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Lifting Strengths in Different Horizontal Distances of Objects to be Lifted

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Abstract: Lifting Strengths in Different Horizontal Distances of Objects to be Lifted: Te-Shiang CHENG, *et al.* Department of Management and Information Technology, Southern Taiwan University of Technology, Taiwan, R.O.C.—This study recruited eleven healthy males and thirteen healthy females to examine their maximum two-handed isometric back lifting strength, upper-body lifting strength, arm lifting strength and shoulder lifting strength in three different horizontal distances of objects to be lifted (toes were anterior to, aligned with, and posterior to the exerted handle). The results showed that human lifting strength decreased significantly as the toe position shifted from anterior of the vertical plane of the exerted handle to posterior of the vertical plane of the exerted handle. The strength order relationship between back lifting strength and upper-body lifting strength was dependent on the horizontal distance of objects to be lifted. This study also observed that the effects of the horizontal distance of objects to be lifted on human lifting postural angles for the four assessed lifting types mainly occurred in the upper extremities. This study recommends that practitioners should not overlook the effects of the horizontal distance of objects to be lifted on lifting strength when evaluating workers' lifting strength for screening purposes.
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Key words: Isometric strength, Horizontal distance of objects to be lifted, Lifting posture, Worker screen

The demands for human strength to accomplish physical activities remain strong despite increasing automation. Numerous studies recommend selecting workers whose strength capabilities are at or above the task demands as an approach for improving work efficiency and preventing musculoskeletal injuries. Hence, a correct knowledge of strength measurement procedures is important for practitioners in selecting workers.

Practitioners have specified fairly standard measurement procedures that should be carefully controlled in isometric muscle strength testing, such as exertion duration, rest period and measuring device[1]. Based on the specified standard measurement procedures, previous studies have elucidated some important knowledge regarding human maximum lifting strengths[2–10]. For example, Kumar and Garand[4] measured isometric and isokinetic lifting strengths in stoop and squat modes at different reach distances and in symmetrical and asymmetrical planes. They revealed that the gender, mode of lifting, postural asymmetry and reach of lifting affected lifting strength significantly, with reach affecting the strength most profoundly followed by postural asymmetry and the mode of lifting. From the viewpoint of biomechanics, the reach factor is closely related to the foot placement. Most previous studies concerning foot placement effects on human lifting strength have mainly focussed on the effects of different foot placement directions on lifting strength[11], i.e. comparing symmetric and asymmetric lifting strengths. However, different foot placements affect maximum strength exertions and occur in symmetric lifting tasks, and the effects of different foot placements are equivalent to the effects of horizontal distance of objects to be lifted. To our knowledge, there are few studies on lifting strengths in short horizontal distances, therefore, this kind of scientific information deserves exploration.

The purpose of this study was to enhance our knowledge of the effects of different anteroposterior horizontal distances of objects to be lifted in the sagittal plane on human isometric lifting strengths and lifting postural angles. Three horizontal distances of objects to be lifted (toes were anterior to, aligned with, and posterior to the exerted handle) and four lifting strength types (back

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Table 1. The means and standard deviations (SD) of the participants' anthropometric characteristics

	Males		Females	
Anthropometric characteristics	Mean	SD	Mean	SD
Age (yrs)	23.3	2.1	22.1	1.1
Stature (cm)	171.9	7.0	158.5	4.0
Weight (kg)	67.6	10.2	54.1	5.8
Chest circumference (cm)	88.9	7.9	84.2	6.3
Waist circumference (cm)	76.9	9.5	65.9	4.6
Knuckle height (cm)	73.0	3.6	68.8	3.5
Foot length (cm)	25.5	1.2	22.8	0.9

lifting strength, upper-body lifting strength, arm lifting strength and shoulder lifting strength) were examined in this study. The three horizontal distances of objects to be lifted differed as toe position shifted from the anterior of the vertical plane of the handle to the posterior of the vertical plane of the handle. This distance was correlated with the horizontal distance from the midpoint of the ankles of the lifters to the point of force application. The hypothesis of this study was that different horizontal distances of objects to be lifted would significantly affect the assumed lifting posture and thus the lifting strength.

Method

Participants

Eleven healthy males and thirteen healthy females participated in this study. All participants were university students and were experienced in lifting tasks in the workplace. Table 1 lists their anthropometric measurements. Participants gave their consent in a form attesting to their understanding of the risk of the experiment.

