motions in two or three planes would cause coupling at several spinal segment levels.

Ferguson and associates (1992) quantified trunk motion characteristics in all three planes of the body about the L5/Sl joint during symmetric and asymmetric lifting tasks. The results of the study showed that motion occurred in all three planes of the body for the symmetric as well as asymmetric lifting conditions. Marras et al. (1992) developed a multivariate model that utilized one parameter from each plane of the body to accurately predict the risk of occupationally-related low back disorders. Marras et al. showed that trunk velocity in the frontal and transverse planes was a particularly strong indicator of risk. However, these studies did not consider the simultaneous timing of motion characteristics among the three planes, just that motions occurred in each plane during the MMH task.

Research objective

In this study, velocity coupling was operationally defined here as simultaneous trunk motions in two or three planes of the body. Velocity coupling was used as a measure of coupling because it also implies positional coupling along with motion coupling. Thus, it was considered a robust indicator of coupling. Tasks that require coupling of trunk motion are commonly found in the industrial workplace. However, there is a void in the literature that explores coupling of back motion during manual material handling (MMH) tasks. Thus, we do not understand how much velocity coupling of the trunk actually exists in common MMH tasks. The goal of this study was to quantify spine velocity coupling as a function of task design.

Methods

Approach

In order to achieve the experimental objective, MMH tasks requiring symmetric as well as asymmetric lifting were tested. The workplace factors of load location and weight were manipulated to simulate asymmetric lifting situations often experienced in industry.

Coupling was measured as a function of the velocity of motion during the MMH tasks. The velocity parameter was chosen because there was a wealth of biomechanical data that indicated the internal activity of the trunk's supporting structures changed dramatically as velocity changed (Marras and Mirka, 1989, 1991). In addition, Marras and colleagues (1992) have shown that velocity was associated with the risk of LBD.

In this study, the maximum voluntary velocity in each plane of the body was elicited from each subject. Velocity coupling was measured as the percentage of time during the MMH task that the velocity was above a specific fractional level of the maximum voluntary velocity. This will be referred to as velocity coupling. It is hypothesized that the more time spent under velocity coupling conditions, the more likely a low back injury.

In this experiment, four types of velocity coupling were defined:
(1) sagittal/transverse (S/T)
(2) sagittal/frontal (S/F)
(3) transverse/frontal (T/F)
(4) sagittal/transverse/frontal (S/T/F)
S/T, S/F, and T/F were two-way velocity coupling. Three-way velocity coupling was S/T/F.

Subjects

Fourteen males with no history of low back pain volunteered to participate in the experiment. The subjects were all students at The Ohio State University. The age of the subjects ranged from 21 to 33 years. Gross anthropometric measurements were collected from all subjects. The mean (standard deviation) standing height was 180.5 cm. (6.3), and weight 74.5 kg. (24.3), respectively.

Equipment

A lumbar motion monitor (LMM) was worn by subjects when performing the experimental MMH tasks. This device is essentially an exoskeleton of the spine and is attached to two pieces of molded plastic (Orthoplast) which anchor the LMM to the hips and shoulders (see figure 1). The LMM measures position changes of the lumbar spine relative to the pelvis in all three planes of the body. The LMM was calibrated on a reference frame so that the potentiometer readings related to trunk position. Marras et al. (1991) have described the calibration and accuracy of the LMM.

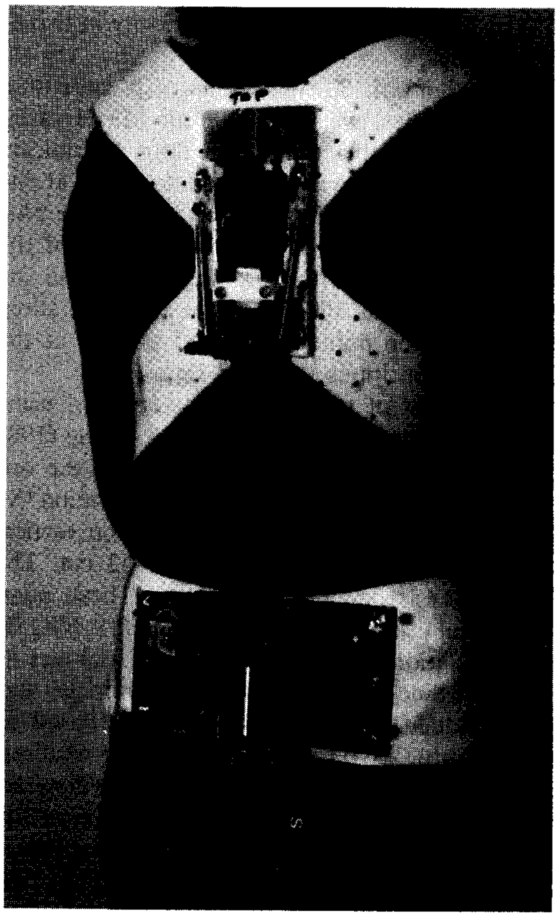

Fig. 1. Lumbar motion monitor.

