

Musculoskeletal Simulation of the Trunk in Normal-Weight Subjects during Back Lifting using OpenCap and OpenSim

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Abstract: Musculoskeletal disorders (MSDs) in the lumbar region are a prevalent cause of disability among construction workers in low- and middle-income countries, where manual material handling remains common due to limited access to mechanization. Traditional ergonomic assessments often rely on observational tools that cannot directly estimate internal loads acting on the spine. This study aimed to characterize the trunk's biomechanical behavior during a manual lifting task frequently observed in construction settings, using kinematic data from OpenCap and musculoskeletal simulation in OpenSim. A cross-sectional descriptive study was conducted with ten healthy Colombian men classified as normal-weight and average-height, according to national anthropometric standards. Participants performed a standardized task involving lateral lifting of a 10 kg load from a 45 cm platform to the contralateral shoulder. Kinematic data were captured using two markerless iPhone cameras analyzed with OpenCap and synchronized with ground reaction forces from a force platform. Biomechanical simulations were run in OpenSim using the Lifting Full-Body model scaled to each subject. Results showed a multiaxial trunk movement pattern, with peak sagittal flexion (29.6°), lateral tilt (25.4°), and axial rotation (14.4°) occurring during the lifting phase. Compressive forces at the L5/S1 segment exhibited a biphasic pattern, with peaks reaching up to 3349 N—close to the 3400 N threshold recommended to prevent disc injury. Variability in movement patterns was observed across subjects, particularly in lateral tilt and rotation, while compressive force estimates remained relatively stable. These findings highlight the importance of considering combined trunk motions when assessing biomechanical risk, even during moderate-load tasks. The integration of OpenCap and OpenSim enabled non-invasive estimation of internal spinal loads and offers a viable alternative for ergonomic assessment in low-resource environments. This approach contributes to the development of context-specific prevention strategies for MSDs in the construction industry.

Keywords: Musculoskeletal simulation, OpenCap, OpenSim, trunk biomechanics, load lifting, occupational ergonomics

1. Introduction

In low- and middle-income countries, such as Colombia, manual handling of loads is common in the construction industry, due to the limited mechanization of tasks (Debrah, Jabaru, Nyuur, Ellis, & Banoeng-Yakubo, 2023; Roy & Koehn, 2006). In contrast to industrialized contexts, where the use of ergonomic aids has significantly reduced the physical load, in low-resource settings human effort continues to be the main driver of material transport and lifting. This technological gap has contributed to physical overload being one of the main causes of occupational musculoskeletal disorders (MSDs) in construction (Neusa Arenas, Saraguro Piarpuezan, Jiménez Rey, & Navarrete Arboleda, 2024). It is estimated that close to 90% of the trades in this sector include manual handling of materials, with lifting and lowering being responsible for up to 30% of MSD cases (CPWR – The Center for Construction Research and Training, 2018).

Construction workers present high rates of MSD, with predominant involvement in the lumbar region (Ghezelbash, Shirazi-Adl, Arjmand, El-Ouaaid, & Plamondon, 2016); in countries such as Nepal, the annual prevalence of low back pain among construction workers exceeds 50% (Adhikari et al., 2021). Similarly, in Colombia, low back pain of occupational origin represents one of the main diagnoses in the processes of qualification of loss of work capacity, both temporary and permanent (Perdomo, Panameño, Polanco, Valderrama, & Agudelo, 2025; Pinto, 2015). A local study showed that 41% of the workers at a construction site reported low back discomfort throughout their working life (Escamilla, 2015). Although located in different geographical regions, both countries share structural conditions typical of developing contexts: low

mechanization, high physical demand and scarce implementation of ergonomic aids. This problem not only compromises workers' health, but also generates economic losses associated with absenteeism and reduced productivity. However, in many Latin American contexts, biomechanical risk assessment continues to depend on observational methods such as REBA or NIOSH's RNLE (Nogareda & Canosa, 2016) which, although practical, have limitations in directly estimating the “internal load” on the spine, especially in dynamic and asymmetric gestures (Dawad, Yasin, Darus, Jamil, & Naing, 2024).

