Interaction effects of stoop, full-squat, and semi-squat lifting techniques and hand-load position, magnitude, and asymmetry on knee and spine loads; a subject-specific musculoskeletal modeling investigation

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Abstract

Main effects of three lifting techniques (LT: stoop, semi-squat, and full-squat) and their interaction effects with task-related parameters (hand-load positions/magnitudes) on spine/knee loads and directions were investigated. Previous studies have investigated the effects of stoop and full-squat LTs on spine/knee loads, ignoring their interaction effects with hand-load positions/magnitudes. Twenty-two individuals performed 36 load-handlings at twelve load positions adopting three LTs. Full-body posture was measured using a Vicon system. Musculoskeletal models in AnyBody software were derived to estimate L5-S1 and knee loads considering four hand-loads. Hand-load magnitudes were simulated in the musculoskeletal model under identical kinematics; trials were recorded without hand-held loads to avoid fatigue. The adopted LT had a significant effect on the L5-S1 load magnitudes and knee load directions ($p<0.05$). All task-related parameters had significant interaction effects with the LT on both the spine and knee loads ($p<0.05$). Adopting a semi-squat technique generated the largest L5-S1 loads (5-20% higher than other LTs) and consequently the highest spine injury risk. The semi-squat LT generally generated similar/smaller knee loads magnitudes as compared to other LTs. Accurate knee injuries risk assessment between stoop and squat LTs, however, required finite element simulations due to the changes in knee load-bearing contact areas at different knee flexions. Semi-squat liftings should be avoided in real workplaces, especially for workers with spinal disorders. Semi-squat lifting was, however, a safer technique than full-squat for individuals with knee injuries. Depending on the hand-load position and magnitude, this study identified the safer lifting technique to prevent spine and/or knee injuries.

1. Introduction

Manual material handling (MMH) activities play an important role in the biomechanical etiology of low back [1] and knee [2] injuries as the most prevalent musculoskeletal disorders [1]. To assess the musculoskeletal risk of injuries knee and spine loads are usually estimated by biomechanical models [3–7]. These loads are affected by several parameters including task-related (e.g., horizontal, vertical, and lateral positions of the hand-load, worker's body posture, and hand-load mass) [8–10] as well as personal-related variables (e.g., worker's body weight/height/mass distribution) [11–13].

Our previous findings [14,15] further indicate that the adopted lifting technique (LT), i.e., stoop (back bent/knee straight), full-squat (back straight/knee bent), and semi-squat affects spine loads. Here, semi-squat is used to denote a free-style, intermediate posture between stoop and full-squat in which both the knees and trunk may flex. Several investigations with contradictory findings have compared spinal loads between squat and stoop liftings. While some have reported that stoop technique generates larger spine loads [16], others have reported either larger loads in squat lifting [17] or no significant difference between the two techniques [18]. Although none of these studies have investigated the semi-squat LT, as the most common technique adopted in the workstations [19], our recent findings indicate that the semi-squat technique generally results in larger L5-S1 spine loads [14].

The effect of lifting variables on knee loads is even less clear. An investigation using a full-body model has concluded that the horizontal, vertical, and asymmetry position of the hand-load significantly affect knee loads [20]. Moreover, few studies have indicated that an increase in knee flexion angle during stand-to-squat activities increases knee loads [21]. A combined musculoskeletal model and muscle electromyography measurement study has found that squat, as compared to stoop technique, creates larger knee moments and muscle activities [22]. Finally, a recent study has used in vivo load measurements from patients with instrumented implants to compare loads between squat and stoop lifting activities [23] They reported no significant differences between the two lifting techniques in knee-load magnitude, spine-load magnitude, or spine resultant orientation, but a significant difference in knee resultant orientation was reported [23].

Previous studies have not investigated the semi-squat technique—one of the most prevalent LTs among workers in real workstations—nor have they evaluated the interaction effects of LTs and hand-load position, magnitude, and asymmetry on knee and spine loads. Moreover, our previous work [14] focused on a smaller cohort (ten subjects) and only a single load condition (i.e., the NIOSH-recommended weight). The current study, therefore, addresses several critical gaps: (1) we included a larger sample of twenty-two participants, thereby enhancing statistical power and the generalizability of our findings; (2) we investigated a broader range of lifting scenarios by incorporating additional levels of horizontal distances, and hand-load magnitudes; (3) we placed special emphasis on the interaction of LTs with the task-related parameters, an aspect not examined before; and (4) we expanded the scope of biomechanical outcomes beyond spinal loads by also examining knee loads as well as the direction of these loads. Consequently, the present study aims to investigate the main effects of three LTs (stoop, full-squat, and semi-squat) and their interaction effects with hand-load position, magnitude, and asymmetry on both knee and spine (L5–S1) load magnitudes and directions using detailed subject-specific musculoskeletal models driven by collected kinematics data. This dual focus on spine and knee loading provides a more holistic understanding of the potential risks associated with different LTs, with important implications for occupational interventions.

