The Effects of Lifting Techniques on the L5-S1 Joint: Lifting Different Loads from Ground Level

Melih Canlıdinç[1*], Mustafa Güleşen[2]

[1*] Kütahya Dumlupınar University, Faculty of Engineering, Department of Mechanical Engineering, Kütahya, Turkey, (ORCID: 0000-0002-4011-9490), melih.canlidinc@dpu.edu.tr, Phone: +905076405550
[2] Kütahya Dumlupınar University, Faculty of Engineering, Department of Mechanical Engineering, Kütahya, Turkey, (ORCID: 0000-0001-8781-2746), mustafa.gulesen@dpu.edu.tr, Phone: +905052590592

Abstract - Manual material lifting is a common activity in daily life and industrial work environments, placing significant stress on the L5/S1 joint in the lower back. This study aims to compare the biomechanical impacts of squat and stoop lifting techniques on the L5/S1 joint to assess load distribution and potential injury risks in manual handling tasks. In contrast to previous studies using boxes with handles, our experiments involve lifting cargo boxes from the bottom without handles, providing a more realistic simulation for cargo handling workers. Five healthy male participants performed squat and stoop lifts with weights of 4, 8, 12, and 16 kg. Markerless motion capture was conducted using the Kinect v2 sensor, and kinematic and kinetic data were analyzed with the OpenSim biomechanical modeling software. Results indicated that squat lifting reduced compression forces by approximately 9% and shear forces by 25% at the L5/S1 joint compared to stoop lifting for heavier loads. These findings align with previous literature, demonstrating that squat lifting may better distribute loads across the lumbar spine, suggesting it as a potentially safer method for handling heavier loads.

Keywords - kinect v2, lifting techniques, musculoskeletal system, opensim

1. Introduction

Despite industrial developments, workers in many sectors perform lifting tasks with handling. Improper body postures during frequently repeated lifting while working can cause musculoskeletal disorders (MSD). These disorders cause low back pain (LBP) and subsequently lead to loss of work capacity. According to a study, back pain has affected approximately 619 million people worldwide [1]. In the United States in 2020, manual lifting-related injuries constituted 31.4% of non-fatal occupational injuries that caused loss of work capacity [2]. Ergonomic risk assessment methods such as NIOSH, RULA, REBA, QEC are used to assess the risk of musculoskeletal diseases that cause loss of work capacity of workers [3-6]. In addition, these methods were examined comparatively in a study [7].

Artificial neural networks (ANN), machine learning, and biomechanical modeling approaches are also used in the estimation of spinal loads during manual lifting. In this context, there are studies in literature using ANN-based models to estimate the loads in the L4/L5 and L5/S1 spine regions [8], whole body posture and spine forces [9] and joint coordinates [10]. Low back pain risk [11] and biomechanical risk [12] have been studied during manuel lifting with machine learning. The biomechanical modeling method includes static models calculating L4/L5 and L5/S1 compression forces [13,14], electromyography (EMG)-supported dynamic spine models [15-17], models based on three-dimensional finite element analysis (FEA) [18], dynamic models that consider body segments separately and three-dimensional geometric body models [19,20]. Three-dimensional musculoskeletal models facilitate dynamic motion analyses and enable comprehensive simulation of body kinematics, kinetics and musculoskeletal forces [21-24]. Recent advances in musculoskeletal modeling approaches in ergonomic analyses have demonstrated the effectiveness of these methods in optimizing lifting techniques to reduce spinal loads [25]. Indeed, some studies in the literature emphasize the biomechanical differences between squat and stoop lifting techniques, supporting the need for detailed biomechanical evaluation of loading in the lumbar region [26-28].

To design these models, position data of the L5/S1 joint and other body parts are required. For this purpose, motion capture systems with skin-mounted markers are commonly used. Position data from markers and sensors help estimate body joint locations. However, implementing these systems is costly and requires specialized laboratory environments, making field studies challenging [29-31].

In recent years, alternative markerless imaging methods have been developed due to the high cost and complexity of marker-based imaging systems. Markerless imaging systems like Kinect v2 are preferred for their cost-effectiveness and ease of use. This sensor has been applied in gait analysis, real-time human movement simulations, and joint angle measurements [32]. Kinect v2, in particular, offers advantages such as human skeleton recognition, portability, and suitability for field use [33–38]. Several studies have shown that a single sensor, when properly positioned, is sufficient to capture joint position data of the human body during dynamic lifting movements [39,40].

In manual lifting tasks, two lifting techniques—squat and stoop—are commonly used. In the squat technique, the lift is performed by keeping the back upright and bending the knees, whereas in the stoop technique, the movement is executed by bending at the waist without flexing the knees [41]. Although the semi-squat technique aims to combine the advantages of both methods, it does not provide a biomechanical benefit due to the simultaneous loading of both the lumbar and knee joints [42]. Moreover, it has been suggested that mechanical loading patterns vary depending on individual lifting strategies, which makes it difficult to define a standard representation for modeling purposes [43].

In this study, the effect of manual lifting movements performed with squat and stoop lifting techniques in an occupational environment on the L5/S1 joint was investigated using the markerless motion capture method Kinect v2 sensor and OpenSim software as an innovative approach. As a result of experiments conducted with lifting techniques of different masses, shear and compression forces acting on the L5/S1 joint were analyzed.

2. Methods

This study was conducted with five healthy male participants (age: 27 years (± 5), height: 184.2 cm (± 2.5), weight: 79.2 kg (± 4.2), BMI: 23.34 kg/m² (± 1.04)) without low back injuries, all employees of the local branch of the cargo industry. This number of participants is consistent with previous biomechanical studies in the literature that used similar samples and obtained valid results using musculoskeletal modeling and motion capture techniques [44-46]. The study protocols were approved by the Kütahya Health Sciences University Ethics Committee (Approval No: 2021/13-16), and informed consent forms were obtained from all participants. Before the study, the necessary movement techniques were explained to the participants verbally and visually, and supervision was provided during the experimental process.

2.1. Equipment

2.1.1. Microsoft Kinect v2

In this study, a single Kinect v2 was used to collect motion data without using markers. This device, developed by Microsoft for the Xbox game console, has the ability to measure distance with a depth sensor and time-of-flight (ToF) principle. Kinect v2 provides color images with a resolution of 1920x1080 pixels and depth data with a resolution of 512x426 pixels, obtaining 30 frames per second. The depth perception angle was determined as 60 degrees vertically and 70 degrees horizontally. In Figure 1, Kinect can detect 25 joints on the user's body. In this study, Kinect v2 was positioned 2.5 meters in front of the participant and 1.5 meters above the ground. This positioning was achieved by optimizing the accuracy in preliminary tests [47].

2.1.2. Ground Reaction Force Measurement

The Zebris™ FDM-2 platform was used to measure the ground reaction forces during each lifting movement. This device has a length of 2120 mm, a width of 605 mm and a height of 21 mm, and records data at a sampling frequency of 100-200 Hz with 15360 sensors on its surface. In Figure 2, The Zebris device reports static posture analyses such as changes in the participant's center of gravity, total load on the right and left feet, and front-back foot load distribution. The participant was tasked with lifting boxes while standing on the platform, and the data obtained were recorded via the Zebris software [48].