This internal load corresponds to a set of forces and moments, such as compressive forces, shear forces, and joint torques, which are generated within the body and act particularly on the intervertebral discs and the ligamentous and bony structures that make up the functional spinal unit (Ghezlbash et al., 2016). Various biomechanical studies have documented that, during manual lifting of loads, the L5/S1 segment bears the highest levels of load, due to its anatomical location and its role in transmitting forces between the trunk and the lower limbs. The NIOSH Revised Lifting Guide establishes a compression limit of 3400 N for this segment to prevent structural damage to the intervertebral disc and its endplates (Donisi et al., 2022; Nogareda & Canosa, 2016). This risk is increased in movements that combine flexion, rotation, and external load, as occurs in asymmetrical lifting, which is widely documented in construction activities (Winiarski, Molek-Winiarska, & Chomątowska, 2025). Lifting packages from lateral or diagonal positions is considered one of the tasks that imposes the greatest mechanical demands on the lumbar region. However, the accurate quantification of these internal loads remains a methodological challenge, given that direct *in vivo* measurements are invasive and ethically restricted (Khoddam-Khorasani, Arjmand, & Shirazi-Adl, 2020), while *in vitro* studies fail to faithfully replicate the complexity of human movement during the functional execution of these tasks (Cuchanski, Cook, Jegapragasan, Whiting, & Cheng, 2010).

Thus, musculoskeletal simulation emerges as a tool for non-invasively quantifying the internal forces acting on the musculoskeletal system. OpenSim (Company name, city), an open-source platform, allows the estimation of muscle and intervertebral reaction forces using validated biomechanical models (Akhavanfar, Brandon, Brown, & Graham, 2019; Delp et al., 2007). Complementarily, OpenCap has democratized access to three-dimensional motion capture, using cell phones to obtain kinematic data without markers (Uhlrich et al., 2022). The combination of both tools enables more accurate characterizations of biomechanical risk in the field, even in contexts without access to specialized laboratories (Salazar, Quiñones, & Arango, 2024).

Despite these innovations, the literature on musculoskeletal simulation applied to asymmetrical manual lifting tasks in Latin American occupational settings remains limited, leaving significant gaps in our understanding of the specific biomechanical risks faced by workers in these conditions. (Senteler, Weisse, Rothenfluh, & Jess, 2016; Verheul, Robinson, & Burton, 2024) Therefore, the present study aims to characterize the biomechanical behavior of the trunk during a typical manual load lifting task in construction, using musculoskeletal simulation with OpenSim and informed by kinematic data obtained through OpenCap. This approach seeks to provide empirical evidence to strengthen the prevention of MSDs in physically demanding work environments such as Colombia.

2. Method

2.1 Study design

A descriptive cross-sectional study was conducted

2.2 Subjects

The sample included ten young Colombian men (aged 18–44), of normal weight and average height according to ACOPLA 95 (Estrada Muñoz, Camacho Pérez, Restrepo Calle, & Parra Mesa, 1998). Participants were selected using convenience sampling. Subjects with musculoskeletal pathologies, or conditions that prevented manual lifting, or who did not complete the experimental protocol were excluded. All signed informed consent forms.

2.3 Procedure

Under laboratory conditions, each participant performed three repetitions of a standardized movement involving lifting a 10 kg weight, located at a height of 45 cm above their right side, and placing it on their left shoulder. Prior to the exercise, a five-minute guided warm-up with dynamic stretching was performed to reduce the risk of injury.

For each subject, two iPhone cameras (iPhone 11 model or higher) were used, positioned 3 meters from the center of the movement, forming an angle of approximately 45 degrees between them. The recording was made in a well-lit environment, with a neutral background and spatial markers on the floor to ensure correct triangulation.

2.4 Motion capture and biomechanical analysis

The kinematics were recorded using two simultaneous approaches: OpenCap, with two iPhone cameras (60 Hz), using markerless computer vision, and Motive-OptiTrack, with eight optoelectronic cameras (100 Hz) and 39 markers on the body.

