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Kinematic contribution and synchronization of the trunk, hip, and knee during free-dynamic lifting

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Abstract. Although there have been numerous studies evaluating the difference between stooped and squat lifting styles, there remains a lack of understanding of whole body kinematics during unrestricted lifting. The current study evaluated nine males and nine females while lifting two box weights (9.1 kg, 18.2 kg) from five origins below the waist (0, 19, 38, 57, and 76 cm above the floor) and from three task asymmetries (sagittally symmetric, 45° clockwise, 45° counter-clockwise). While the lifting style was significantly influenced by the height of lift origin and to a lesser extent gender, box weight, and task asymmetry, none of the conditions resulted in pure squat or stoop lifting style. However, for lifts above knee height, the lifting style resembled more of a stoop lift while lifts originating below knee height were more of a squat lift. As the origin moved closer to the floor, participants relied more on their hips to accomplish the sagittal flexion but overall adopted a more coordinated whole-body lifting style. All together, as more sagittal flexion is required, more joints are relied upon in a more coordinated effort. The current study indicates that caution needs to be exercised when applying results of pure squat or pure stoop lifting studies to free-style (realistic) lifting.

Keywords: Lifting style, biomechanics, manual material handling, coordination, low back

1. Introduction

Many researchers have investigated biomechanical differences between stooped lifting (straight legs) and squat lifting (bent knee) lifting [7–9,11,12,14,16,17,20,22–25,38,39,42,44,45]. Several researchers have reported higher physiological and metabolic demand for squat lifting as compared to stooped lifting [2,3,11,12,15,16,29,41,43,45]. The biomechanical loading findings are more complicated, with squat lifting being the method of choice (i.e. reduced loads) only when the load was placed within the base of support of the feet [44]. However, these studies have generally concentrated on pure squat lifting versus pure stooped lifting. Under realistic conditions (free lifting), there has been limited quantification of actual lifting styles [2,3,29,41]. Individuals would probably adopt a lifting style that combines both

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stoop and squat styles when performing realistic lifts. Thus, results of previous studies evaluating pure squat or pure stoop lifting may not be entirely applicable to realistic lifting.

The actual type of lift style may be dependent upon the starting location [4,40]. The heights of the origin and destinations during a lift have been reported to influence trunk kinematics. Marras et al. [30, 31] reported more trunk flexion for lower starting positions of the lift while Davis et al. [6,30] found similar results for the destination heights. In addition, several studies have shown knee and hip flexion has a larger role when lifting from low heights as compared to lifting from waist level [10,30,34–37]. Others have also shown that trunk kinematics were influenced by the load lifted as well as task asymmetry [1,5, 26]. However, these authors failed to simultaneously quantify the relative contributions of the hip, trunk, and knee during unconstrained lifting.

For pure squat or stoop lifting, lifting coordination may not be reflective of the coordination in unconstrained lifting when lifting style is more of a mixture of squat and stoop lifting. During restricted lifting (controlled feet posture), there is evidence that individuals coordinate motions of the hips/pelvis, knees and trunk during lifting [2,29]. However, when more realistic and unconstrained lifting is evaluated, it is possible that this coordination between the joints may be interrupted. Furthermore, the coordination between the joints may be directly influenced by the relative contribution of the flexion angle from the trunk, hips, and knee, which may be linked to the position of the origin of the lift. Thus, the adoption of a particular lifting style may influence not only the angles of the individual joints themselves but also the interaction with the other joints within the lower body musculoskeletal system.

Lifting style may also be dependent upon the gender of the individual. One study [27] reported that females lifted more with their hips while males performed the lifts using predominantly trunk motion. However, these conditions were performed while the feet remained stationary. In general, females have smaller anthropometric measurements (e.g. height, body mass, knee height, waist height, etc.) than males [32]. Furthermore, the female lifting strength ranges between 40% and 73% of male strength [13, 18–21,46]. The combination of different body sizes and lifting strengths may produce gender specific lifting motions, in that different joints may dominate the lifting motions under realistic lifting conditions.

The objective of this study was to quantify trunk, hip and knee kinematics during realistic lifting conditions, paying particular attention to how height of origin, box weight, and task asymmetry alter the use of these joints for both males and females.