2. Materials and Methods

2.1. Experiment

Two levels for each of the hand-load vertical distance (VD) and load asymmetry (LA) angle, three levels for each of the hand-load horizontal distance (HD) and LTs (stoop, full-squat, and semi-squat), and four levels for hand-load weight (LWs) were considered (Table 1). Full-body motion data were collected from twenty-two healthy male individuals (73.1±9.8 kg, 177.7±4.1 cm, and 24±2 years) performing unloaded tasks (i.e., lifting and lowering tasks without any hand-load) [24,25] which was used to derive the musculoskeletal models. Based on previous posture assessments [24], to simulate the effects of hand-load weights (5, 10, and 15 kg), identical body postures were assumed for each subject and LT in the musculoskeletal modeling environment. Accordingly, hand-load weight (LW) in this study denotes a simulated model condition applied to the same measured posture to isolate mechanical effects of external load. This approach allowed us to analyze the impact of external loads on the biomechanical outcomes while maintaining consistency with the unloaded motion data. Therefore, while subjects physically performed the lifting tasks without hand-loads, the musculoskeletal models incorporated the specified load conditions in the simulations.

Forty-one plug-in gait skin marker coordinates were recorded using 10 Vicon cameras (Vicon Motion Systems Inc., Oxford, UK) [26,27]. Full-body posture data of 792 activities were therefore recorded; 22 subjects × 36 unloaded tasks (Figure 1a and b). All experiments were carried out after institutional ethics committee approval (approval ID: IR.IUMS.REC.1401.740) and informed consents from the subjects.

2.2. Musculoskeletal modeling

A full-body musculoskeletal model was developed in AnyBody Modeling System (AMS) v. 7.3 (AnyBody Technology A/S, Aalborg, Denmark) using the Plug-in-gait Simple as the blueprint of the model. The model was scaled for each subject to match his body segment lengths [28]. Muscle forces were estimated for each task through an optimization procedure that minimized a third-order polynomial cost function [29]. As ground reaction forces were not collected during the tasks with a hand-load, they were estimated by AMS using a validated prediction approach described elsewhere [7,29,30] (Figure 1c, d, and e). The modeling procedure of each task was carried out four times; without any hand-load and with a 5, 10 and 15 kg load in both hands (2.5, 5 and 7.5 kg in each hand) resulting in a total of 3168 models (792 tasks × 4 LWs). Finally, the L5-S1 load magnitudes (resultant of proximodistal, anteroposterior, and mediolateral loads) and the knee load magnitudes (resultant of proximodistal, anteroposterior and mediolateral loads) were calculated using the inverse dynamic approach. In addition, the angle between the resultant load vectors and the normal vector of knee and spine horizontal planes were obtained as the direction of spine and knee loads (Figure 1f and g). This angle was calculated using the following equation:

$$\text{Angle} = \tan^{-1}\frac{Total\ Shear}{Total\ Compression} \quad (1)$$

where, the total compression was assumed to be the proximodistal load and the total shear was calculated as the resultant of the anteroposterior and mediolateral loads. This angle effectively represents the direction of load. Since the mediolateral load for both the spine and knee was significantly smaller than the anteroposterior load (less than 1%), the load vector was mostly oriented in the sagittal plane of the knee and spine.

2.3. Statistical analyses

The normality of the data was evaluated by the Shapiro–Wilk test. Also, the sufficiency of the sample size was investigated by G*Power analysis method. Repeated measures analysis of variance (ANOVA), with Fisher least significant difference post-hoc, was implemented to evaluate the main effect of LT as well as the interaction effects of LT and task-related parameters on spine/knee loads and directions [14]. A $p<0.05$ was considered to show a significant difference. When an interaction was significant, we did not perform additional level-wise hypothesis tests to limit multiplicity. In such cases, we do not interpret the qualified main effects and restrict interpretation to the interaction pattern shown in the figures.