At the same time, reaction forces on the floor were recorded using a BTS P6000 platform. The data was integrated and exported to OpenSim, where the Lifting Full-Body (LFB) model was used, adjusted to the individual anthropometry of each subject.

The biomechanical analysis included:

- Inverse kinematics to estimate joint angles of the trunk in the sagittal, frontal, and transverse planes.
- Static optimization and joint reaction to calculate compressive and shear forces in the L5/S1 segment.

2.5 Statistical analysis

The data were processed in Excel and SPSS v21. Measures of central tendency and dispersion were calculated. The Kolmogorov-Smirnov test was used to verify the normality of the anthropometric variables. The kinematic and kinetic values were presented as averages per phase of the movement, including coefficients of variation to assess inter-subject consistency.

2.6 Ethical considerations

This research is part of the macro-project “Influence of anthropometric factors of Colombian workers on the biomechanical risk to the lumbar spine during manual lifting of loads in construction activities using computer simulation,” which was endorsed and renewed by the Ethics Committee of the Universidad del Valle, under code 198-020. In addition, this specific study was presented and approved by the same committee, under code 009-024. All participants signed an informed consent form, in accordance with the ethical principles established in the Declaration of Helsinki and national regulations for research involving human subjects.

3. Results

Ten participants classified as “normal weight and average height” were included, according to the criteria of the ACOPLA 95 study. Table 1 shows the general anthropometric characteristics. The average age was 27.7 years (SD = 6.0), ranging from 20 to 37 years. The average body weight was 67.7 kg (SD = 3.5) and the average height was 1.69 m (SD = 0.01), corresponding to an average BMI of 23.6.

Leg length measurements (actual and from the greater trochanter) showed averages close to 90.1 cm and 87.2 cm, respectively, with moderate variability between individuals. The floor-to-shoulder height was 140.2 cm (SD = 3.3) and the floor-to-waist height was 106.8 cm (SD = 2.4), showing individual differences in body structure. For the kinematic analysis, the gesture was segmented into three phases based on the movement of the trunk:

- Phase 1: Initial standing position (1)
- Phase 2: Lateral bending and trunk flexion to reach and grasp the load (2)
- Phase 3: Lifting and placing the load on the shoulder, with partial return to upright alignment (3)

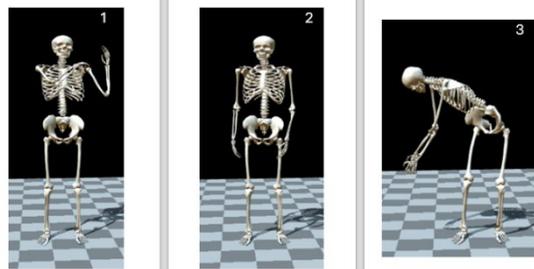


Figure 1. Phases of lifting a load for kinematic analysis

For the kinetic analysis, focused on estimating intervertebral reaction forces, three phases were also defined (Figure 2), oriented toward load handling:

- **Phase A (Grasping):** Holding the load from the side platform at a height of 45 cm;
- **Phase B (Positioning):** Lifting the load to shoulder height;
- **Phase C (Returning):** Returning to the initial position after setting down the load.

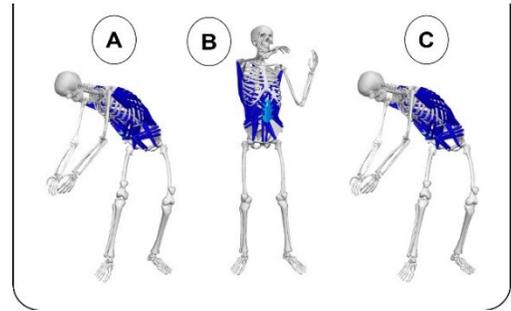


Figure 2. Phases of lifting a load for kinematic analysis

3.1 Trunk kinematics

During the lift, consistent patterns of multiaxial trunk movement were observed. The greatest sagittal flexion (29.6°), lateral tilt (25.4°), and axial rotation (14.4°) occurred in Phase 2, corresponding to the active lifting of the load. In the initial (Phase 1) and final (Phase 3) phases, the angular values were considerably lower, showing a progressive return to vertical alignment.