Experimental Apparatus

A digital Lafayette strength evaluation system (model 32528, Lafayette instrument, Indiana, USA) was used for measuring participants' maximum isometric two-handed lifting strength. The load cell of the strength evaluation system was fixed to the ground and the strength signals were sampled at a frequency of 60 Hz. A 60 cm long handle bar (diameter, 3.5 cm) was used for two-handed exertion. A steel chain was used to connect the handle bar with the load cell, and the handle bar was adjusted to different lifting heights for strength testing.

Experimental Design

This study investigated the effects of three different horizontal distances of objects to be lifted on four isometric lifting strengths. The three horizontal distances of objects to be lifted differed in the distance from the toes to the vertical plane of the handle bar as depicted in Fig. 1. Horizontal distances 1, 2 and 3 refer to participants' toes being one-third foot length anterior to, aligned with, and one-third foot length posterior to the vertical plane of the handle bar, respectively. The one-third foot length for male and female participants was set according to their mean anthropometrical data, and corresponded to approximately 8.5 and 7.5 cm for male and female participants in this study. The four isometric lifting strengths assessed in this study included back lifting strength, upper-body lifting strength, arm lifting strength, and shoulder lifting strength. Figure 2 shows the typical postures for exerting the four isometric lifting strengths. Participants assumed a stoop posture for back lifting, with two hands approximately at knee height. For upper-body lifting, participants stood erect with back, legs and elbows straight and placed two hands in front of the body at knuckle height. For arm lifting, participants stood erect with back and legs straight and kept the forearms horizontal. For shoulder lifting strength, participants stood erect with back and legs straight and two elbows fully flexed in front of the body. For all strength tests, participants looked straight ahead and grasped the handle with two palms up with the feet separated shoulder witdth apart.

Procedure

Participants were given a standardized demonstration of the strength testing postures and procedures, then allowed to perform practice exercises to familiarize themselves with the strength testing postures and procedures in a two-week period prior to the formal experiment. Participants were directed to perform all 12 lifting conditions (three horizontal distances of objects to be lifted × four isometric lifting types) in a random order. Participants tested their strengths in bare feet set parallel and exerted as hard as they could with their maximum voluntary effort on the handle without jerking and maintained the maximal exertion for about 4 s[1].

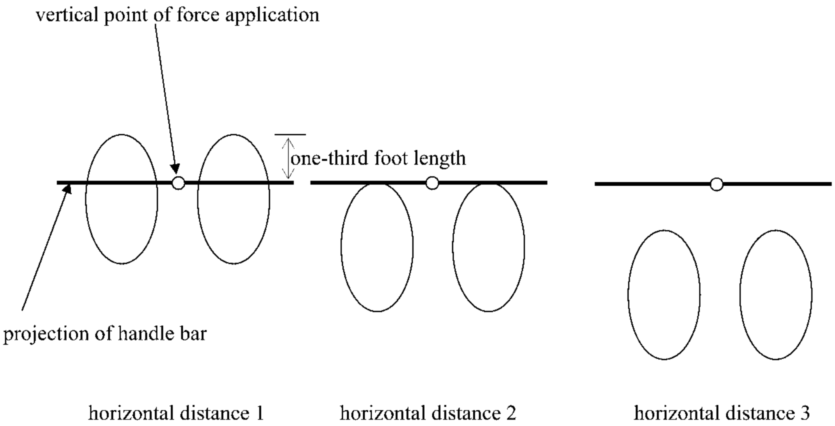

Fig. 1. The schematic top view of the geometrical relationship between participants' toes and the handle bar for the three horizontal distances of objects to be lifted in this study. Horizontal distances 1, 2 and 3 refer to participants' toes one-third foot length anterior to, aligned with, and one-third foot length posterior to the handle bar, respectively.