3. Results and Discussion

The normality of the load data was confirmed ($p>0.05$). A G*Power analysis revealed that our sample size of 3168 data was sufficient for the ANOVA analysis (statistical power>0.9).

3.1. Main effects

The effect of LT on the spine load magnitude and knee load direction was significant (Table 2), i.e., LT had no significant effect on the knee load magnitude and spine load direction. Post-hoc analyses indicated that the L5-S1 load magnitude for semi-squat LT was significantly larger (by ~10% in average for all tasks) than those of full-squat and stoop LTs (Figure 2a) with no significant difference between the two latter LTs. Moreover, the angle of knee load direction for stoop was significantly smaller than those of the full-squat and semi-squat LTs (by ~75%) with no significant difference between the two latter LTs (Figure 2b).

3.2. Interaction effects (spine):

LT had significant interaction effects with all VD, LA, HD and LW parameters for spine load magnitudes (Table 2 and Figure 3a and b). Since the LT× [VD, LA, HD and LW] interaction was significant ($p < 0.05$), the LT main effect was not interpreted here, and interpretation was restricted to the interaction pattern shown in Figure 3a and b. Post-hoc analyses revealed that semi-squat LT produced larger spinal loads (by 5-20%) as compared to other LTs for all hand-load position/asymmetry conditions and different hand load magnitudes (Figure 3a and b). Moreover, full-squat LT resulted in significantly larger (by 5-10%) spine loads than stoop LT for VD = 0 cm, HD = 60 cm, LA = 45° and LW = 15 kg. However, stoop LT created significantly larger (by 8%) spine loads than full-squat LT for VD = 30 cm. For other hand-load position/asymmetry conditions and LWs, the generated spine loads were almost similar for stoop and full-squat LTs (Figure 3a and b). The spine load direction only slightly varied (by less than 2 degrees although in some cases statistically significant) for different hand-load position/asymmetry conditions and LWs (Figure 3c and d).

3.3. Interaction effects (knee):

Although LT had no significant effect on knee load magnitudes, it had interaction effects with all VD, LA, HD and LW parameters for the knee load magnitude (Table 2). With significant LT×[VD, LA, HD, LW] interactions ($p < 0.05$), interpretation was restricted to the interaction-qualified patterns (Figure 4a and b) rather than a global LT main effect. For VD = 30 cm, HD = 60 cm, LA = 45°, LW = 15 kg and LW = 10 kg, stoop LT caused considerably larger knee load magnitudes (by 10-20%) as compared to other LTs (Figure 4a and b). On the other hand, full-squat LT resulted in higher knee load magnitudes for HD = 30 cm, and LW = 0 kg. The semi-squat LT generated similar or smaller knee loads magnitudes as compared to other LTs (Figure 4a and b) for most hand-load position/asymmetry conditions and LWs. For different hand-load position/asymmetry conditions and LWs, the knee load direction varied between 12 to 18 degrees for stoop LT and 62 to 70 degrees for semi- and full-squat LTs (Figure 4c and d).

3.4. Discussion

This study investigated the effects of three LTs on spine and knee load magnitudes and directions during 144 lifting activities using detailed subject-specific musculoskeletal models driven by motion data from twenty-two subjects. In agreement with our previous findings [14], results indicated that the L5-S1 spine load magnitudes were significantly larger (by ~10% in average for all tasks) in semi-squat LT as compared to stoop and full-squat techniques (Figure 2a). Moreover, the adopted LT significantly affected the knee load direction, i.e., stoop LT created significantly smaller (by ~75% in average) knee load angles (the angle between load and normal of knee horizontal plane) than other LTs. The adopted LT had no significant effects on the knee load magnitude and spine load direction. However, due to significant interactions between LT and task-related parameters (i.e., vertical distance (VD), horizontal distance (HD), load asymmetry (LA), and load weight (LW)), these main-effect findings should be interpreted in the context of the interactions [31].