In terms of timing, the angular peaks were distributed between 20% and 70% of the movement cycle, with common sequences among participants. Inter-subject variability was lower in Phase 2 (CV < 0.35) and higher in Phase 3, especially in lateral tilt (CV = 0.75) and rotation (CV = 0.45), reflecting individual differences in postural recovery.

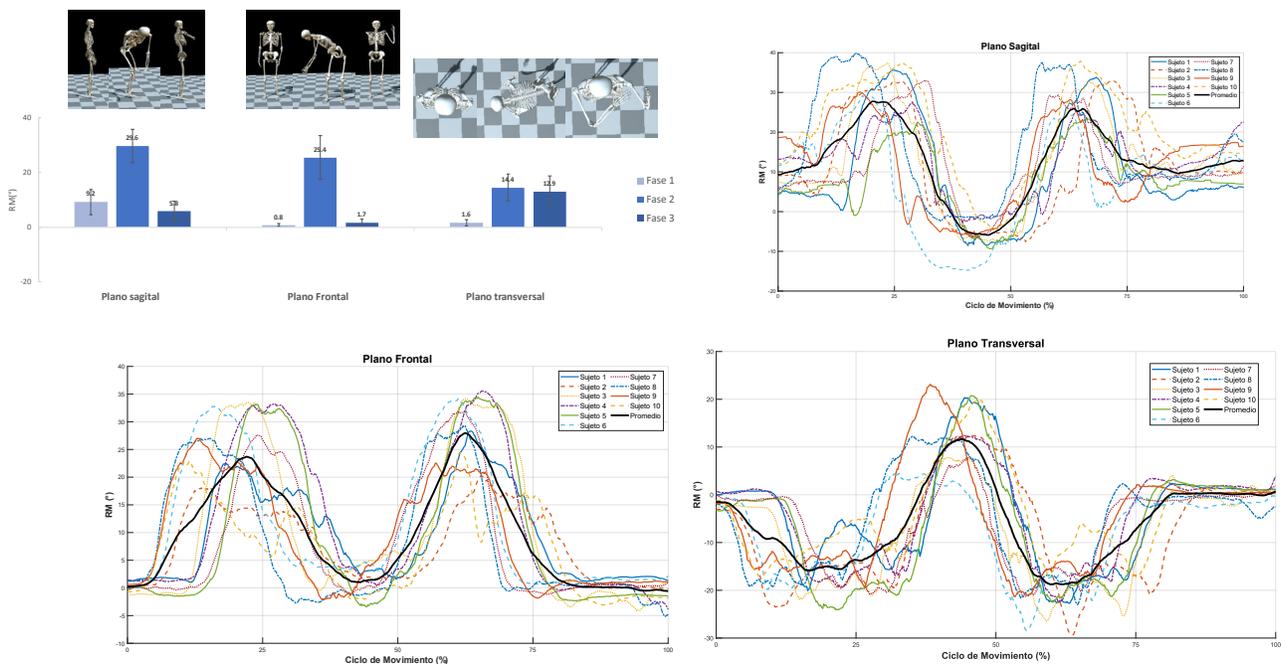


Figure 3. Average bag lifting Figure 4. Movement pattern for lifting a heavy object

Table 2. Coefficient of variation for bag lifting

"LOAD LIFTING – KINEMATIC ANALYSIS"									
	Phase 1			Phase 2			Phase 3		
	Plano Sagital	Plano Frontal	Plano Transverso	Plano Sagital	Plano Frontal	Plano Transverso	Plano Sagital	Plano Frontal	Plano Transverso
PROMEDIO	9.23	0.79	1.60	29.64	25.44	14.43	5.79	1.69	12.92
DS	4.62	0.48	1.16	6.08	7.96	5.00	3.68	1.28	5.83
CV	0.50	0.60	0.72	0.21	0.31	0.35	0.64	0.75	0.45

3.2 Kinetic behavior L5/S1

In the L5/S1 segment, compressive forces showed a biphasic pattern, with peaks occurring during the grip (Phase A) and return (Phase C) phases, and a marked reduction in the intermediate phase (Phase B), when the load is stabilized on the shoulder. The magnitudes ranged from 15.0 to 43.9 N/kg, remaining below risk thresholds reported in the literature.