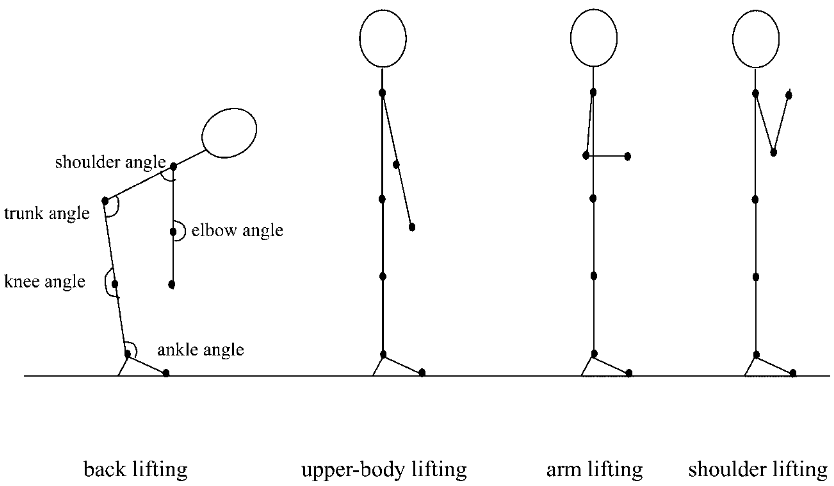

Fig. 2. The lifting postures assumed by participants for the four isometric lifting strengths in this study

Precautions to prevent strength data contamination from fatigue, feedback and the presence of spectators[12–14] were adhered to in all tests. Each participant attempted five repetitions, one repetition per day, for all 12 lifting conditions in five days. For each test, the participants' peak lifting strength was measured and adjusted for the inertial forces due to the weight of the handle bar and steel chain. A digital camera was placed 5.5 m orthogonal to participants' sagittal plane with the focus on participants' waist to record participants' postural angles while lifting. Seven spherical reflective markers (diameters of about 2.5 cm each) were placed on participants' right heads of ulna (wrist) and radius (elbow), acromion process (shoulder), greater trochanter (hip), lateral tibial plateau (knee), and lateral malleolus (ankle) and toe nail (toe). With the aid of the digital camera, the participants' elbow, shoulder, trunk, knee and ankle angles (as shown in Fig. 2) were captured via the spherical reflective markers and were subjected to analysis.

Results

Table 2 lists the means and standard deviations of the male and female participants' lifting strengths for all 12 lifting conditions. Analysis of variance (ANOVA) examined the effects of participant, repetition, horizontal

Table 2. The means and standard deviations (SD) for the maximum isometric lifting strengths (N) exerted in all 12 lifting conditions

	Males						Females					
	Horizontal distance						Horizontal distance					
Lifting type	1		2		3		1		2		3	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Back	958.7	208.2	850.2	183.0	567.6	113.1	541.3	92.5	489.2	93.9	370.0	71.0
Upper-body	1044.4	275.4	822.8	233.4	503.8	116.5	594.1	144.2	477.6	143.6	304.9	74.9
Arm	315.5	56.1	310.9	50.9	304.4	52.6	185.4	31.2	185.7	32.5	176.5	29.3
Shoulder	448.3	71.9	407.4	52.1	332.4	57.1	308.6	55.8	258.5	44.4	197.9	42.1

distance of objects to be lifted, lifting type and the interaction effect of horizontal distance of objects to be lifted and lifting type on male and female participants' lifting strengths separately, showing that all factors significantly affected participants' lifting strengths with the exception of repetition ($p>0.05$). Fig. 3 demonstrates the effects of horizontal distance of objects to be lifted and lifting type on lifting strengths. The highest to lowest order for maximum lifting strength across the three horizontal distances of objects to be lifted was horizontal distance 1, horizontal distance 2 and horizontal distance 3. Duncan's multiple range tests reveal that the lifting strengths across the three horizontal distances of objects to be lifted differed significantly to each other ($p<0.01$) for all four lifting types with the exception of arm lifting strength. Additionally, the highest to lowest order for maximum lifting strength across the four lifting types depended on the horizontal distance of objects to be lifted. Fig. 3 shows that the horizontal distance of objects to be lifted can change the strength order between back lifting strength and upper-body lifting strength. Duncan's multiple range tests indicate that back lifting strength was significantly higher than upper-body lifting strength in horizontal distance 2 and horizontal distance 3, while it was significantly lower in horizontal distance 1.

The mean and standard deviation of the ratios of lifting strengths for females and males across the 12 lifting conditions was 0.60 and 0.04, respectively, ranging from 0.56 to 0.69, with a coefficient of variation of 6.6%.

Table 3 compares the postural angles among the three horizontal distance conditions. The bold and italic values indicate significantly larger and smaller angles among the three horizontal distances of objects to be lifted based upon the results of Duncan's Multiple Range Test at 0.01 significance. Table 3 reveals that the effects of horizontal distance of objects to be lifted on postural angles were similar between male and female participants. The horizontal distance of objects to be lifted had most influence on the shoulder angle in back and upper-body liftings, and on elbow and shoulder angles in arm and shoulder liftings.