Potentiometers were used to measure the instantaneous changes in position of the LMM in each plane of the body. The data collection rate was 60 Hz. The signal from the LMM was sent via hard wire to the analog-to-digital converter board, resident on a Compaq 386 microcomputer, where it was stored.

The data were first analyzed using custom software, which determined the position of the spine in three-dimensional space. The software differentiated the position data to determine the velocity in each plane of the body. The software also determined the percentage of time that the velocity was above 15%, 25%, 35%, 50%, and

75% of the maximum voluntary velocity in two or three planes.

A wooden box, 30 cm × 30 cm × 28 cm with a lid and handles, was used for all MMH tasks. Footprints were placed on the floor to indicate where the subject was supposed to stand at the beginning of the lift. Figure 2 shows a floor plan of the testing facility. The handle height of the box at the origin of the lift was 45 cm and the handle height was 107 cm at the lift destination. The destination point was moved to each of the asymmetric positions shown in figure 2.

The weight of the box was determined using the *Work Practices Guide for Manual Lifting* (1981 NIOSH). The horizontal location (H) at the origin of the lift was 48 cm. The vertical location (V) at the origin of the lift was 45 cm. The vertical travel distance (D) of the lift was 62 cm. The frequency was one lift per minute. These numbers were used as inputs to the 1981 NIOSH guide equation and the action limit (AL) was 88 Newtons. Since the guide has no asymmetry factor, an added correction factor of 0.7 (based on previous studies by Garg (1986)) was assumed and multiplied by the action limit. The new action limit was 61.6 N, which was approximated to 62 N. The weights used for the MMH tasks were 62 N (AL) and 186 N (3AL or MPL). The, 1981 NIOSH guidelines indicate that over 99% of males can perform lifts at the action limit and only 25% of men have strength capability to perform at the maximum permissible limit.

Experimental design

The experiment was a two-way repeated measures design. The two independent variables, asymmetry and weight, had 7 and 2 levels, respectively. These 14 lifting tasks were all repeated three times thus, a total of 42 lifts were performed. The 42 lifting tasks were completely randomized in their presentation order. This randomization of the tasks created a situation similar to that of a sorting operation in industry. In this manner, an experimental task resembling a realistic industrial task was used to quantify trunk motion characteristics.

The first *independent variable* task asymmetry had seven levels: 0 (sagittally symmetric), 30, 60, 90, 120, 150 and 180 degrees. The experimental

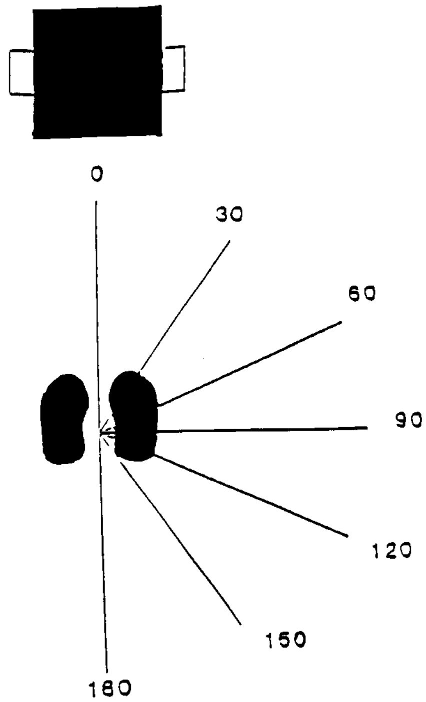

Fig. 2. Floor plan.

positions were marked on the floor as shown in figure 2. The second *independent variable* task weight had two levels: 62 and 186 Newtons.