3.4.1. Analysis of results

A number of parameters such as trunk flexion angle (being larger in stoop than squat LTs), hand-load moment arm with respect to the L5-S1 joint (being larger in squat than stoop LT), upper body weight moment arm with respect to the L5-S1 joint (being larger in stoop than squat LTs), passive joint moments (being larger in stoop than squat LTs), and intervertebral disc inclination (being larger in stoop than squat LTs) affect spinal loads [14]. In general, semi-squat LT produced the largest spine loads for different load positions (Figure 3a and b) and as this LT is the most adopted LT by workers [19], precautionary measures should be taken when adopting this LT during occupational activities. Our interpretation of semi-squat being the most hazardous LT is purely mechanical, i.e., larger predicted L5–S1 loads under the same measured posture. Semi-squat LT typically combines moderate trunk flexion (increasing the moment arm of torso center of mass) with appreciable knee/hip flexion that keeps the hands farther forward (increasing the hand-load moment arm). Under the same kinematics, these concurrent moment arms raise the external lumbar flexion demand thereby generating greater L5–S1 compression loads as compared to stoop or full-squat LTs. The interaction effects of LT with hand-load HDs, VDs, LA and LWs parameters for L5-S1 loads were significant; a finding that may explain the contradictory results of previous studies when comparing spinal loads between squat and stoop liftings with some reporting larger spine loads in stoop technique [16], some reporting larger loads in squat lifting [17] and others reporting no significant difference between the two techniques [18]. For instance, while for VDs = 30 cm, stoop produced larger spinal loads than full-squat, for VDs = 0 cm, full-squat created larger spinal loads than stoop (Figure 3a). Our findings are also in agreement with those of a recent in vivo study concluding that during stoop and squat LTs the direction of spine loads varies insignificantly [23]. The present study, however, included more lifting activities and investigated interaction of LTs with other lifting parameters.

While the focus of risk assessment programs is on the spinal loads [1], pain in the lower extremity joints is also a common problem among workers [32]. Our findings indicated that although LT did not significantly affect the generated knee load magnitude (Table 2), the hand-load position/asymmetry conditions and LWs had significant interactions with LTs (Table 2). For instance, while stoop created larger knee loads for VD = 30 cm, HD = 60 cm, LA = 45°, LW = 15 kg and LW = 10 kg, full-squat produced larger knee loads for HD = 30 cm, and LW = 0 kg. Moreover, the semi-squat technique generally produced almost equal or lower knee loads as compared to other LTs (Figure 4a and b). Our findings for magnitude and direction of knee loads were in agreement with those of a recent in vivo study concluding that during stoop and squat LTs the magnitude of knee loads varies insignificantly but the direction of knee loads varies significantly [23]. Some studies have, however, revealed that squatting from an upright standing posture increases knee loads [21]. Finally, significant changes in the direction of knee loads between stoop and squat LTs (Figure 4c and d) indicated that shear forces were significantly larger for squat LTs as compared to stoop LT, i.e., risk of shear injuries are greater in squat LTs.

It is important to note that for every 30° increase in knee flexion the load-bearing contact area at this joint diminishes by ~4 percent [33]. We may, therefore, conclude that full-squat LT had a greater risk of knee injury than semi-squat LT for most hand-load position/asymmetry conditions and LWs (except HD=60 cm), since it generally produced, compared to semi-squat, similar or larger knee loads (Figure 4) with smaller knee joint load-bearing contact areas [33] thus resulting in greater knee joint stresses. Stoop and squat techniques could not be compared in the regard, as although stoop technique generally generated larger knee loads (Figure 4) but knee joint load-bearing contact areas are also larger for stoop LT. For a more comprehensive understanding of knee risk of injury during various LTs, however, accurate estimations of the knee stresses and load-bearing contact areas are required via finite element modeling investigations.

3.4.2. Limitations

Considering task-related parameters out of the range of included levels (e.g., LA>45°) may change the discussed interaction effects. Due to high number of tasks performed by each subject and to avoid fatigue, in our experimental setup lifting tasks were performed without a weight in hands. The hand-load was, however, properly considered in the musculoskeletal model by assuming similar postures between the loaded and unloaded tasks [24]. Similar body postures between loaded and unloaded tasks are also expected since knee posture is fixed by subjects for each LT; however, at higher loads some body posture change may occur. Accordingly, any effects involving LW should be interpreted as mechanical consequences conditional on the measured posture, not as behavioral adaptations to weight. In addition, while we report the main effect of LT, the presence of significant interactions between LT and other task parameters suggests that the main effect should be interpreted with caution, as the standard ANOVA recommends evaluating each significant interaction in context [31]. Moreover, in the AMS musculoskeletal model, knees were simplified as hinge joints thus calling for more detailed musculoskeletal or finite element knee models when investigating accurate knee stresses and load directions.