The anteroposterior and mediolateral forces followed similar trends, although with greater dispersion. High variability was evident in the anteroposterior axis during positioning (CV > 1.0), while the compressive components were the most stable (CV < 0.15), suggesting consistent biomechanical execution among participants.

Figure 5. Intervertebral forces L5/S1 during lifting a heavy object

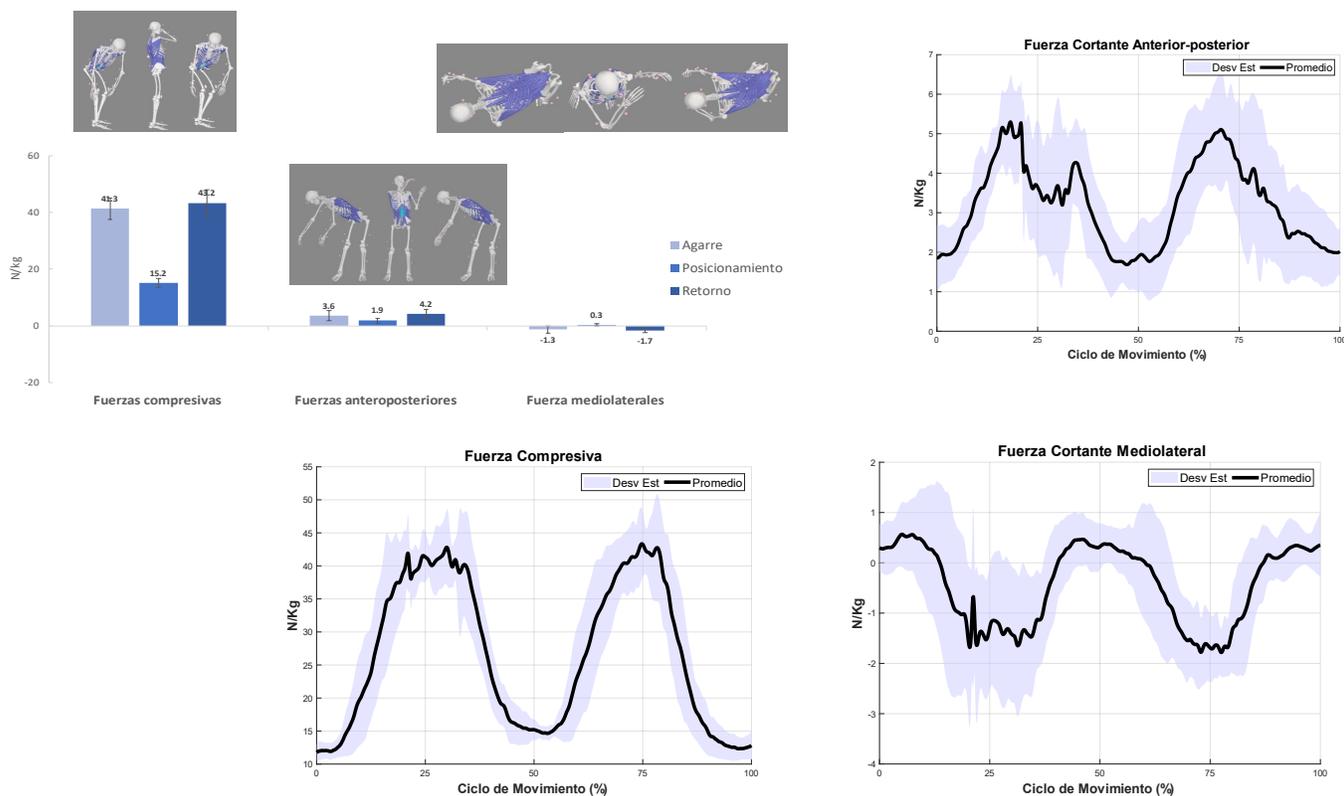


Figure 6. Average pattern of L5/S1 forces

Table 3. Coefficient of variation of forces

	Phase A (Grasping)			Phase B (Positioning)			Phase C (Returning):		
	Compressive force	Mediolateral force	Anteroposterior force	Compressive force	Mediolateral force	Anteroposterior force	Compressive force	Mediolateral force	Anteroposterior force
	SEGMENTO L5/S1								
MEAN	41.28	3.63	-1.27	15.22	1.89	0.32	43.20	4.18	-1.70
DS	3.75	1.69	1.24	1.56	0.88	0.46	4.77	1.65	0.69
CV	0.09	0.47	-0.98	0.10	0.46	1.43	0.11	0.39	-0.41

4. Discussion

The results of this study show that lifting heavy objects involves a multiaxial kinematic pattern characterized by peaks of flexion (29.6°), lateral bending (25.4°), and trunk rotation (14.4°) during the active phase of the movement. The literature has pointed out that the combined movements in multiple planes, such as those observed in this case, increase compressive and shear forces on the lumbar segments (Coenen et al., 2014; Hilmi, Hamid, & Ibrahim, 2024), creating a mechanical environment prone to overuse and structural wear, even in tasks with moderate loads.

At the kinetic level, the maximum compressive force estimated in the L5/S1 segment reached 3349 N, a value close to the threshold of 3400 N established by Chaffin et al. (2007) (Chaffin & Page, 1994) as the recommended limit to prevent structural damage to the intervertebral disc. This proximity is biomechanically significant when considering that the load handled was only 10 kg, which shows that it is not only the weight that determines the level of vertebral stress, but also the configuration of the movement, characterized by combined flexion, lateral bending, and rotation. This combination can increase the magnitude of compressive and shear forces, especially in asymmetrical tasks such as lifting packages, in which the center of mass shifts outside the sagittal axis. Thus, accurate estimation of these forces allows for a better understanding of the potential risk associated with common functional movements in physically demanding work environments.