2. Methods

2.1. Participants

Nine male and nine female student volunteers participated in this study. The mean (std dev) height, weight, and age for the females were 162.9 (5.5) cm, 63.4 (6.7) kg, and 22.7 (4.1) years and for the males were 179.9 (6.9) cm, 80.8 (24.6) kg, and 21.6 (2.6) years, respectively. All participants were right handed and had no previous history of musculoskeletal disorders.

2.2. Experimental design

The independent variables were box weight, task asymmetry, and origin lift height. Two weights were used in the current study: 9.1 and 18.2 kg. Participants lifted boxes from three task asymmetries of origin: 45° clockwise (CW), 45° counter-clockwise (CCW), sagittally symmetric and five origin height positions: 0 cm, 19 cm, 38 cm, 57 cm, and 76 cm above the floor, respectively.

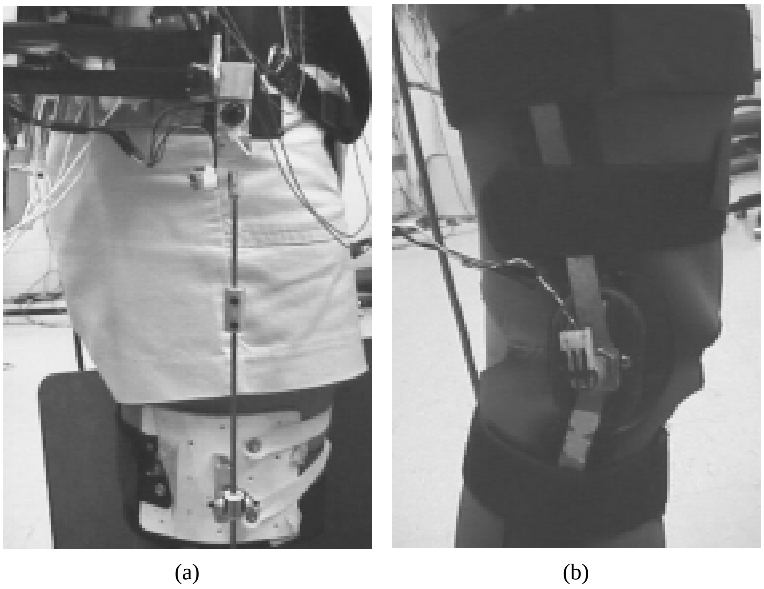

Fig. 1. The electrogoniometers used to measure the motions in (a) hip and (b) knee during the lifting tasks.

The dependent variables were the peak angles for the hip (sagittal flexion and abduction), trunk (sagittal flexion, lateral flexion, and twisting), and knee (sagittal flexion). Correlations were calculated between the continuous data of the angles for each joint direction to provide a measure of synchronicity between kinematic measures. The peak angles provide measures of the relative joint contribution to the overall lifting posture while the correlations between the joint angles represents joint coordination.

2.3. Apparatus

The lumbar motion monitor (LMM) measured the trunk motion characteristics (sagittal, lateral and twisting angles) during the lifting tasks. The LMM is essentially an exoskeleton of the spine in the form of a triaxial electro-goniometer that measures the instantaneous three-dimensional position, velocity, and acceleration. For more detail about the design, accuracy, and application of the LMM, refer to Marras et al. [28].

An electro-goniometric device was used to monitor the hip sagittal flexion and abduction. The device was developed in the Biodynamics Laboratory and consists of two potentiometers and a rod running along the femur that is connected to a cuff positioned on the upper leg (thigh) via a Velcro strap (Fig. 1). Another electro-goniometer was positioned across the knee joint (Fig. 1). This knee goniometer had a rotary potentiometer connected to two thin metal strips and was attached to a flexible knee brace. Basically, the potentiometers measured the angles between two segments of the body, either defined by the rod on the leg relative to horizontal (in both flexion and abduction) or the two metal strips for the knee. This technology has been widely used in laboratory research and has been published in literature [33].

Cardboard boxes with no handles with the dimensions: 40 cm wide, 31 cm deep, and 19 cm high were used for all conditions.