4. Conclusions

Within our fixed-kinematics modeling framework, semi-squat produced the largest predicted L5–S1 load across most tested hand-load positions and asymmetry conditions, while stoop and full-squat were generally similar and differed by task geometry. Because hand-load weight (LW) was applied in the model under posture invariance, these findings should be interpreted as mechanical, conditional on the same LT and kinematics, not as evidence about strategy changes under actual loading. Accordingly, we do not prescribe universal technique rules; rather, risk trade-offs are task-specific. For example, in our tests, at VD = 0 cm, HD = 60 cm, LA = 45°, and LW = 15 kg, the stoop LT yielded lower predicted spine load than full-squat, whereas at VD = 30 cm the reverse held. For other hand-load positions and asymmetry conditions the two were similar. Knee-joint risk was less clear: full-squat tended to show greater modeled knee risk than semi-squat in many conditions, reflecting similar or larger knee loads combined with smaller load-bearing contact areas [33], but this inference remains more tentative and warrants direct validation. Overall, our results suggest that semi-squat is generally disadvantageous for spine loading under matched kinematics, while the stoop vs full-squat choice should be guided by the specific hand-load geometry and validated against knee demands and real-world posture adaptation.

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Authors' Credit

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Seyede Niloofar Hosseini: Formal analysis, Investigation, Methodology, Software

Mahdi Mohseni: Conceptualization, Formal analysis, Investigation, Project administration, Supervision, Writing – review and editing

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Conflicts of interest

■The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Figure captions

Figure 1: Skin-marker setup from (a) front and (b) back views, including 39 full-body plug-in gait markers plus T12 and S1 markers for improved spine kinematics. Musculoskeletal models for symmetric load handling using (c) stoop, (d) semi-squat, and (e) full-squat techniques. Resultant load directions on the (f) knee and (g) spine are shown, where α is the angle between the resultant load and the normal vector of the horizontal plane.

Figure 2: The main effects of lifting technique (LT) on: (a) L5-S1 load magnitude, and knee load magnitude and (b) the L5-S1 load direction and knee load direction. * indicates a significant difference ($p<0.05$).

Figure 3: The interaction effects of (a and c) hand-load HD and VD and (b and d) LA angle and LWs with LT on L5-S1 load magnitude and direction, respectively. * indicates a significant difference ($p<0.05$).

Figure 4: The interaction effects of (a and c) hand-load HD and VD and (b and d) LA angle and LWs with LT on knee load magnitude and direction, respectively. * indicates a significant difference ($p<0.05$).

Table captions

Table 1: Task-related parameters and factor levels used in the lifting trials.

Table 2: The P-values and F-values for the main effects of lifting technique (LT) and its interaction effects with task-related parameters on the L5-S1 spine and knee load magnitudes and directions (significant effects, $p<0.05$ are presented in bold).

Figures

Figure 1:

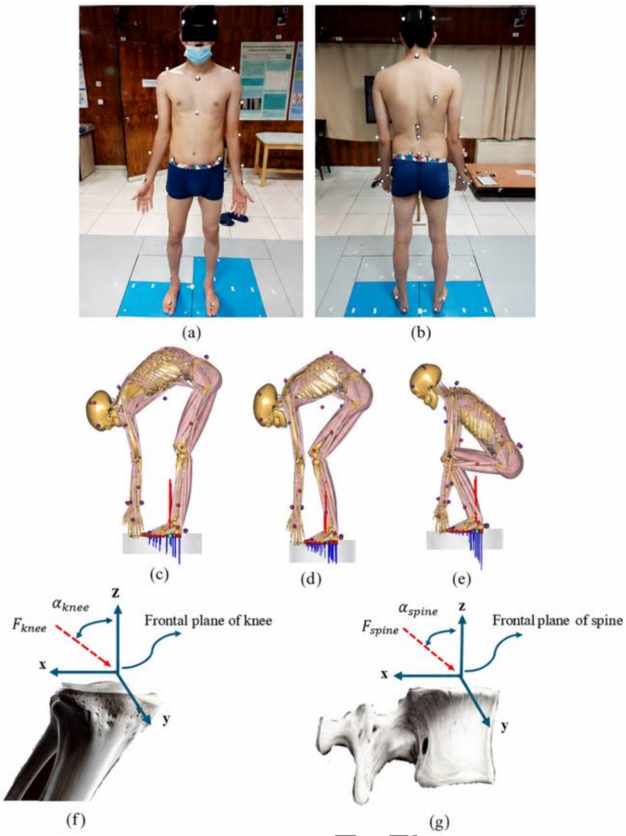


Figure 2:

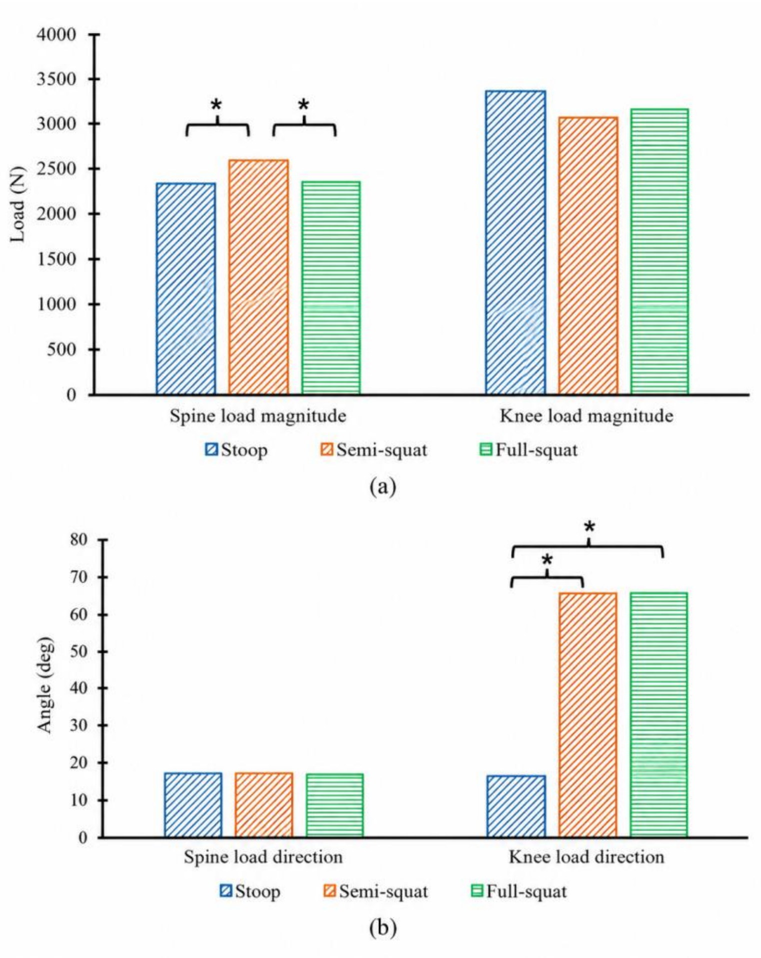

4000
3500
3000
2500
2000
1500
1000
500
0
Load (N)
*
*
Spine load magnitude
Knee load magnitude
Stoop
Semi-squat
Full-squat
(a)
80
70
60
50
40
30
20
10
0
Angle (deg)
*
*
Spine load direction
Knee load direction
Stoop
Semi-squat
Full-squat
(b)