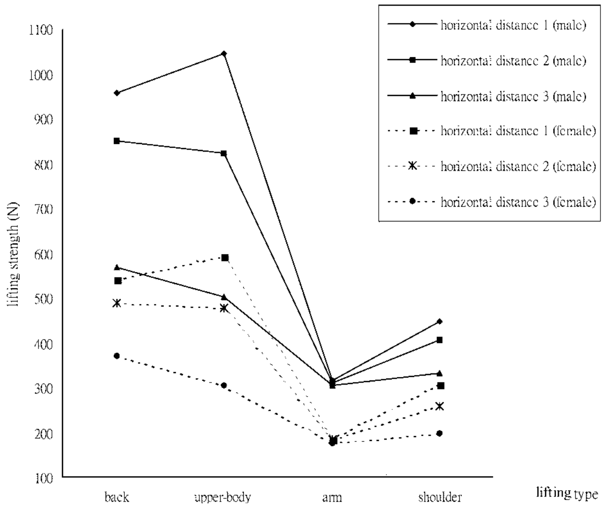

Fig. 3. The effects of the horizontal distance of objects to be lifted and lifting type on lifting strengths.

Discussion

Our data show that maximum lifting strength differed significantly across the three horizontal distances of objects to be lifted. The highest to lowest order for maximum lifting strength across the three horizontal distances of objects to be lifted was horizontal distance 1, horizontal distance 2 and horizontal distance 3 for all four lifting types. The lifting strength associated with horizontal distance 1 was approximately one to two folds of the lifting strength associated with horizontal distance 3, depending on lifting types. The horizontal distance of objects to be lifted had the most effect on lifting strength for upper-body lifting and the least effect on arm lifting. For example, the differences in male participants' upper-body lifting strength between horizontal distance 1 and

Table 3. Comparisons of participants' postural angles (degrees) among the three horizontal distances of objects to be lifted

Males Lifting type	Horizontal distance	Postural Angle									
		Elbow		Shoulder		Trunk		Knee		Ankle	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Back	1	159.7	3.6	*36.5*	*7.2*	111.3	7.7	177.6	5.3	112.6	3.1
	2	159.8	8.4	*40.9*	*10.2*	114.2	8.3	178.7	8.6	111.0	5.8
	3	159.1	14.2	**48.2**	**8.5**	117.4	8.1	177.8	10.4	111.3	5.1
Upper-body	1	**173.4**	**7.6**	*9.2*	*4.2*	172.9	3.6	175.6	6.6	102.4	7.6
	2	**174.0**	**8.9**	13.1	7.4	176.1	5.5	176.1	5.4	104.5	7.7
	3	*168.7*	*12.2*	**20.0**	**8.3**	172.5	5.9	178.0	4.8	104.6	6.4
Arm	1	*75.3*	*8.5*	*–31.1*	*5.7*	181.2	5.5	176.5	5.0	104.6	5.3
	2	*78.2*	*7.5*	–23.2	7.2	183.2	6.3	176.2	4.7	104.1	6.8
	3	**83.7**	**7.8**	**–9.9**	**7.4**	183.0	6.4	175.0	5.8	102.8	6.1
Shoulder	1	*44.0*	*7.5*	*17.9*	*12.8*	185.5	4.9	176.4	6.3	103.4	5.3
	2	*47.9*	*7.6*	*20.5*	*8.7*	184.3	5.9	176.0	5.8	105.1	6.0
	3	**57.6**	**5.1**	**27.5**	**8.6**	183.5	4.8	177.7	3.6	105.1	6.0