Another interesting finding was the biphasic behavior of the loads: the compression peaks were concentrated during the initiation and return of the movement, while the intermediate phase—when the package stabilizes on the shoulder—showed a significant reduction in loads (up to 15.2 N/kg). This transition between high- and low-demand phases has previously been described by Marras & Schoenmarxlin (1993) (Marras, Ferguson, Lavender, Splittstoesser, & Yang, 2014) as a component in the accumulation of spinal fatigue, especially in repetitive tasks.

In addition, marked inter-subject variability was observed in the frontal and transverse planes, with differences in the sequence and amplitude of joint angles, despite standardized instructions. This variability evidence individual postural compensation strategies influenced by factors such as motor control, experience, and joint mobility (Carnegie, Zehr, Howarth, & Beach, 2022; Phan et al., 2022). Despite this variability in movement, vertebral compressive forces showed low coefficients of variation ($CV < 0.15$), possibly due to the anthropometric homogeneity of the sample and the use of a standardized load.

The integration of OpenCap and OpenSim allowed for the non-invasive estimation of internal forces in the lumbar spine during a functional loading movement, overcoming the limitations of observational methods. While OpenCap offers an accessible solution for capturing three-dimensional kinematics, its musculoskeletal model restricts the detailed analysis of lumbar segments, requiring its use to be complemented with more detailed models in OpenSim. This methodological combination, although dependent on certain technological resources, represents a viable alternative for biomechanical studies in environments with infrastructure and technology limitations, such as many of those present in Latin America.

4. Conclusions

This study characterized trunk biomechanics during manual load lifting, a common task in construction. Even with moderate loads, combined trunk motions produced compressive forces near risk thresholds, highlighting the importance of postural patterns in risk assessment. The integration of OpenCap and OpenSim enabled robust kinematic and kinetic estimations, though detailed analysis still requires specialized equipment. Nonetheless, accessible open-source tools offer valuable opportunities to advance ergonomic research in Latin America and support the development of context-specific preventive strategies.