Figure 3

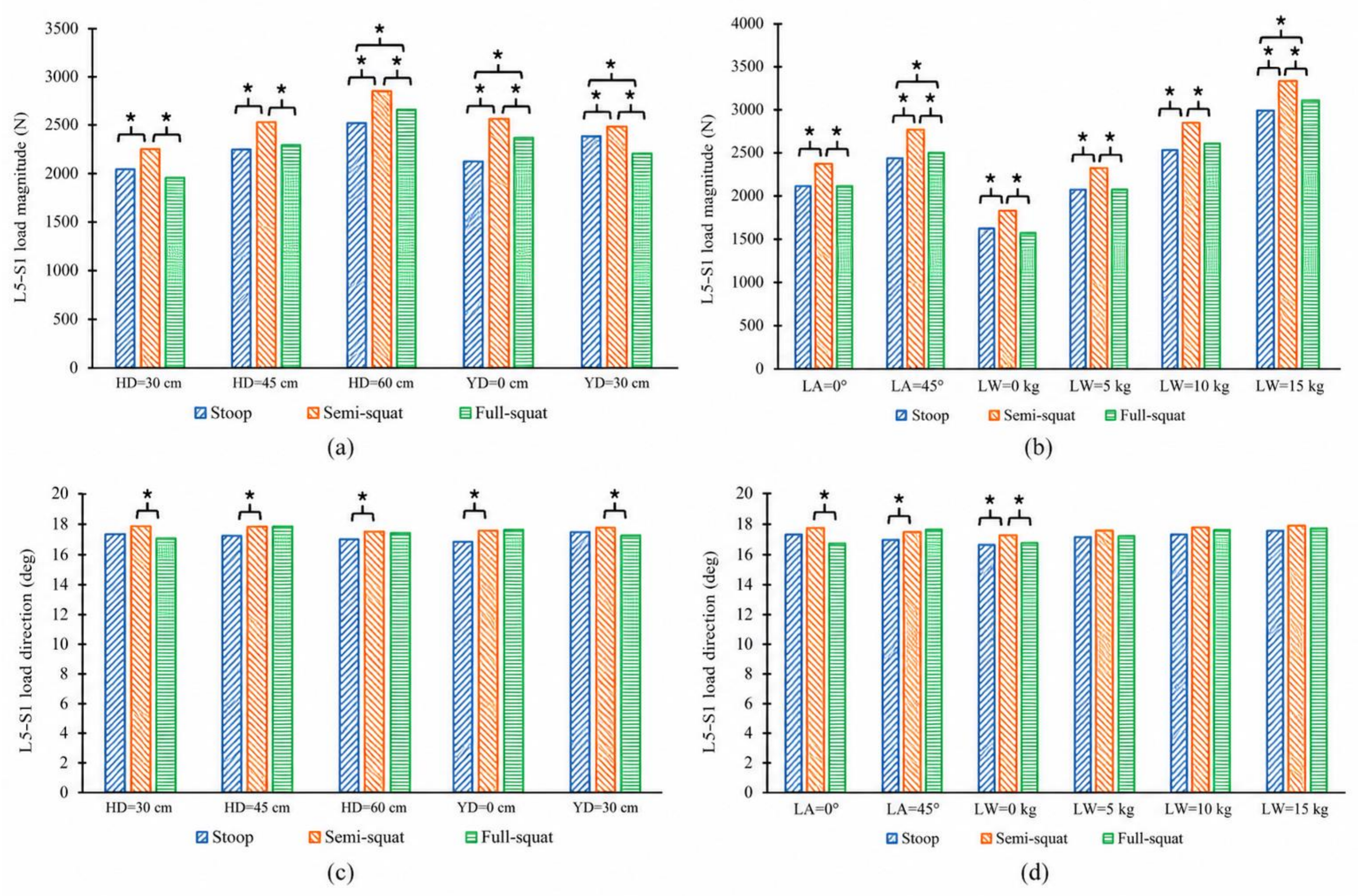
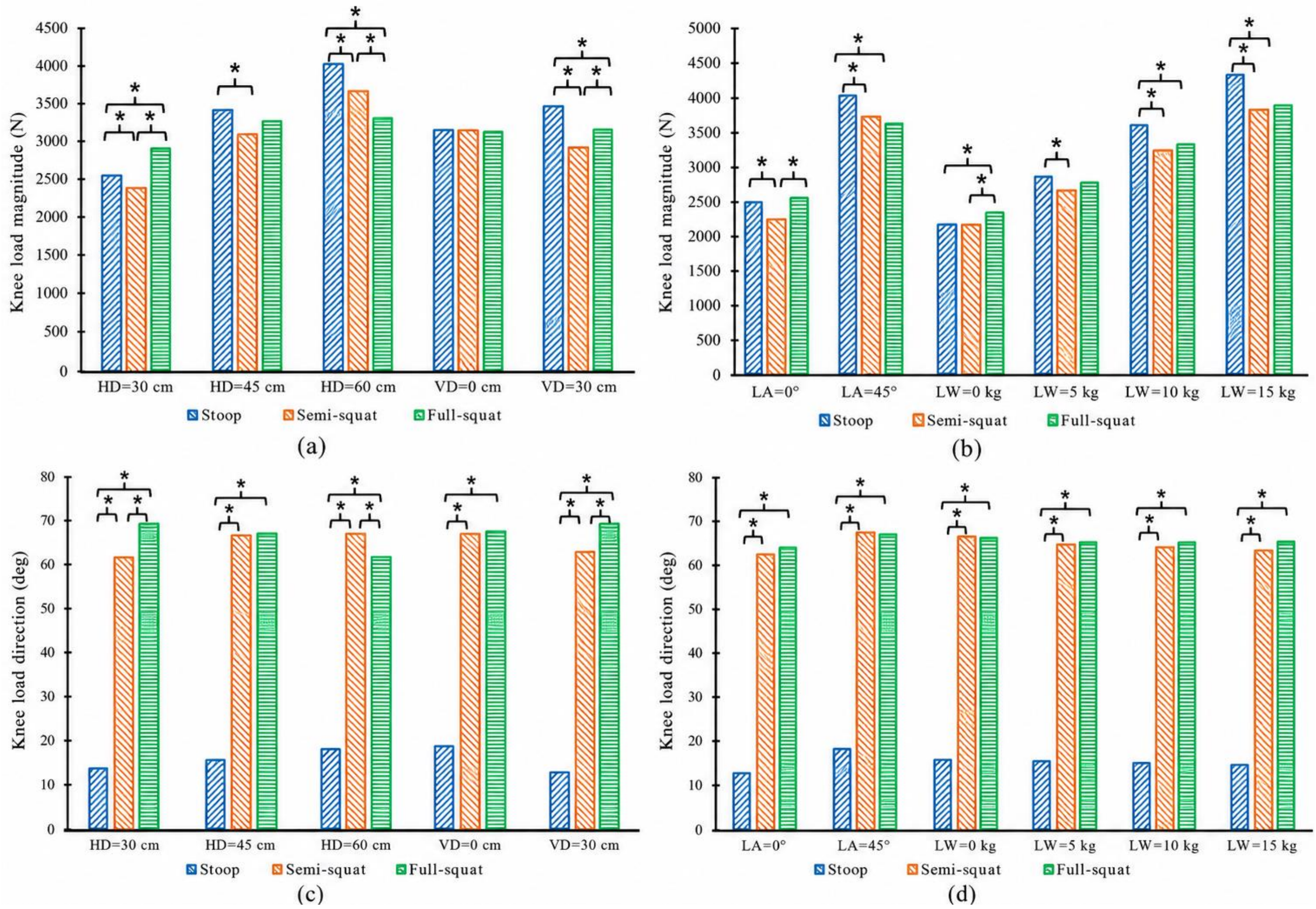