Females Lifting type	Horizontal distance	Postural Angle									
		Elbow		Shoulder		Trunk		Knee		Ankle	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Back	1	166.9	6.1	*46.6*	*7.3*	108.5	8.3	183.8	6.9	117.4	5.9
	2	167.1	7.9	*48.9*	*6.9*	113.3	9.1	184.3	6.9	113.2	3.7
	3	165.5	9.0	**56.0**	**6.9**	113.3	8.9	186.5	7.8	115.2	3.6
Upper-body	1	173.8	8.4	*8.8*	*2.9*	175.5	5.7	180.2	3.3	102.8	5.4
	2	173.5	9.2	11.1	3.9	176.5	5.2	180.5	3.4	103.2	5.2
	3	169.5	9.7	**17.8**	**6.5**	174.8	6.7	181.0	3.4	104.3	4.6
Arm	1	*74.4*	*5.5*	*–32.2*	*5.0*	180.7	2.7	179.5	4.2	104.1	5.2
	2	78.7	6.3	–22.4	7.0	182.9	3.9	178.2	3.8	104.5	7.1
	3	**84.5**	**3.7**	**–7.6**	**6.0**	182.3	4.3	178.7	3.1	102.7	4.9
Shoulder	1	*37.1*	*7.9*	*17.8*	*8.4*	182.3	3.0	180.8	2.8	105.2	5.4
	2	*41.7*	*6.7*	*18.6*	*6.9*	184.3	3.8	179.7	3.4	106.7	5.7
	3	**54.1**	**5.0**	**26.0**	**6.6**	183.8	3.4	178.8	4.9	104.5	5.5

Bold and italic values indicate significantly larger and smaller levels among the three horizontal distances of objects to be lifted based upon the results of Duncan's Multiple Range Test at 0.01 significance.

horizontal distance 3 could reach 540 N while showing only a 10 N difference for arm lifting strength. This phenomenon was attributed to the different horizontal distances from the body to the handle. There is already a consensus that the horizontal distance from the midpoint of the ankles of lifters to the point of force application has a large effect on the lifting strengths of lifters. The NIOSH lifting equations[15] also regard the horizontal distance as one of the main factors in estimating the relative risk of lifting heavy loads. From the view point of biomechanics, the differences between the factor of horizontal distance of objects to be lifted in this study and the factor of the horizontal distance from the midpoint of the ankles of the lifters to the point of force application are equivalent in nature.

The NIOSH lifting equations[15] establish a reverse proportional relationship (a multiplier factor of H/25 cm, H must be equal or larger than 25 cm) between the horizontal distance (H) from the midpoint of the ankles of the lifters to the point of force application and the recommended weight-lifting limit. In this study, the horizontal distance (H) from the midpoint of the ankles of the lifters to the point of force application for the three horizontal distances of objects to be lifted can be roughly estimated. For example, male participants had a mean foot length of 25.5 cm and about 5 cm distance between heel and midpoint of the ankle, hence the horizontal distance from the midpoint of the ankles of the lifters to the point of force application for horizontal distance 1, 2 and 3 were approximately 12, 20.5 and 29 cm, respectively. Applying the reverse proportional relationship (H/25 cm) in NIOSH lifting equations[15], the recommended weight-lifting limit for horizontal distance 1 and horizontal distance 2 should be 2.4 and 1.4 folds of that for horizontal distance 3, respectively. These values do not match the ratios of lifting strengths measured in this study. For example, Table 2 shows the back lifting strength for horizontal distance 1 and horizontal distance 2 was 1.7 and 1.5 folds of that for horizontal distance 3, respectively. The larger difference occurring in horizontal distance 1 condition might be attributable to the NIOSH lifting equations[15] not being applicable to the case of H smaller than 25 cm.

The horizontal distance of objects to be lifted determines participants' lifting postures in terms of angle. This study clearly showed that the horizontal distance of objects to be lifted affected shoulder angle in all lifting types and affected elbow angle in arm lifting and shoulder lifting. From the biomechanical consideration, a more positive shoulder angle in this study indicates a more flexed shoulder joint as compared with 0 degree shoulder angle. A more flexed shoulder joint is associated with a farther distance from the handle to the body and thus inhibits the upward exertion and transfer of biceps strength to the handle. For back and upper-body liftings, the shoulder angle increased by approximately 9 to12 degrees as the horizontal distance of objects to be lifted changed from horizontal distance 1 to horizontal distance 3. The increase in shoulder angle from horizontal distance 1 to horizontal distance 3 explained the decreasing trend in back and upper-body lifting strengths. For arm and shoulder liftings, both elbow and shoulder angles changed simultaneously across the three horizontal distances of objects to be lifted and complicated the explanation of lifting strength. However, lifters with both larger elbow angle and shoulder angle in horizontal distance 3 for shoulder lifting also had a longer distance from the handle to the shoulder, which was responsible for the lower lifting strength. The role of lifters' center of gravity on strength exertion might be another important factor and hence should be noted. Horizontal distance 1 had a center of gravity closer to the exertion handle, thus helping the efficiency in muscle strength transfer to the handle. The high variability of lifting strengths across the three horizontal distances of objects to be lifted indicates the horizontal distance of objects to be lifted is an important factor in lifting strength and practitioners should be cautious in specifying lifters' horizontal distance of objects to be lifted when examining lifters' lifting strength in worker selection.