2.2. Musculoskeletal Model

In this study, the whole-body musculoskeletal model developed by Rajagopal et al. (2016) was used. OpenSim software allows the model we used in the experiments to be scaled according to the anthropometric data of each participant. This is achieved by adjusting the body segment lengths and mass properties of each participant [49].

This model represents a male individual weighing 76 kg and being 172 cm tall. There are 22 body parts connected by joints in the musculoskeletal structure. For the lower body, there are the pelvis, femur, calcaneus, talus, patella, tibia/fibula, toes, and for the upper body, there are the head-trunk junction, humerus, ulna, radius, and hand joints. There are a total of 37 degrees of freedom (DoF) in the model: 20 DoF in the lower body (6 for the pelvis, 7 for the right and left legs) and 17 DoF in the upper body (3 for the lumbar joint, 7 for the right and left arms). The coordinate system for each body part in the model is aligned as follows: the x-direction corresponds to the anterior direction, the y-direction corresponds to the proximal/superior direction, and the z-direction is to the right [49].Considering the differences in BMI among the participants, it was assumed that small deviations in the model had negligible effects on the results.

2.3. Experiment Procedure

The participants performed two standard lifting techniques: squat and stoop. Before the experiment, participants were given verbal and visual information about both lifting techniques; Supervision is provided to ensure that they can apply it in the correct form and safely. During the squat lifting movement, the information was given that the knees should be fully flexed, the heels should be lifted in such a way that the contact with the ground was cut off, and the body should be close to the vertical position (Figure 3a). During the stoop lift, the participant was instructed to extend the knees without bending and bend the torso to lift the box from the ground in an upright position (Figure 3b) [50].

Each participant lifted boxes weighing 4, 8, 12 and 16 kg. The dimensions of the box were 40 cm x 40 cm x 35 cm (width x depth x height). The box was placed in the middle of the sagittal plane. The participants lifted the box on the ground (0 cm above the ground) by grasping it symmetrically from below the bottom with both hands and held it upright at L5/S1 joint (waist) level. Participants were asked to perform squat and stoop lifting techniques with the knees and torso slightly bent; Since it was thought that the lateral movement of the pelvis could affect the flexion and torsional torques, they were made to keep their feet stable during the lifting [51]. Participants repeated each lifting process 5 times, and a total of 200 lifting movements were performed in 8 different conditions.

The distance between the participant's body and the box was standardized at approximately 25 cm, measured from the toes to the nearest edge of the box. This distance was chosen to replicate common manual material handling scenarios where loads are lifted from the ground directly in front of the worker. The decision to consider only one load distance and a ground-level position was motivated by the study's primary objective: to investigate lumbar spine loading during lifting from a typical low-back risk scenario.

The positioning of the devices used in the experiment and the data collection process are shown in Figure 4. Kinematic data was collected with the Kinect v2 sensor operating at a 30 Hz sampling rate. While the participants performed the movement, the Kinect v2 sensor recorded the position data of each joint throughout the movement. In the kinetic analysis, ground reaction forces (GRF) and moments were recorded using the Zebris FDM-2 platform with a 100 Hz sampling rate. The Zebris platform was used to determine the participant's foot position and load distribution. All data obtained were analyzed in OpenSim 4.0 software [52,53].

2.4. Biomechanical Analysis

The model was scaled according to the anthropometric data of each participant. The process of transferring the position data of human body joints from Kinect v2 and ground reaction force (GRF) data from the Zebris FDM 2 platform to the human model in OpenSim was started. Using the joint position information obtained from the Kinect v2 sensor, the joint angles of the participant in each lifting movement were obtained by the inverse kinematic calculation method. Using the collected data, L5/S1 joint moments were calculated with the help of OpenSim's Inverse Dynamics Tool, and the obtained moments were decomposed into muscle forces with the static optimization method [48,49]. This analysis process was carried out with the OpenSim workflow shown in Figure 5.

3. Results

Participants performed the lifting tasks at their self-selected comfortable speed to simulate realistic working conditions. Figure 6 illustrates the time-dependent variation in lumbar (L5/S1) joint angles throughout the lifting process (0–100%) for both squat and stoop lifting techniques. The differences in joint angles between the two techniques reflect the inherent biomechanical distinctions of each movement strategy.

In the initial phase of lifting (0–40%), the stoop technique involved greater lumbar flexion, with joint angles exceeding 65 degrees, whereas squat lifting began with a more upright spinal posture, showing joint angles below 60 degrees. This indicates that stoop lifting relies more heavily on trunk flexion, while squat lifting distributes movement more evenly across the lower extremities.

As the lifting progressed (40–100%), the spine gradually moved toward a more upright position in both techniques, and lumbar flexion decreased accordingly. Particularly during the final 30% of the movement, joint angle values converged between the two techniques, resulting in similar spinal postures at the end of the lift. The error bars (standard deviations) demonstrate overall consistency in participant performance, although inter-individual variability was slightly higher in the initial phase of stoop lifting. Despite variations in load magnitude, no significant differences were observed in L5/S1 joint angles within each lifting technique.

In general, the stoop and squat lifting motion of the spine are associated with the 3-D lumbar spine at the L5/S1 joints. Figure 7 presents the extension moments in the lumbar region (L5/S1) during the lifting of various weights (4, 8, 12, and 16 kg) using both techniques. The highest moment values appear at the beginning of the lifting process for both techniques. While maximum L5/S1 extension moments between squat and stoop lifting were similar at 4 and 8 kg, they were higher during squat lifting at 12 and 16 kg, likely due to increased muscle activation needed to stabilize knee flexion.

L5/S1 joint reaction forces were analyzed in the vertical (SI) and horizontal (AP) directions, representing compression and shear forces. In Figure 8, compression forces were relatively consistent across participants, varying by lifting technique and weight. In squat lifting, compression forces ranged from 49.38 N/kg to 60.95 N/kg (3911-4827 N), while in stoop lifting, they ranged from 44.05 N/kg to 55.78 N/kg (3489-4418 N).

In Figure 9, L5/S1 joint shear forces were greater during stoop lifting compared to squat lifting. Shear forces were observed to be 9.23 N/kg – 15.64 N/kg (731-1239 N) in squat, while stoop lifting produced forces of 12.25 N/kg – 19.48 N/kg (970-1543 N), highlighting the increased demand on spinal stability in stoop lifting.

4. Discussion and Conclusion

This study investigates the impact of manual lifting on the L5/S1 joint, which is one of the most vulnerable regions in the lumbar spine. Unlike traditional studies where boxes with handles are used, our model simulates real-world cargo lifting conditions by requiring participants to lift boxes from the bottom, without handles. This approach better represents typical scenarios encountered by cargo workers and may yield insights that more accurately reflect the occupational risks associated with manual lifting.

When comparing compression forces with those reported in the literature, our findings appear to be consistent with the results reported by Arx et al. (2021), who observed a 5% reduction in compression forces during stoop lifting compared to squat lifting [27]. Beaucage-Gauvreau et al., however, observed a 17% decrease, suggesting differences in load handling approaches and study methods [25]. Figure 10 illustrates these comparisons, with our squat lifting forces at 57.01-60.95 N/kg for 12 and 16 kg loads, and a decrease to 51.83-55.78 N/kg for stoop lifting [25-27].