The *dependent variables* were the percentage of time during the lift that the four types of velocity coupling (S/T, S/F, T/F, S/T/F) occurred. The operational definition of velocity coupling was simultaneous motion in two or three planes of the body. The four types of velocity coupling were measured at five percentages (15%, 25%, 35%, 50% and 75%) of maximum voluntary velocity. For example, 15% velocity coupling occurred when both the sagittal plane and transverse plane velocities were simultaneously above 15% of their maximum voluntary velocity, respectively. Table 1 shows the percentage of maximum velocity coupling for S/T coupling. These same five percentages of maximum velocity coupling were quantified for S/F, T/F, and S/T/F coupling, thus twenty dependent variables were created. Table 2 lists the levels of velocity coupling and the direction of the coupling that were used as dependent variables.

The maximum voluntary velocity was measured with the lumbar motion monitor in a sepa-

Table 1

Percentage of velocity coupling for S/T coupling.

	Sagittal plane				
	15%	25%	35%	50%	75%
Transverse plane					
15%	×				
25%		×			
35%			×		
50%				×	
75%					×

Note: ×'s indicate the percentage of velocity coupling that were quantified.

rate experiment. This ensured that fatigue was not a factor in eliciting maximum voluntary velocity. Subjects performed three five-second exertions. These exertions were randomized to reduce order effects. Subjects were instructed to repeatedly flex and extend as fast as possible in the sagittal, frontal and transverse planes during a 5-second test period. The maximum voluntary velocity of four exertions were averaged to define the maximum velocity for each subject. Next, these average maximum velocities were averaged across all the subjects.

Table 2

Dependent measures.

Level of velocity coupling	Direction of coupling	Abbreviation
15%	Sagittal/Transverse	S/T
15%	Sagittal/Frontal	S/F
15%	Transverse/Frontal	T/F
15%	Sagittal/Transverse/Frontal	S/T/F
25%	Sagittal/Transverse	S/T
25%	Sagittal/Frontal	S/F
25%	Transverse/Frontal	T/F
25%	Sagittal/Transverse/Frontal	S/T/F
35%	Sagittal/Transverse	S/T
35%	Sagittal/Frontal	S/F
35%	Transverse/Frontal	T/F
35%	Sagittal/Transverse/Frontal	S/T/F
50%	Sagittal/Transverse	S/T
50%	Sagittal/Frontal	S/F
50%	Transverse/Frontal	T/F
50%	Sagittal/Transverse/Frontal	S/T/F
75%	Sagittal/Transverse	S/T
75%	Sagittal/Frontal	S/F
75%	Transverse/Frontal	T/F
75%	Sagittal/Transverse/Frontal	S/T/F

Procedure

The subjects were given the following instructions prior to the practice session: (1) Begin each lift with your feet on the foot prints; (2) Once the box is off the low stand, you may move your feet to accommodate the task; (3) Lift the box at a comfortable pace (speed). All the asymmetry and weight conditions were practiced prior to placing the LMM on the person.

Statistical analysis

Each repetition of a condition was entered into a data base. A multivariate analysis of variance (MANOVA) was performed at each percentage of velocity coupling, to analyze the collective behavior of the dependent measures. This was followed by individual analyses of variance (ANOVAs) for each significant dependent measure. Finally, the Ryan-Einot-Gabrial-Welsch F (REGWF) post hoc test was performed on each significant dependent measure.

Results

Significance

The results of the MANOVAs, shown in table 3, indicated that at the 15% and at the 25% velocity levels significant coupling occurred. The 15% velocity coupling responded to both task

Table 3

MANOVA summary of p values.

Percentage of velocity coupling	Independent measures		
	Asymmetry	Weight	Asy × Wt
15%	0.0001 [a]	0.03600 [a]	0.3533
25%	0.0351 [a]	0.1148	0.4792
35%	0.0896	0.1237	0.1509
50%	0.5404	0.3718	0.4628
75%	0.4526	0.3952	0.4264

[a] Significance at 0.05.

Table 4

ANOVA significance levels at 15% velocity coupling for each type of velocity coupling during lifting.

Type of velocity coupling	Asymmetry	Weight
S/T15	0.0001 [a]	0.0030 [a]
S/F15	0.0196 [a]	0.9936
T/F15	0.0001 [a]	0.9187
S/T/F15	0.0061 [a]	0.9403

[a] Significance at 0.05.

asymmetry and weight. The 25% velocity coupling measure was observed to be statistically significant in response to asymmetry only.

Effect of asymmetry at 15% velocity coupling

At 15% velocity coupling, the individual ANOVA's indicate that all four types of velocity coupling were significant due to task asymmetry. However, only the S/T coupling was significantly affected by changes in weight. The significance values for the ANOVA's are summarized in table 4.