2.4. Procedure

Upon arrival to the Biodynamics Laboratory, the participants were briefed about the lifting tasks and asked to read and sign a consent form (approved by the University Institutional Review Board). The participants were then fitted with the LMM and electro-goniometers, followed by initial recordings of the monitoring equipment. Participants then lifted boxes from positions corresponding to the origin heights and task asymmetries (as described above) to a destination shelf located 85 cm in front of the participant and 97 cm high.

Participants were instructed to lift in a natural, “freestyle” manner (e.g. moving however they wished). The participants were allowed to step and “square up” to the boxes if they desired. Lifting from the origin to the destination shelf was typically performed in one fluid, continuous motion. Kinematic data was collected from the LMM and hip and knee goniometers starting when the participant first touched the box and ending when the box touched down on the destination shelf.

2.5. Data analyses

Angles from the hip and knee goniometers were all measured relative to angles recorded while the participant was standing in an upright posture. Voltages from each of the potentiometers were converted into angles through known calibrations (determined prior to collection on calibration apparatus). Peak values for trunk sagittal flexion, hip sagittal flexion, hip abduction and knee flexion were identified within each trial. Correlations were calculated from the continuous data for each combination of joint angles.

2.6. Statistical analyses

A split-plot repeated measures analysis of variance (ANOVA) was used to determine whether significant differences exist for the peak values and correlations as a function of the independent variables and interactions. For all significant independent variables, post-hoc analyses in the form of Tukey multiple pairwise comparisons were performed to determine the source of the significant effect(s) ($\alpha < 0.05$).

3. Results

Results of the ANOVA statistical analyses are summarized in Table 1. The only difference found between the genders was for sagittal trunk flexion. Task asymmetry had a significant impact on the hip sagittal flexion and abduction, and trunk lateral flexion and twisting. Box weight significantly impacted sagittal flexion in the hip, trunk, and knee as well as hip abduction, while starting height impacted all joint angles except trunk twisting. There were also a few interactions that were significant.

Table 2 provides a summary of the impact of the independent factors on the joint angles during the lifting conditions. Overall, males bent farther forward (about 5°) with the trunk than females. Additionally, an increase box weight from 9.1 to 18.2 kg resulted in slight increases in maximum sagittal flexion angle for trunk (2.0°), hip (3.4°), and knee (3.6°) and hip abduction angle (2.8°). Lifting to the right (CW) increased hip flexion by about 3°. There was a trade-off between lateral flexion and twist when lifting from the asymmetric positions so that lifting CW relied on lateral flexion more while lifting CCW result more from twist.

As the height of the lift origin became closer to the floor, the sagittal trunk flexion, hip flexion, and knee flexion increased significantly as did hip abduction. In short, loads placed closer to 76 cm high (about waist height) required less joint motion on the part of the participant. For changes in height of 19 cm, larger increases in hip flexion (more than 12°) occurred above the 19 cm position than between the floor and 19 cm heights (about 8°). When lifting from origins above 38 cm, changes of 19 cm resulted in about 12° more of trunk flexion and about 8° less in knee flexion. The opposite trend was

Table 1
Statistical results from the spilt-plot analyses of variance tests

Effect	Kinematics					
	Hip sagittal flexion	Hip abduction	Trunk sagittal flexion	Trunk lateral flexion	Trunk twist	Knee flexion
Gender (GNDR)			*			
Task asymmetry (ASYM)	**	**		**	**	
Box weight (WGHT)	**	**	**			**
Starting height (HGHT)	**	**	**	*	*	**
GNDR *ASYM				*	**	
GNDR *WGHT						
GNDR*HGHT	**				*	
WGHT*ASYM						
ASYM*HGHT					**	
WGHT*HGHT			*			

*significant at $\alpha < 0.05$, **significant at $\alpha < 0.01$

true when lifting from origins below 38 cm. A drop in the height of 19 cm resulted in about 3° more in hip abduction.