When compared with the literature, it is seen that the shear forces of the L5/S1 joint are higher during the stoop lift than during the squat lift. For example, Beaucage-Gauvreau et al. (2019) reported a 20% decrease in stoop shear forces, closely aligning with our findings, as seen in Figure 11 [25-27].

Our findings reveal that stoop lifting reduces compression forces at the L5/S1 joint by approximately 9% compared to squat lifting for 12 and 16 kg , suggesting that squat lifting may distribute loads more safely across the lumbar region. On the other hand, shear forces were approximately 25% higher during stoop lifting, which may pose a greater risk to lumbar stability, as increased shear loading has been linked to disc injury and spinal instability in the literature [18,54,55]. These findings support the use of squat lifting as a potentially safer method for handling heavier loads, with practical implications for manual labor-intensive occupations. However, a limitation of our study is that the biomechanical model did not account for spinal ligaments or intra-abdominal pressure, which are important factors in lumbar spine stabilization during lifting.

Future research should continue to refine biomechanical models and standardize lifting methods to improve the safety and efficiency of manual material handling tasks, consider incorporating ligamentous structures and intra-abdominal pressure to enhance model accuracy. Additionally, exploring a broader range of lifting conditions—such as varying box dimensions, handle placements, and participant demographics—could provide a more comprehensive understanding of lumbar loading dynamics. In addition, different approaches can be used, such as integrating the obtained data with advanced machine learning techniques [56].

Acknowledgements

This study, derived from the doctoral thesis of Melih Canlıdinç (Supervisor: Asst. Prof. Dr. Mustafa GÜLEŞEN), has been conducted under the approval of the ethics committee, with findings and analyses performed within the framework of ethical guidelines (Ethics Committee Decision No: 2021/13-16).

References

1. "Low back pain fact sheet", WHO, (2023). https://www.who.int/news-room/fact-sheets/detail/low-back-pain.

2. "Percentage of nonfatal occupational injuries and illnesses involving days away from work due to overexertion in the United States", Statista, (2020). https://www.statista.com/topics/1624/material-handling-industrial-trucks.

3. Waters, T. R., Putz-Anderson, V., Garg, A., et al. "Revised NIOSH equation for the design and evaluation of manual lifting tasks", Ergonomics, **36**, pp. 749–776 (1993), https://doi.org/10.1080/00140139308967940.

4. McAtamney, L., and Corlett, E. N., "RULA: a survey method for the investigation of work-related upper limb disorders", Appl Ergon, **24**, pp. 91–99 (1993), https://doi.org/10.1016/0003-6870(93)90080-s.

5. Hignett, S., and McAtamney, L., "Rapid entire body assessment (REBA)", Appl Ergon, **31**, pp. 201–205 (2000), https://doi.org/10.1016/S0003-6870(99)00039-3.

6. David, G., Woods, V., Li, G., et al. "The development of the Quick Exposure Check (QEC) for assessing exposure to risk factors for work-related musculoskeletal disorders", Appl Ergon, **39**(1), pp. 57–69 (2008), https://doi.org/10.1016/j.apergo.2007.03.002.

7. Zargarzadeh, S., Bahramian, M., Mohseni, M., et al. "Comparison of ten widely-use ergonomic risk assessment tools based on evaluations of various manual materials handling activities", Scientia Iranica (2024), https://doi.org/10.24200/sci.2024.63530.8451.

8. Arjmand, N., Ekrami, O., Shirazi-Adl, et al. "Relative performances of artificial neural network and regression mapping tools in evaluation of spinal loads and muscle forces during

static lifting", J Biomech, **46**(8), pp. 1454–1462 (2013), https://doi.org/10.1016/j.jbiomech.2013.02.026.

9. Aghazadeh, F., Arjmand, N., and Nasrabadi, A. M., "Coupled artificial neural networks to estimate 3D whole-body posture, lumbosacral moments, and spinal loads during load-handling activities", J Biomech, **102**, p. 109332 (2020), https://doi.org/10.1016/j.jbiomech.2019.109332.

10. Mohseni, M., Zargarzadeh, S., and Arjmand, N., "Multi-task artificial neural networks and their extrapolation capabilities to predict full-body 3D human posture during one- and two-handed load-handling activities", J Biomech, **162**, p. 111884 (2024), https://doi.org/10.1016/j.jbiomech.2023.111884.

11. Snyder, K., Thomas, B., Lu, M. L., et al. "A deep learning approach for lower back-pain risk prediction during manual lifting", PLoS One, **16**(2), p. e0247162 (2021), https://doi.org/10.1371/journal.pone.0247162.

12. Conforti, I., Mileti, I., Del Prete, Z., et al. "Measuring biomechanical risk in lifting load tasks through wearable system and machine-learning approach", Sensors, **20**(6), p. 1557 (2020), https://doi.org/10.3390/s20061557.

13. Bruno, A. G., Bouxsein, M. L., and Anderson, D. E., "Development and validation of a musculoskeletal model of the fully articulated thoracolumbar spine and rib cage", J Biomech Eng, **137**(8), pp. 1–10 (2015), https://doi.org/10.1115/1.4030408.

14. Rajaee, M. A., Arjmand, N., Shirazi-Adl, et al. "Comparative evaluation of six quantitative lifting tools to estimate spine loads during static activities", Appl Ergon, **48**, pp. 22–32 (2015), https://doi.org/10.1016/j.apergo.2014.11.002.

15. Jia, B., Kim, S., and Nussbaum, M. A., "An EMG-based model to estimate lumbar muscle forces and spinal loads during complex, high-effort tasks: Development and application to residential construction using prefabricated walls", Int J Ind Ergon, **41**(5), pp. 437–446 (2011), https://doi.org/10.1016/j.ergon.2011.03.004.

16. McGill, S. M., Marshall, L., and Andersen, J., "Low back loads while walking and carrying: Comparing the load carried in one hand or in both hands", Ergonomics, **56**(2), pp. 293–302 (2013), https://doi.org/10.1080/00140139.2012.752528.

17. Parnianpour, M., and Shirazi-Adl, A., "Application of a kinematics-driven approach in human spine biomechanics during an isometric lift", Scientia Iranica, **15**(5), (2008).

18. Bazrgari, B., Shirazi-Adl, A., and Arjmand, N., "Analysis of squat and stoop dynamic liftings: Muscle forces and internal spinal loads", Eur Spine J, **16**(5), pp. 687–699 (2007), https://doi.org/10.1007/s00586-006-0240-7.

19. Kingma, I., Bosch, T., Bruins, L., et al. "Foot positioning instruction, initial vertical load position and lifting technique: Effects on low back loading", Ergonomics, **47**(13), pp. 1365–1385 (2004), https://doi.org/10.1080/00140130410001714742.

20. Yanikören, M., Yilmaz, S., and Gündoğdu, Ö., "3D biomechanical model that can perform dynamic analysis of the upper extremity and L5/S1 joints without the use of force sensor", Sādhanā, **49**, p. 241 (2024), https://doi.org/10.1007/s12046-024-02590-0.

21. Faber, G. S., Kingma, I., Chang, C. C., et al. "Validation of a wearable system for 3D ambulatory L5/S1 moment assessment during manual lifting using instrumented shoes and an inertial sensor suit", J Biomech, **102**, p. 109671 (2020), https://doi.org/10.1016/j.jbiomech.2020.109671.