Figure 4:



Tables

Table 1:

	Design of the tasks	
Task parameter	**Number of levels**	**Levels**
Lifting technique (LT+)	3	Stoop, semi-squat, full-squat
Hand-load horizontal distance (HD)	3	~30, 45 and 60 cm from the heels
Hand-load vertical distance (VD)	2	0 and 30 cm from the floor
Load asymmetry (LA) angle	2	0 and 45° from the sagittal plane
Hand-load weight (LW)	4	0, 5, 10 and 15 kg

Table 2:

Statistical analysis results										
Joint loads	**LT**		**LT * HD**		**LT * VD**		**LT * LA**		**LT * LW**	
	P-value	**F-value**	**P-value**	**F-value**	**P-value**	**F-value**	**P-value**	**F-value**	**P-value**	**F-value**
L5-S1 load magnitude	**<0.001**	712.01	**<0.001**	8.75	**<0.001**	122.92	**0.001**	7.05	**<0.001**	4.18
Knee load magnitude	0.249	1.44	**<0.001**	35.85	**<0.001**	28.94	**<0.001**	20.54	**<0.001**	9.17
L5-S1 load direction	0.07	2.85	**<0.001**	6.64	**<0.001**	27.45	**<0.001**	37.45	0.541	0.84
Knee load direction	**<0.001**	206.64	**<0.001**	34.61	**<0.001**	117.53	**0.002**	6.37	0.672	0.67

Biographies

Sajjad Daroudi earned his MSc degree in mechanical engineering from Sharif University of Technology, Tehran, Iran. His research interests include occupational biomechanics, movement biomechanics, and musculoskeletal modeling, with a focus on understanding human motion and biomechanical loading during physical tasks. His work involves the application of experimental motion analysis and computational modeling approaches to evaluate musculoskeletal function and loading conditions. He has contributed to research related to load-handling activities and biomechanical assessment of human movement, particularly in contexts relevant to ergonomics, injury prevention, and occupational health.

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