Although there were several interactions that were significant, the impact of these effects was very limited (less than 3°), especially with respect to both trunk lateral flexion and twisting. However, the gender by height interaction (as seen in Fig. 1) indicated that females had larger increases in hip flexion for the upper three lift origins (38 and 76 cm) while the largest increases for the males occurred between 19 and 57 cm above the floor. Figure 2 also provides a picture of the trade-offs between the hip, trunk, and knee joints. Females used all three joints similarly in all positions while males accomplished forward bending predominantly through their hips and trunk. For the two lowest origins, males relied upon more flexion from the trunk than hips.

4. Discussion

The results indicate that the lifting style adopted depended on the height of the lift origin and gender. Females predominantly relied equally on all three joints (e.g. hips, knees, and trunk) for flexion when lifting from the higher origins (57 and 76 cm origins). For these upper origins, lifting style was a mixture between stoop and squat. However, for origins close to the floor (at the 0 and 38 cm lift origins), the hips dominated and lifting style resembled more of a squat lift than a stoop lift. Males adopted a slightly different lifting style with the knees providing a lesser contribution to the overall flexion. Males adopted a more stoop type lifting style when lifting in the upper regions (at 57 and 76 cm above floor) but a more squat lifting style in the lower levels (below 19 cm). For the middle origin (38 cm), males adopted a mixture of the two styles. Thus, in general, origins that are slightly below knee height resemble more of a squat lift while origins above knee height resembled more of a stoop lift.

It appeared that box weight and task asymmetry had relatively limited (as compared to origin height) influence on the lifting style. Participants modified their hip abduction angle in response to greater box weight. This increased hip abduction was combined with small increases in the hip, knee, and trunk sagittal flexion. Trunk lateral flexion and twisting was slightly greater in magnitude when lifting CW as compared to CCW. The opposite trend was found for hip abduction (CCW > CW), indicating a trade-off

Table 2

Means (standard deviations) of hip, trunk and knee angles as a function of box weight, height of origin of lift and task asymmetry of origin of lift[1]

	Hip sagittal flexion	Hip abduction	Knee flexion	Trunk sagittal flexion	Trunk lateral flexion	Trunk twist
Gender						
Male	57.7^{A}	17.6^{A}	41.7^{A}	55.4^{A}	2.3^{A}	-3.2^{A}
	(23.0)	(10.4)	(19.4)	(14.8)	(8.8)	(7.7)
Female	52.0^{A}	18.1^{A}	46.9^{A}	45.8^{B}	-0.6^{A}	-3.0^{A}
	(20.5)	(11.8)	(24.3)	(17.9)	(9.3)	(9.4)
Box Weight (kg)						
9.1	53.2^{A}	16.4^{A}	42.6^{A}	49.6^{A}	0.5^{A}	-2.8^{A}
	(22.3)	(10.2)	(22.7)	(17.5)	(8.9)	(8.4)
18.2	56.6^{B}	19.2^{B}	46.2^{B}	51.6^{B}	1.2^{A}	-3.4^{A}
	(21.6)	(11.8)	(21.7)	(16.6)	(9.4)	(8.8)
Height from Floor (cm)						
76	28.6^{A}	12.6^{A}	26.1^{A}	29.0^{A}	1.0^{AB}	-1.7^{A}
	(10.6)	(6.7)	(12.8)	(9.5)	(8.2)	(9.5)
57	40.6^{B}	14.4^{A}	34.3^{B}	43.0^{B}	0.8^{AB}	-3.7^{A}
	(12.4)	(7.9)	(14.7)	(8.6)	(8.5)	(8.2)
38	57.5^{C}	17.4^{B}	41.0^{C}	53.3^{C}	0.8^{AB}	-3.7^{A}
	(12.2)	(10.3)	(16.7)	(9.3)	(9.4)	(8.1)
19	69.9^{D}	20.6^{C}	53.5^{D}	61.5^{D}	2.1^{A}	-3.8^{A}
	(13.1)	(10.7)	(18.1)	(11.4)	(9.1)	(7.9)
Floor	78.5^{E}	25.1^{D}	69.6^{E}	67.5^{E}	-0.5^{B}	-2.6^{A}
	(13.7)	(14.4)	(18.9)	(12.3)	(10.5)	(9.1)
Task Asymmetry (deg)						
45°W	58.0^{A}	16.6^{A}	43.4^{A}	50.2^{A}	4.2^{A}	-2.0^{A}
	(21.2)	(10.2)	(23.8)	(17.2)	(8.5)	(9.8)
Sag. Sym.	55.3^{B}	17.1^{A}	45.0^{A}	51.0^{A}	0.7^{B}	-3.1^{AB}
	(22.6)	(12.8)	(22.0)	(17.2)	(9.2)	(6.4)
45°CW	51.2^{C}	19.8^{B}	44.9^{A}	50.7^{A}	-2.4^{C}	-4.2^{B}
	(21.8)	(9.8)	(20.9)	(16.9)	(8.5)	(9.1)