22. Koopman, A. S., Kingma, I., Faber, G. S., et al. "Estimating the L5S1 flexion/extension moment in symmetrical lifting using a simplified ambulatory measurement system", J Biomech, **70**, pp. 242–248 (2018), https://doi.org/10.1016/j.jbiomech.2017.10.001.

23. Hammer, M., Wenzel, T., Santin, G., et al. "A new method to design energy-conserving surrogate models for the coupled, nonlinear responses of intervertebral discs", Biomech Model Mechanobiol, **23**, pp. 757–780 (2024), https://doi.org/10.1007/s10237-023-01804-4.

24. Varrecchia, T., Chini, G., Serrao, M., et al. "Lifting activities assessment using lumbosacral compression and shear forces", Appl Sci, **14**(14), p. 6044 (2024), https://doi.org/10.3390/app14146044.

25. van der Have, A., Van Rossom, S., and Jonkers, I., "Musculoskeletal-modeling-based, full-body load-assessment tool for ergonomists (MATE): Method development and proof of concept case studies", Int J Environ Res Public Health, **20**(2), p. 1507 (2023), https://doi.org/10.3390/ijerph20021507.

26. Beaucage-Gauvreau, E., Robertson, W. S. P., Brandon, S. C. E., et al. "Validation of an OpenSim full-body model with detailed lumbar spine for estimating lower lumbar spine loads during symmetric and asymmetric lifting tasks", Comput Methods Biomech Biomed Engin, **22**(5), pp. 451–464 (2019), https://doi.org/10.1080/10255842.2018.1564819.

27. Kingma, I., Faber, G. S., and van Dieën, J. H., "Supporting the upper body with the hand on the thigh reduces back loading during lifting", J Biomech, **49**(6), pp. 881–889 (2016), https://doi.org/10.1016/j.jbiomech.2015.09.035.

28. von Arx, M., Liechti, M., Connolly, L., et al. "From stoop to squat: A comprehensive analysis of lumbar loading among different lifting styles", Front Bioeng Biotechnol, **9**, p. 1070 (2021), https://doi.org/10.3389/fbioe.2021.769117.

29. Stambolian, D., Asfour, S., and Eltoukhy, M., "Using vicon bodybuilder and plug-in-gait to generate L5/S1 angles, forces and moments", in Proc IEEE Aerospace Conf, Big Sky, MT, USA, pp. 1–7 (2014), https://doi.org/10.1109/AERO.2014.6836487.

30. Gholipour, A., and Arjmand, N., "Artificial neural networks to predict 3D spinal posture in reaching and lifting activities; Applications in biomechanical models", J Biomech, **49**(13), pp. 2946–2952 (2016), https://doi.org/10.1016/j.jbiomech.2016.07.008.

31. Nail-Ulloa, I., Zabala, M., Sesek, R., et al. "Estimating compressive and shear forces at L5-S1: Exploring the effects of load weight, asymmetry, and height using optical and inertial motion capture systems", Sensors, **24**(6), p. 1941 (2024), https://doi.org/10.3390/s24061941.

32. Mobini, A., Behzadipour, S., and Saadat Foumani, M., "Hand acceleration measurement by Kinect for rehabilitation applications", Scientia Iranica, **24**(1), pp. 191–201 (2017), https://doi.org/10.24200/sci.2017.4025.

33. Vilas-Boas, M. do C., Choupina, H. M. P., Rocha, A. P., et al. "Full-body motion assessment: Concurrent validation of two body tracking depth sensors versus a gold standard system during gait", J Biomech, **87**, pp. 189–196 (2019), https://doi.org/10.1016/j.jbiomech.2019.03.008.

34. Roozbahani, H., Alizadeh, M., Ustinov, et al. "Development of a novel real-time simulation of human skeleton/muscles", J Biomech, **114**, (2021), https://doi.org/10.1016/j.jbiomech.2020.110157.

35. Xu, X., and McGorry, R. W., "The validity of the first and second generation Microsoft KinectTM for identifying joint center locations during static postures", Appl Ergon, **49**, pp. 47–54 (2015), https://doi.org/10.1016/j.apergo.2015.01.005.

36. Matthew, R. P., Seko, S., Bajcsy, R., et al. "Kinematic and Kinetic Validation of an Improved Depth Camera Motion Assessment System Using Rigid Bodies", IEEE J Biomed Health Inform, **23**(4), pp. 1784–1793 (2019), https://doi.org/10.1109/JBHI.2018.2872834.

37. Asadi, F., and Arjmand, N., "Marker-less versus marker-based driven musculoskeletal models of the spine during static load-handling activities", J Biomech, **112**, p. 110043 (2020), https://doi.org/10.1016/j.jbiomech.2020.110043.

38. Mokari, M., Mohammadzade, H., and Ghojogh, B., "Recognizing involuntary actions from 3D skeleton data using body states", Scientia Iranica, **27**(3), pp. 1424–1436 (2020), https://doi.org/10.24200/sci.2018.20446.

39. Bonnechere, B., Jansen, B., Salvia, P., et al. "Validity and reliability of the Kinect within functional assessment activities: comparison with standard stereophotogrammetry", Gait Posture, **39**(1), pp. 593–598 (2014), https://doi.org/10.1016/j.gaitpost.2013.09.018.

40. Xu, X., McGorry, R. W., Chou, L. S., et al. "Accuracy of the Microsoft Kinect™ for measuring gait parameters during treadmill walking", Gait Posture, **42**(2), pp. 145–151 (2015), https://doi.org/10.1016/j.gaitpost.2015.05.002.

41. Duplessis, D. H., Greenway, E. H., Keene, K. L., et al. "Effect of semi-rigid lumbosacral orthosis use on oxygen consumption during repetitive stoop and squat lifting", Ergonomics, **41**(6), pp. 790–797 (1998), https://doi.org/10.1080/001401398186649.

42. Straker, L., "Evidence to support using squat, semi-squat and stoop techniques to lift low-lying objects", Int J Ind Ergon, **31**(3), pp. 149–160 (2003), https://doi.org/10.1016/S0169-8141(02)00191-9.

43. Marras, W. S., and Karwowski, W., "Managing Low-Back Disorder Risk in the Workplace", in Handbook of Human Factors and Ergonomics, pp. 597–629 (2021), https://doi.org/10.1002/9781119636113.ch22.

44. van der Have, A., Van Rossom, S., and Jonkers, I., "Squat lifting imposes higher peak joint and muscle loading compared to stoop lifting", Appl Sci, **9**(18), p. 3794 (2019), https://doi.org/10.3390/app9183794.

45. Alemi, M. M., Geissinger, J., Simon, A. A., et al. "A passive exoskeleton reduces peak and mean EMG during symmetric and asymmetric lifting", J Electromyogr Kinesiol, **47**, pp. 25–34 (2019), https://doi.org/10.1016/j.jelekin.2019.05.003.

46. Yanikören, M., Yilmaz, S., and Gündoğdu, Ö., "Determining sex-related behavioral differences in manual material lifting and lowering movements during daily life", Scientia Iranica (2024), https://doi.org/10.24200/sci.2024.63603.8492.

47. Sarbolandi, H., Lefloch, D., and Kolb, A., "Kinect range sensing: Structured-light versus Time-of-Flight Kinect", Comput Vis Image Underst, **139**, pp. 1–20 (2015), https://doi.org/10.1016/j.cviu.2015.05.006.