Horizontal distance of objects to be lifted affected the strength order relationship between back lifting strength and upper-body lifting strength. Figure 3 shows back lifting strength might be higher or lower than upper-body lifting strength, depending on the horizontal distance of objects to be lifted. This can be attributed to a more efficient force transmission from upper-body to the handle due to a closer horizontal distance from hand to shoulder. This implies practitioners should be cautious in comparing, evaluating and interpreting human lifting strength between upper-body lifting strength and back lifting strength.

Lifting types significantly determined the vertical locations of the hands of the participants and lifting strengths. The vertical location of the hands increased as the lifting types changed from back lifting, through whole-body lifting and arm lifting, to shoulder lifting. The vertical location of the hands in lifting is also an important task factor cited in the NIOSH lifting equations, in which a height of 75 cm suggests highest lifting strength. Though the NIOSH lifting equations suggest an increasing-decreasing relationship between vertical location of the hands and lifting strength, this study showed that the relationship between vertical location of the hands and lifting strength was not as simple as that. This study indicated that an increasing-decreasing-increasing relationship between vertical location of the hands and lifting strength for horizontal distance 1, and decreasing-increasing relationships for horizontal distance 2 and horizontal distance 3. The merit or priority of this study was that the horizontal distance of objects to be lifted was carefully controlled in examining the relationship between vertical location of the hands and lifting strengths. Though previous studies[8, 9] examining the effects of vertical locations of the hands on lifting strengths did not control horizontal distance of objects to be lifted in experiments, their results still stand in practice since lifters would select their most suitable horizontal distances of objects to be lifted for the different vertical locations of the hands to maximize their lifting strengths.

The ratios of lifting strengths for females and males were similar across the 12 lifting conditions, ranging from 0.56 to 0.69, mean 0.60 with a coefficient of variation of 6.6%. Several researchers noted that the effect of sex differences on strength seemed to be task-dependent and was more pronounced for the upper extremities than for the lower ones[16, 17]. The small variability among female/male strength ratios across the 12 lifting conditions might also be attributable to similar exertion muscles for males and females, and the study design in which the horizontal distance of objects to be lifted was standardized for participants.

This study performed basic research to investigate the effects of the horizontal distance of objects to be lifted on lifting strength. Some variables in the experiments, such as the condition of horizontal distance 1 in shoulder lifting or horizontal distance 3 in back lifting, may not be realistic in practical use since lifters might not assume such horizontal distance of objects to be lifted in lifting due to the handle being too close to the body or the lifters' center of gravity reaching the forefront of the foot so that lifters cannot exert more lifting strength without losing their postural balance. Though the location of lifters' center of gravity is an important factor in lifting strength, this study did not reveal the relationship, something which requires a motion analysis system or a force plate. Additionally, the calculation of the location of lifters' center of gravity (COG) to their foot length needs a sophisticated biomechanical model and estimation, which might lead to large errors due to anthropometrical assumptions, since human anteroposterior functional base of support (FBOS) length for body' center of gravity to locate in balanced postures is in general only 11.9 cm, which is 47% of human foot length (the theoretical BOS length)[18]. Hence, even a 1 cm error in COG estimation may cause an 8.4% error. This makes the exploration of the relationship between the location of COG and lifting strength very difficult and constituted a methodological limitation of this study.

Conclusion

This study examined the effects of horizontal distance of objects to be lifted on human lifting strength. The experimental results verified the hypothesis of this study and demonstrated that the horizontal distance of objects to be lifted significantly affected human lifting strength. Human toes one-third foot length anterior to the handle bar were associated with the highest lifting strength. This horizontal distance of objects to be lifted benefits lifting strength from the shorter horizontal distance from the body to the handle (the body's center of gravity closer to the handle) and thus a lesser shoulder angle (more extended) in the upper extremities. Additionally, the effects of the horizontal distance of objects to be lifted on the behaviors of lifting strength were similar for both male and female participants. The results of this study suggest that practitioners should not overlook workers' horizontal distance of objects to be lifted when evaluating their lifting strengths in worker selection.

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