[1] Significant differences are indicated by different alpha characters.

between hip and trunk motion. Marras and Davis [26] also noted kinematic differences between CW and CCW asymmetry but it was limited to velocity measures, most likely resulting from the stationary feet conditions. In addition, greater hip axial rotation (asymmetric motion of hips) occurred when lifting from the CW positions while the feet remained stationary.

Several researchers have noted changes in coordination between the hips and back during different phases of lifting [10,16,34,36,37]. During the first portion of the lift, while the hips and trunk are still mostly flexed, hip extension dominates trunk extension. During the later portions of the lift, when the lift is nearly complete, this trend reverses and the trunk extends more then the hips. The height of lift origin appears to result in a trade-off between hip and trunk flexion during lifting when the lift is not constrained to a certain lifting style. A similar trade-off was observed during this study.

Participants appeared to coordinate their hips, back, and knees during the lift, particularly at the lower origins (Fig. 3). At the higher origin heights, the coordination between the joints was relatively low (correlation values below 0.6) indicating independent movement of the joints, particularly the knees. However, as the lifts begin closer to the floor (below 38 cm), the motion was much more coordinated (all correlations above 0.75). With a predominant back or stoop lift, the coordination between hips, knees and back was weak since motion was minimal from the hips and knees. However, the coordination between

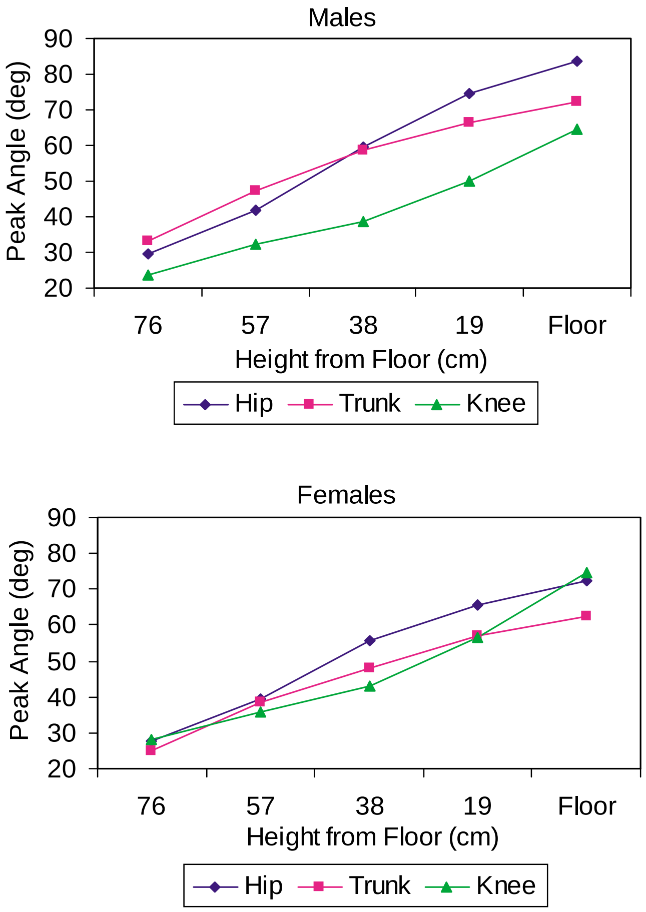

Fig. 2. Flexion angle for the hip, knee, and trunk as a function of origin height for males and females.

these joints increased, as the lifting style became more squat-oriented. Thus, the motion originated from all three joints during the lifts using a squat lifting style (lifting from lower origins).