48. "The zebris FDM System—gait and roll-off analysis in practice", Zebris Medical GmbH, Tübingen, Germany, 25 Apr. (2022). https://www.zebris.de/fileadmin/Editoren/zebris-PDF/zebris-Prospekte-EN/27_9_FDM_EN_150.pdf.

49. Rajagopal, A., Dembia, C. L., DeMers, M. S., et al. "Full-body musculoskeletal model for muscle-driven simulation of human gait", IEEE Trans Biomed Eng, **63**(10), pp. 2068–2079 (2016), https://doi.org/10.1109/TBME.2016.2586891.

50. Wang, Z., Wu, L., Sun, J., et al. "Squat, stoop, or semi-squat: A comparative experiment on lifting technique", J Huazhong Univ Sci Technol Med Sci, **32**(4), pp. 630–636 (2012), https://doi.org/10.1007/s11596-012-1009-3.

51. Plamondon, A., Gagnon, M., and Gravel, D., "Moments at the L5/S1 joint during asymmetrical lifting: effects of different load trajectories and initial load positions", Clin Biomech, **10**(3), pp. 128–136 (1995), https://doi.org/10.1016/0268-0033(95)93702-U.

52. Seth, A., Hicks, J. L., Uchida, T. K., et al. "OpenSim: Simulating musculoskeletal dynamics and neuromuscular control to study human and animal movement", PLoS Comput Biol, **14**(7) (2018), https://doi.org/10.1371/journal.pcbi.1006223.

53. Delp, S. L., Anderson, F. C., Arnold, A. S., et al. "OpenSim: Open-source software to create and analyze dynamic simulations of movement", IEEE Trans Biomed Eng, **54**(11), pp. 1940–1950 (2007), https://doi.org/10.1109/TBME.2007.901024.

54. Gallagher, S., and Marras, W. S., "Tolerance of the lumbar spine to shear: a review and recommended exposure limits", Clin Biomech, **27**(10), pp. 973–978 (2012), https://doi.org/10.1016/j.clinbiomech.2012.08.009.

55. McGill, S., Low back disorders: evidence-based prevention and rehabilitation, Human Kinetics, ISBN: 0736066926 (2007).

56. Samadi, B., Raison, M., Mahaudens, P., Detrembleur, C., and Achiche, S., "Development of machine learning algorithms to identify the Cobb angle in adolescents with idiopathic scoliosis based on lumbosacral joint efforts during gait (Case study)", arXiv preprint, arXiv:2301.12588 (2023), https://doi.org/10.48550/arXiv.2301.12588.

Biographies

Melih Canlıdinç is an Assistant Professor in the Department of Mechanical Engineering at Kütahya Dumlupınar University, Turkey. He received his Bachelor of Science degree in Mechanical Engineering from Kütahya Dumlupınar University in 2014. He completed his Ph.D. in Mechanical Engineering at the same university in 2022. Dr. Canlıdinç continues his research in the fields of robotics, biomechanics, and topology optimization, with a particular focus on computational modeling, structural analysis, and the dynamic behavior of mechanical and biomedical systems.

Mustafa Güleşen is an Assistant Professor in the Department of Mechanical Engineering at Kütahya Dumlupınar University, Turkey. He received his Bachelor of Science degree in Mechanical Engineering from Kütahya Dumlupınar University in 2002 and earned his Ph.D. in Mechanical Engineering from Eskişehir Osmangazi University in 2013. Dr. Güleşen's research interests include powder metallurgy, biomechanics, and nozzle design. His work focuses on computational fluid dynamics (CFD) and CAD-based modeling techniques for the analysis and design of mechanical systems in engineering and biomedical applications.

Figure Captions

Figure 1. 3D skeleton joints tracked by the Kinect v2 sensor.
Figure 2. Zebris™ FDM-2 system used for lifting analysis in experiments.
Figure 3. (a) Squad lifting and (b) Stoop lifting.
Figure 4. a) Experimental setup, b) Lifting motions of the biomechanical model.
Figure 5. OpenSim workflow.

Figure 6. Joint angles of lumbar in different weights (4,8,12, and 16 kg) during squat and stoop lift.
Figure 7. Lumbar (L5/S1) extension moments during squat and stoop lift.
Figure 8. L5/S1 joint compression forces during squat and stoop lifting.
Figure 9. L5/S1 joint shear forces during squat and stoop lifting.

Figure 10. Comparison of L5/S1 joint compression forces during squat and stoop lifting movements.
Figure 11. Comparison of L5/S1 joint shear forces during squat and stoop lifting.

Figures

Figure 1. 3D skeleton joints tracked by the Kinect v2 sensor.

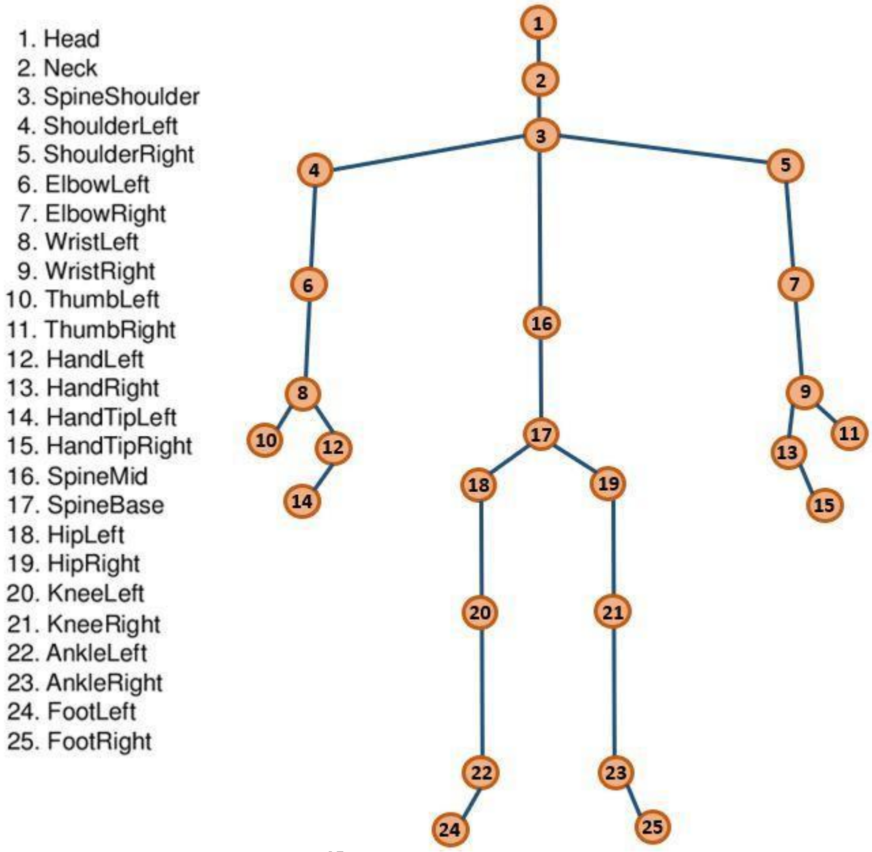


Figure 2. Zebris™ FDM-2 system used for lifting analysis in experiments.