Figure 3 shows the S/T, S/F, T/F, and S/T/F coupling as a function of increasing task asymmetry. S/T velocity coupling shown in figure 3 steadily increased as task asymmetry increased up to 120 degrees. The S/F velocity coupling response to increasing task asymmetry was opposite to the S/T. Figure 3 also shows that the percentage of time S/F velocity coupling occurred decreased as task asymmetry increased from 0 to 90 degrees followed by an increase in velocity coupling as task asymmetry increased from 120 to 180 degrees. This figure also shows that T/F coupling and S/T/F velocity coupling had similar response patterns to increasing task asymmetry. Generally, both T/F and S/T/F velocity coupling increased as a function of increasing task asymmetry, except for a significant decrease at 90 degrees.

Effect of weight at 15% velocity coupling

As shown in table 3 the percentage of time S/T coupling occurred changed significantly as a function of weight. The 15% velocity coupling significantly increased from 13% of lifting time to 16.5% of lifting time as task weight decreased from 186 N to 62 N.

Effect of asymmetry at 25% velocity coupling

The individual ANOVA results of 25% velocity coupling indicated that the S/T coupling was the only type of significant coupling ($p < 0.0001$, $df = 6$). As with 15% S/T velocity coupling the percentage of time 25% S/T coupling occurred increased as task asymmetry increased up to 120 degrees. This response was similar in pattern to that of the S/T coupling at 15% velocity coupling, but at a much lower magnitude.

Total percentage of 15% velocity coupling

Since the three types of two-way velocity coupling all had different response patterns, the percentages of time for all three were added together to determine the total percentage of veloc-

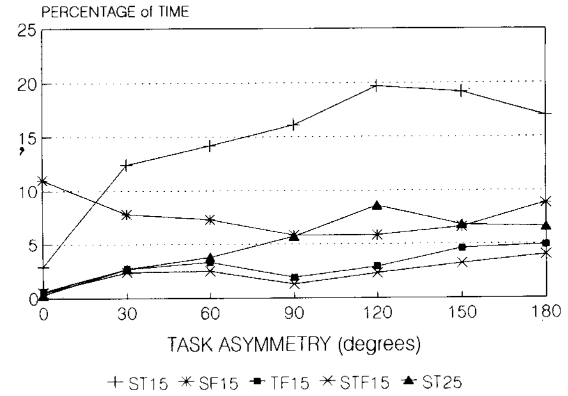

Fig. 3. Velocity coupling as a function of task asymmetry for lifting.

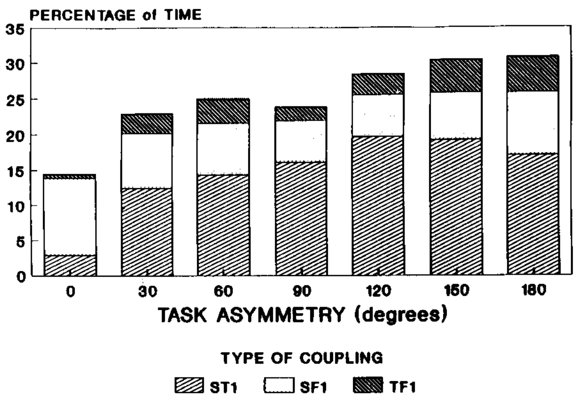

Fig. 4. Total percentage of velocity coupling time for lifting tasks.

ity coupling for a lifting task. The percentage of time that three-way coupling occurred was not added to the sum because it is already included in the three types of two-way coupling. The goal was to collectively examine all three types of two-way coupling. An ANOVA was performed on the total time variables. The results indicated that the total percentage of coupling significantly changed as a function of asymmetry ($p < 0.0007$, $df = 6$). The total percentage of coupling time for lifting is shown in figure 4. A post hoc REGWF test indicated that a statistically significant increase in the total percentage of coupling time occurred as task asymmetry increased from 0 to 30 degrees. At task asymmetries beyond 30 degrees, the percentage of time velocity coupling occurred did not change appreciably. Note that for lifting there was twice as much coupling at task asymmetries beyond 120 degrees as compared to zero. In addition, the sagittally symmetric lifting condition showed the largest percentage of S/F velocity coupling.