The current results may have broader ramifications with respect to risk of injury to the overall musculoskeletal system. The kinematic pattern adopted by the participants may be an attempt to limit the risk across all of the joints by minimizing the stress on each of the joints by potentially reducing the joint moments. The more coordinated motions for the more "risky" lifting origins (e.g. closer to the floor) may signal more balanced joint motion as well as smoother motion, which may tend to reduce coactivity around the joints. In other words, the body minimizes the loading on the individual joints by sharing the loads. For the lower origins, the hips had a more dominate role in the overall motion, potentially reducing the impact on the trunk that may be more susceptible to injury during these more biomechanically challenging lifts.

Several issues need to be considered when interpreting the results of the current study. First, the hip and knee monitors only measured the motion on the right leg. Hence, the left leg may have a different response depending upon the lifting style adopted by the individual. When the legs are squared up to the box (as was typically done in this study), the two legs would most likely have very similar kinematic profiles. Second, the kinematic profiles and relative contributions may potentially be affected by the lift rate required by the individual. In the current study, no rate was enforced. If the participants were

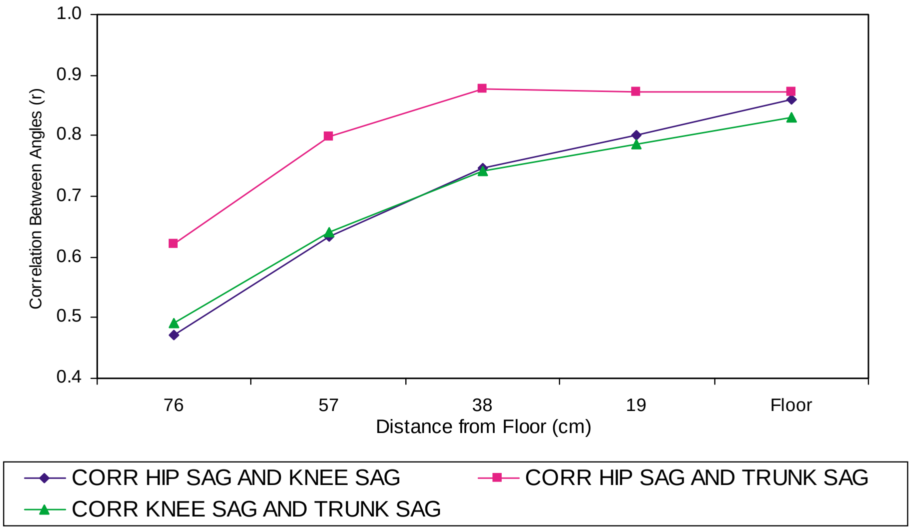

Fig. 3. Correlation of the angles for the hip, knee, and trunk during each lift as a function of origin height (Correlations were obtained between the instantaneous angles of two joints).

required to lift at a high lift rate, the lifting style may be impacted [16]. Third, fatigue has been found to have a large role in the lifting style adopted. Since the current study evaluated only a few lifts at a time, the impact of fatigue on the resulting lifting styles was unknown. However, other researchers [29, 41] have reported participants adopt more of a stooped lifting style as they fatigued during repeated lifting below the waist. Fourth, the participants were limited students that have limited manual material handling experience. More experienced lifters may adopt entirely different kinematic profiles. Thus, the current results would be most applicable for inexperienced manual material handlers.

5. Conclusions

None of the conditions resulted in pure squat or stoop lifting indicating discretion is needed when applying the results of pure squat or pure stoop lifting studies to the more realistic lifting. However, lifting style was significantly influenced by the height of lift origin and was somewhat dependent on gender. In general, lower lift origins employed greater hip angles, resembling a squat lift with a bent back while a more stoop lifting style was adopted when the lift origin was above knee height and approached waist level. Furthermore, participants adopted a whole-body lifting style that was more coordinated as the lift origin approached the floor. In other words, trunk motion was more coordinated with knee and hip motion during the lower lifts than lifts from waist height.

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