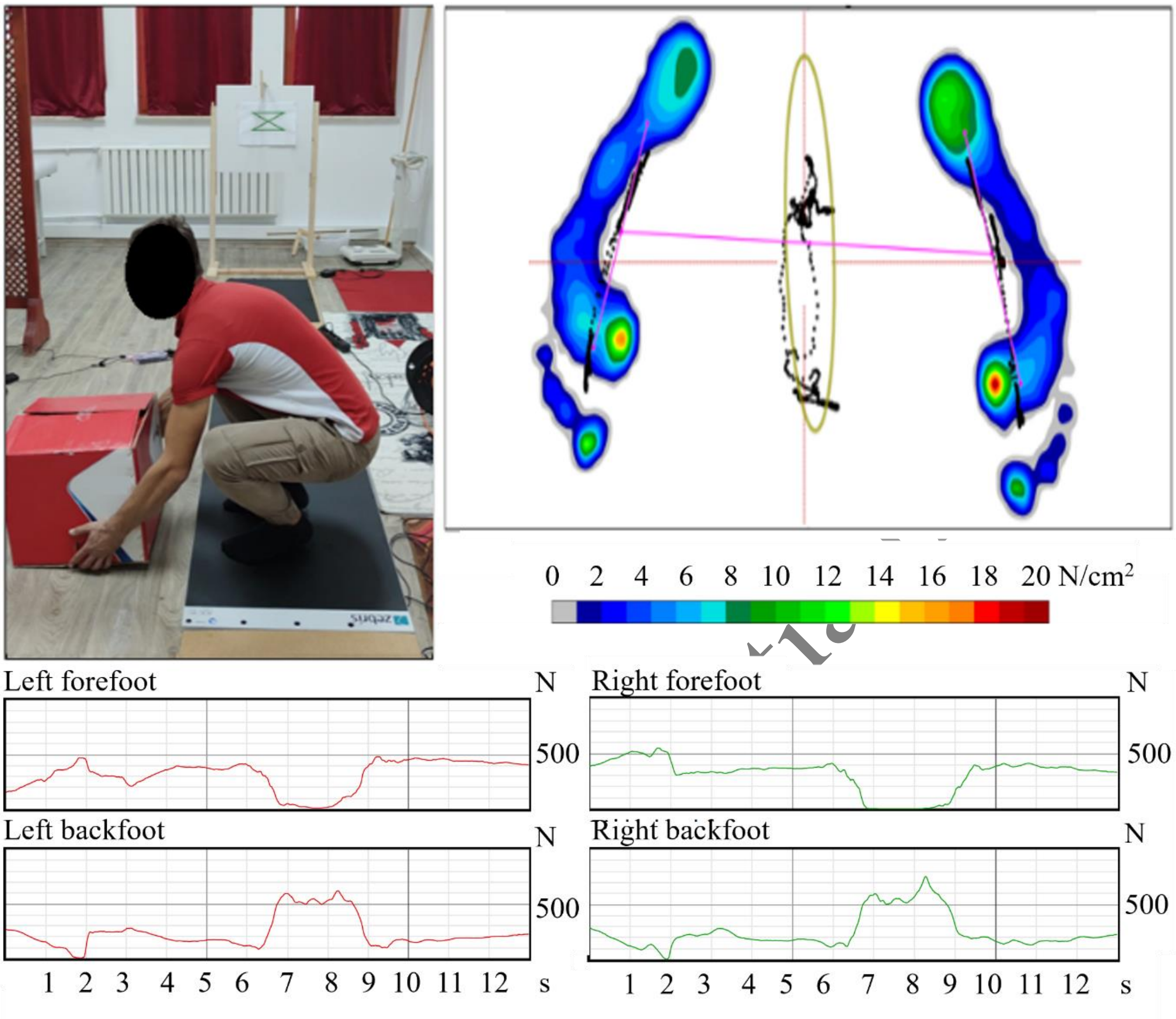


Figure 3. (a) Squad lifting and (b) Stoop lifting.

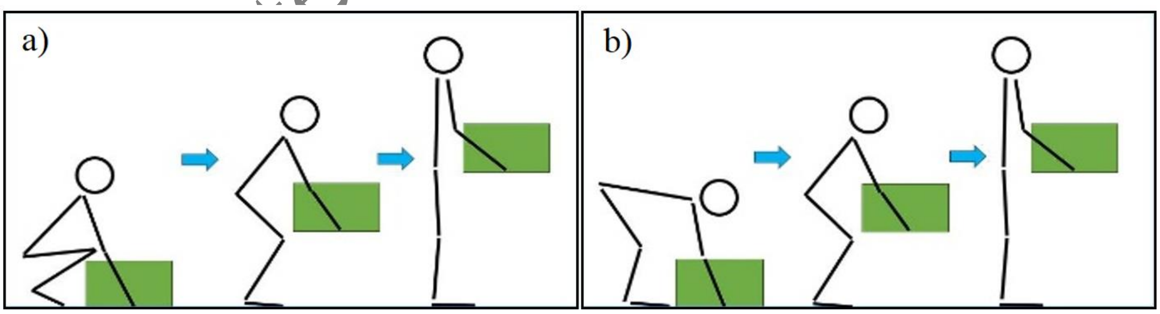


Figure 4. a) Experimental setup, b) Lifting motions of the biomechanical model.

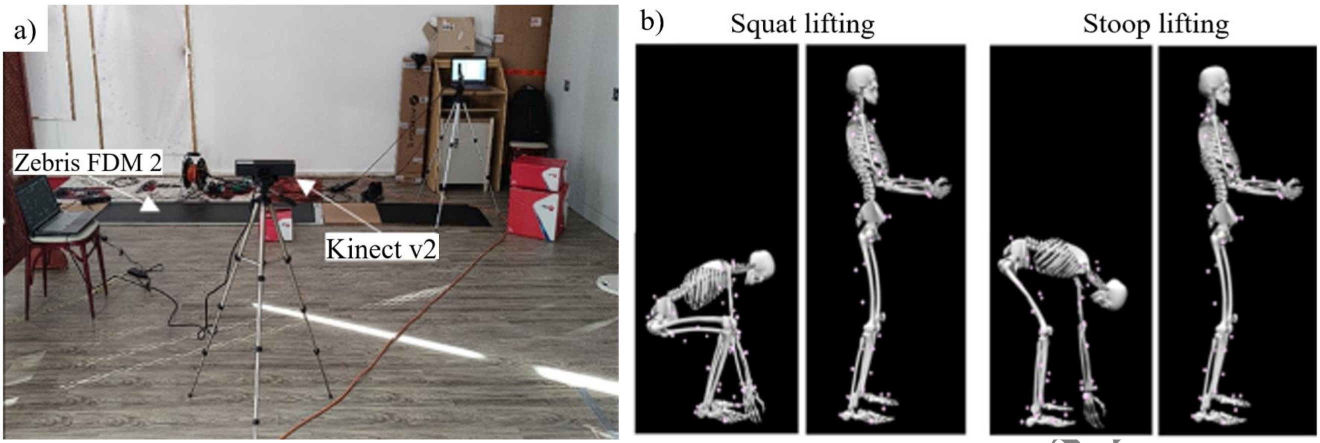


Figure 5. OpenSim workflow.