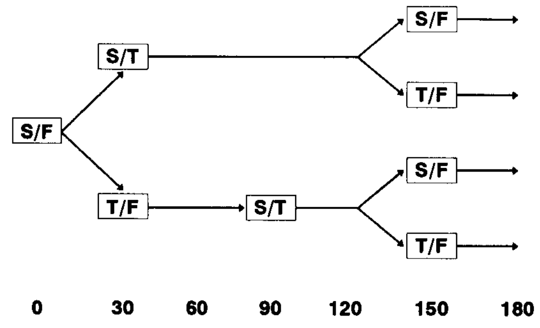

Fig. 5. Trade-offs in two-way velocity coupling as a function of task asymmetry.

Discussion

This study has quantified the percentage of time velocity coupling that occurred between different planes for both symmetric and asymmetric tasks.

The sagittally symmetric lifting task had the highest percentage of S/F coupling. This indicates that frontal plane motion was occurring even during sagittally symmetric lifts and perhaps plays a role in making corrective motions throughout a lift. Thus, the assumption of symmetry employed by sagittally symmetric biomechanical models may underestimate spinal loading. Spinal loading would also be underestimated due to the dynamic components of motion in the sagittal plane. In addition, the internal load on the spine could be underestimated due to the moment arm of the trunk in the frontal plane as well as the trunk velocity in the frontal plane of the body. Marras and associates (1992) have shown that frontal plane velocity was a LBD risk factor.

The results of this study can also be related to trunk strength. Marras and Mirka (1991) found trunk strength decreased as isokinetic trunk velocity increased in the sagittal plane. The results of the current study show an increase in the total percentage of velocity coupling during asymmetric lifting. Since velocity coupling is defined as a function of trunk velocity, an increase in coupling would indicate an increase in total trunk velocity. Therefore, in asymmetric lifting conditions, trunk strength would decrease due to the increasing velocity in all three planes of the body. However, synergistic motion may decrease strength even more than sagittal velocity only.

The results have shown that the response pattern of the S/T/F coupling was similar to the T/F coupling response patterns to increased task asymmetry. T/F coupling had the lowest percentage of coupling time among the three types of two-way coupling. Thus, the percentage of time three-way coupling occurred would be limited by the minimal quantity of two-way coupling. The different two-way coupling response patterns suggest a trade-off in motion as task asymmetry increases.

Figure 5 shows the patterns of trade-off as a function of increasing task asymmetry. As task asymmetry increases from 0 to 120 degrees, S/F coupling was traded-off to S/T or T/F coupling. At 90 degrees of task asymmetry, there was a decrease in both T/F and S/F coupling. Thus, motion was traded-off to S/T coupling. S/T coupling became S/F or T/F coupling at task asymmetries beyond 120 degrees. One explanation for the different response patterns is that lifting style changed as task asymmetry increased. The difference among the response patterns emphasizes the need to measure all three types of two-way coupling.

Studies have shown that these coupled positions of the spine greatly increase fiber strain in the disc (Shirazi-Adl et al., 1989). The addition of motion to this condition would exacerbate the effect. Also, clinical evidence has indicated that disc failure occurs due to a combination of bending, torsion and tension (White and Panjabi, 1990).

The results showed that coupling decreased as the task weight increased at 15% velocity coupling. The external moment arm due to the weight of the object would increase as task weight increased. Also, the internal loading on the spine would increase due to the increase in task weight. Since coupling was based on velocity, a decrease in velocity coupling would indicate a decrease in trunk velocity. The external moment due to the velocity of the trunk would decrease. Thus, the internal loading on the spine would decrease due to the decrease in trunk velocity. Therefore, the overall internal loading on the spine may or may not increase due to increased task weight.

The results of this research are limited to the conditions studied. Changes in lift rate, horizontal location, vertical location, or vertical travel distance and weight level may significantly affect the percentage time velocity coupling occurs. Even with these limitations, the ergonomist should realize from the results of this study that motion occurs in all three planes of the body during lifting. Thus, the usefulness of sagittal plane models are limited and there is a need for future research quantifying and modeling motion in all three planes of the body.

Conclusion

This study quantified the percentage of time coupling occurred in the S/T, S/F, T/F and S/T/F based on the velocity of motion. Generally, there were trade-offs among the three types of two-way coupling as a function of increasing task asymmetry. Cumulatively, there was significantly less two-way coupling for the symmetric condition compared to the asymmetric tasks. At task asymmetries greater than 120 degrees, twice as much coupling occurred as compared to symmetric lifts. In addition, this research pointed out the problem with the assumption of a sagittally symmetric lift, which is prominent in ergonomic literature. The assumption did not even hold at a task asymmetry of zero degrees, which is sagittally symmetric.

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