5. References

- Adhikari, B., Ghimire, A., Jha, N., Karkee, R., Shrestha, A., Dhakal, R., ... Bhandari, N. (2021). Factors associated with low back pain among construction workers in Nepal: A cross-sectional study. *PLOS ONE*, *16*(6), e0252564. doi:10.1371/journal.pone.0252564
- Akhavanfar, M. H., Brandon, S. C. E., Brown, S. H. M., & Graham, R. B. (2019). Development of a novel MATLAB-based framework for implementing mechanical joint stability constraints within OpenSim musculoskeletal models. *Journal of Biomechanics*, *91*, 61–68. doi:10.1016/j.jbiomech.2019.05.007
- Carnegie, D. R., Zehr, J. D., Howarth, S. J., & Beach, T. A. C. (2022). Kinematic adaptations to restricting spine motion during symmetrical lifting. *Journal of Electromyography and Kinesiology*, *67*, 102716. doi:10.1016/j.jelekin.2022.102716
- Chaffin, D. B., & Page, G. B. (1994). Postural effects on biomechanical and psychophysical weight-lifting limits. *Ergonomics*, *37*(4), 663–676. doi:10.1080/00140139408963681
- Coenen, P., Gouttebauge, V., van der Burght, A. S. A. M., van Dieën, J. H., Frings-Dresen, M. H. W., van der Beek, A. J., & Burdorf, A. (2014). The effect of lifting during work on low back pain: a health impact assessment based on a meta-analysis. *Occupational and Environmental Medicine*, *71*(12), 871–877. doi:10.1136/oemed-2014-102346
- CPWR – The Center for Construction Research and Training. (2018). *The Construction Chart Book: The U.S. Construction Industry and Its Workers*. (CPWR, Ed.) (Sixth Edition).
- Cuchanski, M., Cook, D., Jegapragasan, M., Whiting, D. M., & Cheng, B. C. (2010). Measurement of disc bulge of the intervertebral disc: An in vitro study using human cadaver lumbar spine segments. *ArgoSpine News and Journal*, *22*(2), 73–80. doi:10.1007/s12240-010-0016-0
- Dawad, N. A., Yasin, S. M., Darus, A., Jamil, A. T., & Naing, N. N. (2024). Modification of the Revised National Institute for Occupational Safety and Health (NIOSH) Lifting Equation to Determine the Individual Manual Lifting Risk in Malaysia's Manufacturing Industry. *Cureus*, *16*(4).
- Debrah, Y. A., Jabaru, A. C., Nyuur, R. B., Ellis, F., & Banoeng-Yakubo, J. (2023). Human resource management and development in construction: Strategic considerations. In *Routledge Handbook on Labour in Construction and Human Settlements* (pp. 158–176). Routledge.
- Delp, S. L., Anderson, F. C., Arnold, A. S., Loan, P., Habib, A., John, C. T., ... Thelen, D. G. (2007). OpenSim: open-source software to create and analyze dynamic simulations of movement. *IEEE Transactions on Biomedical Engineering*, *54*(11), 1940–1950.
- Donisi, L., Cesarelli, G., Capodaglio, E., Panigazzi, M., Addio, G. D', Ponsiglione, A. M., & Romano, M. (2022). *Biomechanical risk classification according to NIOSH in workers affected by occupational pathologies*. In *2022 E-Health and Bioengineering Conference (EHB)* (pp. 1–4). IEEE. doi:10.1109/EHB55594.2022.9991311
- Escamilla, S. M. (2015). Prevalencia de desórdenes musculoesqueléticos y diseño de un manual de promoción de la salud y prevención de esta patología en trabajadores de la obra entre verde, de la empresa Construcciones Tarento SAS.
- Estrada Muñoz, J., Camacho Pérez, J. A., Restrepo Calle, M. T., & Parra Mesa, C. M. (1998). Parámetros antropométricos de la población laboral colombiana 1995 (Acopla95).
- Ghezelbash, F., Shirazi-Adl, A., Arjmand, N., El-Ouaaid, Z., & Plamondon, A. (2016). Subject-specific biomechanics of trunk: musculoskeletal scaling, internal loads and intradiscal pressure estimation. *Biomechanics and Modeling in Mechanobiology*, *15*, 1699–1712.
- Hilmi, A. H., Hamid, A. R. A., & Ibrahim, W. A. R. A. W. (2024). Current trends and risk factors in low back pain: An ergonomic perspective on prevention and management. *Malaysian Journal of Ergonomics (MJER)*, *6*, 105–118.
- Khoddam-Khorasani, P., Arjmand, N., & Shirazi-Adl, A. (2020). Effect of changes in the lumbar posture in lifting on trunk muscle and spinal loads: A combined in vivo, musculoskeletal, and finite element model study. *Journal of Biomechanics*, *104*, 109728.
- Marras, W. S., Ferguson, S. A., Lavender, S. A., Splittstoesser, R. E., & Yang, G. (2014). Cumulative Spine Loading and Clinically Meaningful Declines in Low-Back Function. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *56*(1), 29–43. doi:10.1177/0018720813496814
- Marras, W. S., & Schoenmarxlin, R. W. (1993). Wrist motions in industry. *Ergonomics*, *36*(4), 341–351.
- Neusa Arenas, G., Saraguro Piarpuezan, R. V., Jiménez Rey, J. F., & Navarrete Arboleda, E. D. (2024). *Prevalence of Manual Handling of Loads and Its Pathologies in Workers in the Construction Industry*. In *International Conference on Applied Engineering and Innovative Technologies* (pp. 158–166). Springer.