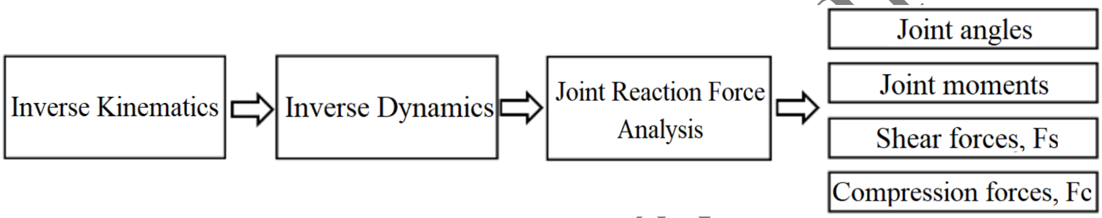


Figure 6. Joint angles of lumbar in different weights (4,8,12, and 16 kg) during squat and stoop lift.

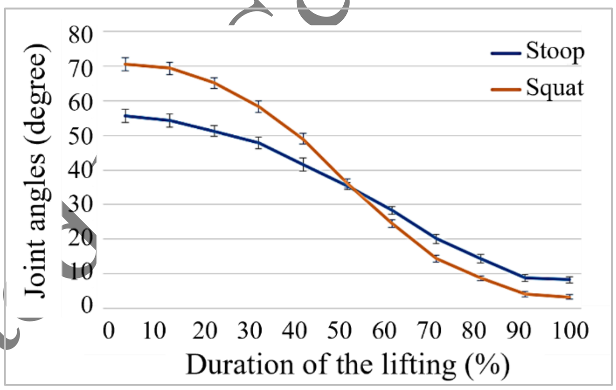


Figure 7. Lumbar (L5/S1) extension moments during squat and stoop lift.

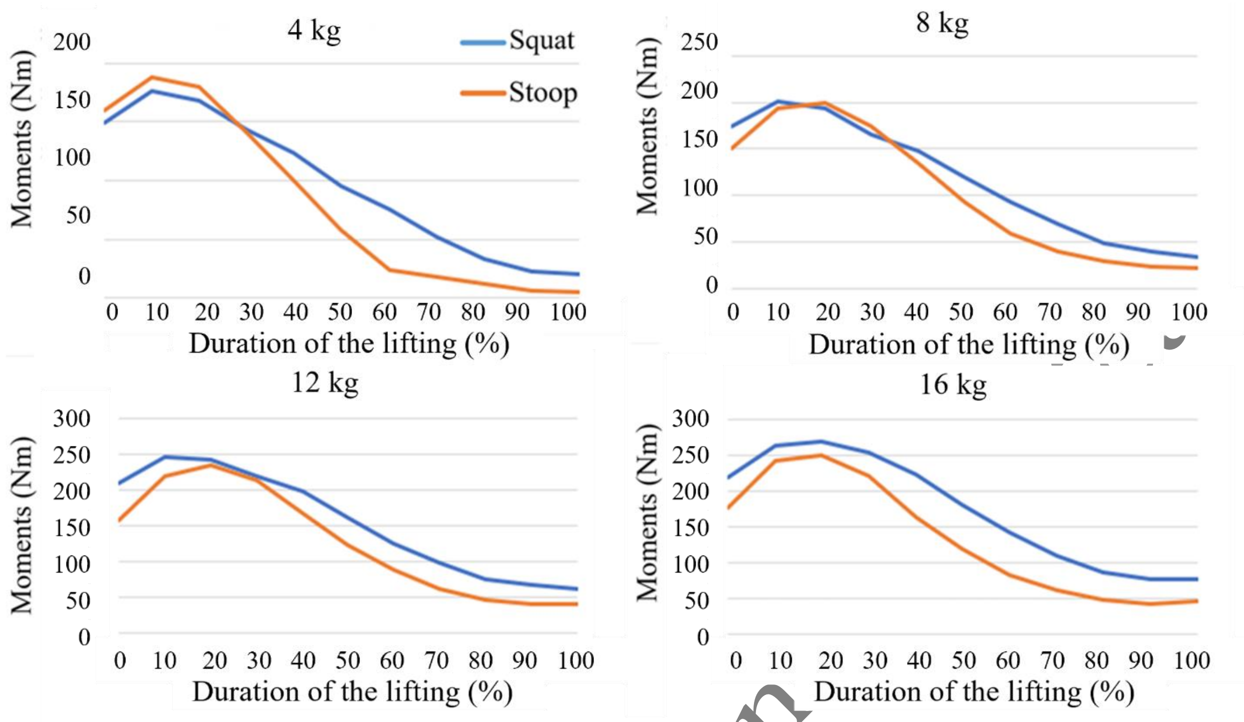


Figure 8. L5/S1 joint compression forces during squat and stoop lifting.

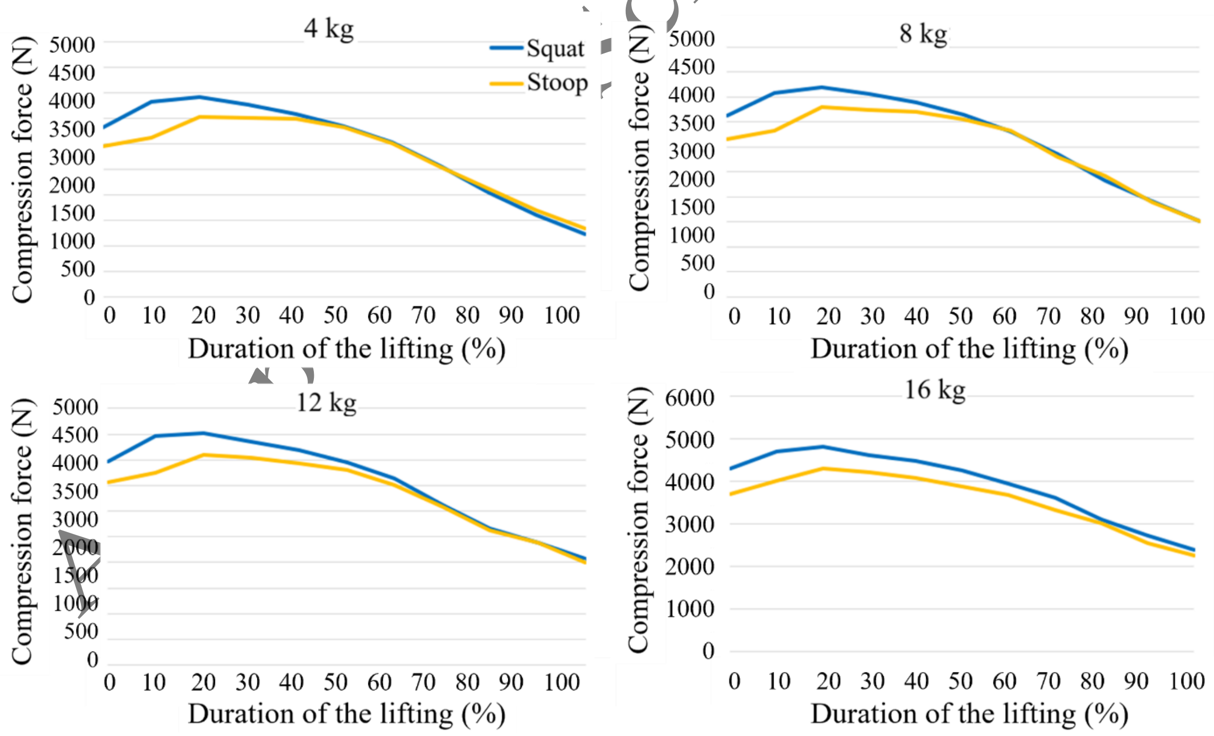


Figure 9. L5/S1 joint shear forces during squat and stoop lifting.