- Nogareda, S., & Canosa, M. d. (2016). Levantamiento manual de cargas: ecuación del NIOSH. *Instituto Nacional de Seguridad e Higiene Del Trabajo, España*.
- Perdomo, G. T., Panameño, C. L. M., Polanco, M. C. C., Valderrama, M. A. C., & Agudelo, A. T. M. (2025). Caracterización de desórdenes músculo esqueléticos más frecuentes de origen laboral en Colombia. *SIGNOS-Investigación En Sistemas de Gestión*, 17(1), 130–148.
- Phan, T. C., Pranata, A., Farragher, J., Bryant, A., Nguyen, H. T., & Chai, R. (2022). Machine Learning Derived Lifting Techniques and Pain Self-Efficacy in People with Chronic Low Back Pain. *Sensors*, 22(17), 6694. doi:10.3390/s22176694
- Pinto, W. J. C. (2015). Factores asociados a la enfermedad discal lumbar de origen laboral, calificados por la junta de calificación de invalidez regional de Meta (Colombia). *Revista Colombiana de Salud Ocupacional*, 5(4), 18–22.
- Roy, S. K., & Koehn, E. (2006). *Construction labor requirements in developing countries*. In *2006 GSW*.
- Salazar, L. G., Quiñones, J. A., & Arango, S. P. (2024). *OpenCap and OpenSim for the 3D Kinematic Analysis of Load Handling Tasks Performed in Construction*. In *2024 International Symposium on 3D Analysis of Human Movement (3DAHM)* (pp. 1–5). IEEE. doi:10.1109/3DAHM62677.2024.10920740
- Senteler, M., Weisse, B., Rothenfluh, D. A., & Jess, G. (2016). Intervertebral reaction force prediction using an enhanced assembly of OpenSim models. *Computer Methods in Biomechanics and Biomedical Engineering*, 19(5), 538–548. doi:10.1080/10255842.2015.1043906
- Uhlrich, S. D., Falisse, A., Kidziński, Ł., Muccini, J., Ko, M., Chaudhari, A. S., ... Delp, S. L. (2022). OpenCap: 3D human movement dynamics from smartphone videos. *BioRxiv*, 2022.07.07.499061. doi:10.1101/2022.07.07.499061
- Verheul, J., Robinson, M. A., & Burton, S. (2024). Jumping towards field-based ground reaction force estimation and assessment with OpenCap. *Journal of Biomechanics*, 166, 112044.
- Winiarski, S., Molek-Winiarska, D., & Chomałowska, B. (2025). From Motion to Prevention: Evaluating Ergonomic Risks of Asymmetrical Movements and Worker Well-Being in an Assembly Line Work. *Applied Sciences*, 15(2), 560. doi:10.3390/AP15020560