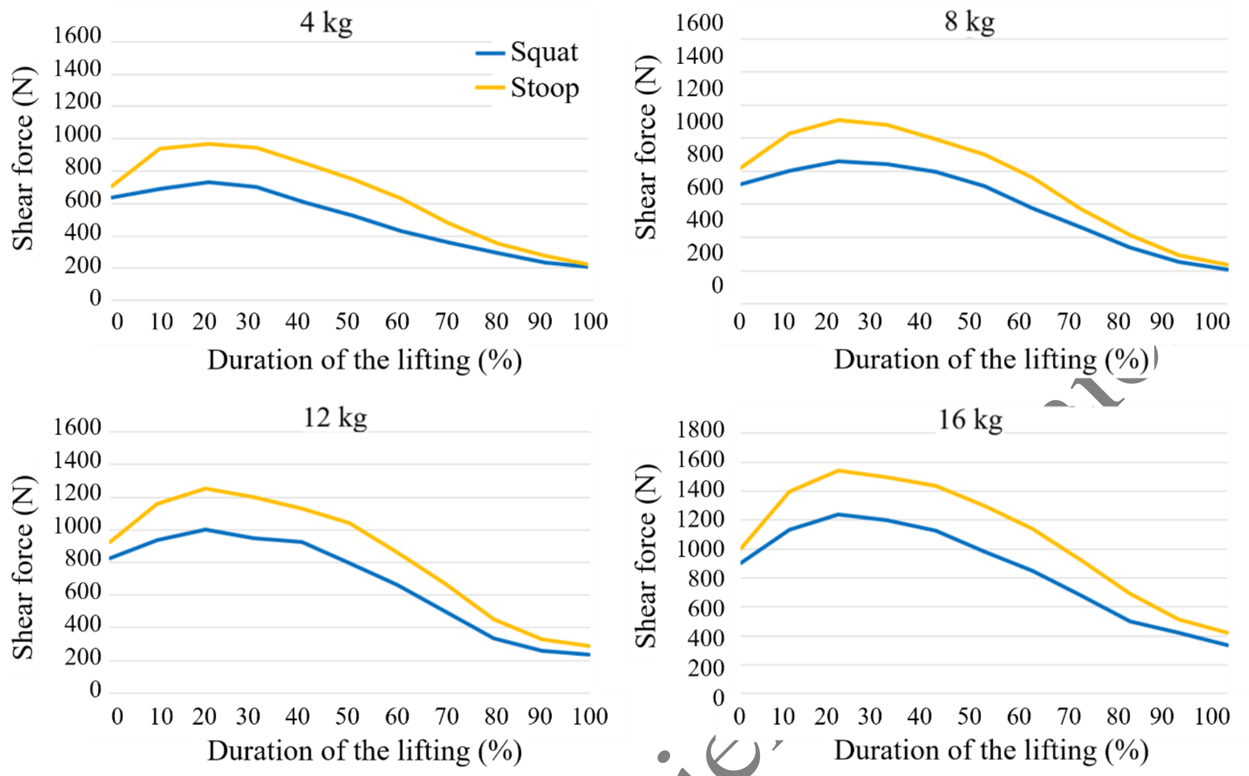


Figure 10. Comparison of L5/S1 joint compression forces during squat and stoop lifting movements.

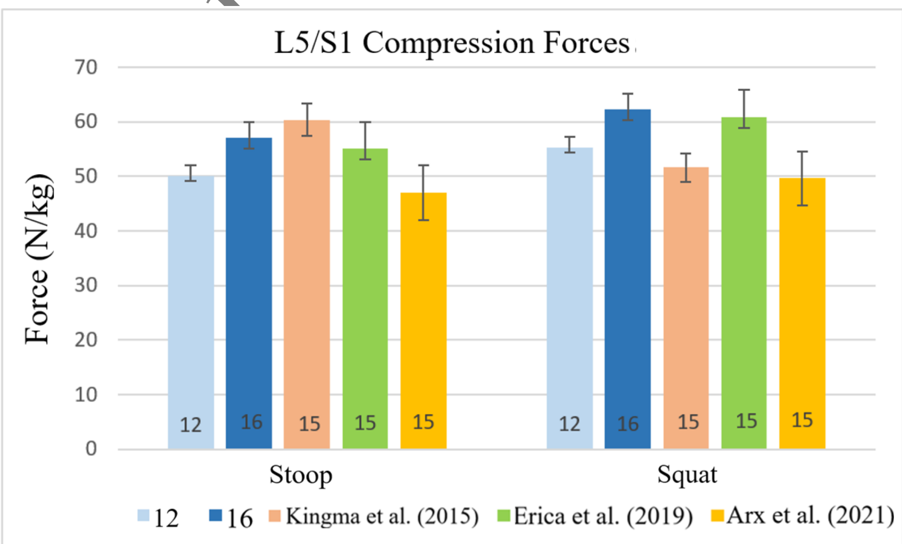
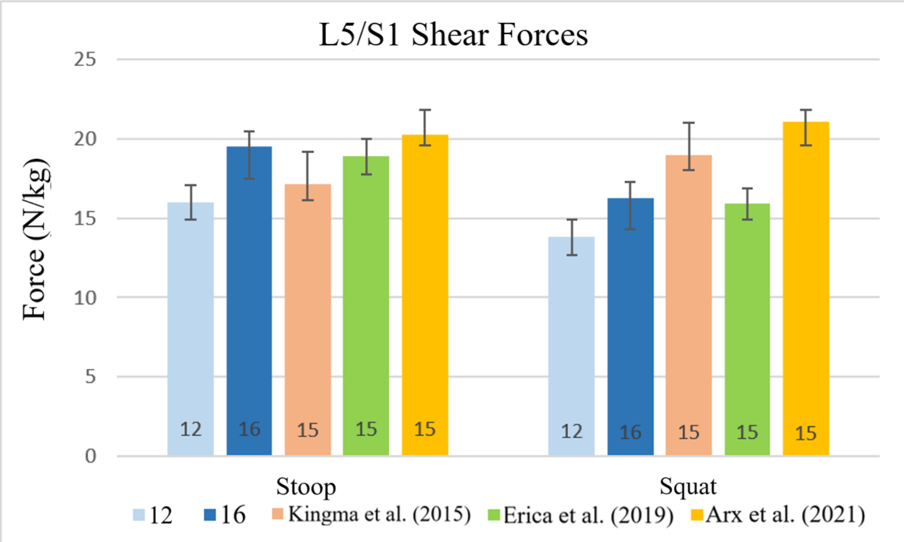


Figure 11. Comparison of L5/S1 joint shear forces during squat and stoop lifting.



L5/S1 Shear Forces
Force (N/kg)
25
20
15
10
5
0
12
16
15
15
15
12
16
15
15
15
Stoop
Squat
12
16
Kingma et al. (2015)
Erica et al. (2019)
Arx et al. (2021)