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Biomechanical Effects on Lower Extremities in Human-Robot Collaborative Agricultural Tasks

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Abstract: The present study pertains to a key aspect of human-robot collaborative systems which is usually underestimated, namely occupational health prolepsis. The aim of this investigation was to assess the biomechanical effects of manual symmetric load lifting related to a synergistic agricultural task that utilizes an unmanned ground vehicle to undertake the carriage of loads. Towards that goal, kinetic and kinematic data were collected from the lower extremities of thirteen experienced workers, by testing three different deposit heights (70, 80, 90 cm) corresponding to possible adjustments of the available agricultural robot. Moreover, the muscle activation levels of three lower extremity muscles and one trunk muscle were evaluated via a wireless electromyography system. Overall, the experimental findings revealed that the lower examined load height was associated with larger knee flexion moments and hip extension moments. Nevertheless, this height was related to lower activation mainly of the erectus spinae muscles. Finally, insignificant alterations were observed for the ankle joint as well as the activation levels of the other muscles. Consequently, a height equal to 90 cm is suggested, however, by avoiding extreme lumbar postures. The current results can be exploited for possible ergonomic interventions concerning the optimal deposit height of a robotic platform when a similar case is designed.

Keywords: experienced workers; symmetric load lifting; musculoskeletal disorders; direct measurement methods; kinematic and kinetic data; electromyography; ergonomics; occupational health prolepsis

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1. Introduction

Agriculture has experienced a lot of technological changes that have contributed towards rendering farms to be more efficient, profitable, and environmentally friendly [1]. However, despite its remarkable modernization, this sector is still considered particularly hazardous [2,3], indicating that health and safety of the farmers are usually ignored or underestimated [4]. Among the most prevalent non-fatal health problems in the agricultural sector, musculoskeletal disorders (MSDs) have reached disquieting proportions [5,6]. The term MSDs involves a host of disorders and injuries, such as tendinitis, osteoarthritis, low-back pain, sprains, and tears. Additionally, disorders related to the contact of the worker with vibrating machinery parts, like hand-arm vibration and carpal tunnel syndromes, are particularly frequent among farmers [7–9].

MSDs primarily originate from labor-intensive manual practices, which are quite common in agriculture owing to either the farmer's incapability to afford the corresponding machinery or the peculiarity of the crop maintenance that necessitates gentle handling [10]. These manual operations usually require iterative hand work, sustained or repetitive trunk bending and kneeling, as well as heavy load carriage and lifting [11]. Focusing on the last activity, agricultural tasks commonly entail the worker to lift a heavy load by bending forward or laterally, twisting, or/and maintaining a static body posture. A plethora of epidemiological studies have highlighted the strong association between lifting and injuries in the region of the low-back [12,13]. As a consequence, estimating the spinal loading during lifting has plausibly attracted the interest of ergonomists and clinicians. Indicatively, Hoozemans et al. [14] concluded that load height and mass are significant determinants of low-back load, as lower heights and higher masses are linked with higher loads in the low-back region. Sorensen et al. [15] explored the lifting stance width, showing that they have an important effect on lifting kinematics, but no significant effect on muscle activation levels of the trunk as well as those of lower extremities. Lavender et al. [16] dealt with the effects of lifting speed, deducing that faster lifts are associated with higher sagittal plane moments. Overall, the so-called revised NIOSH (National Institute for Occupational Safety and Health) lifting equation is widely accepted to assess the risks related to back injuries during lifting. In particular, the Recommended Weight Limit (RWL) is provided by:

$$RWL = LC\ (51) \times HM \times VM \times DM \times AM \times FM \times CM \quad (1)$$

The basic variables to be considered in the above equation are as follows: (a) The horizontal distance of the load relative to the body (HM), (b) The vertical distance of the load relative to the ground (VM), (c) The vertical distance between the initial and destination lift point (DM), (d) The angle of asymmetry (AM), (e) The frequency and time span of lifting (FM), and (f) The coupling of the worker's grip on the object (CM). Finally, the NIOSH equation utilizes a load constant (LC) equal to 51 pounds, representing the maximal load weight recommended under ideal conditions [17,18].

Another factor that has to be taken into account is the experience of workers, since experienced workers tend to use different lifting techniques, as for example bending their lumbar region less and more their knees [19] compared to novice ones. In general, the most incorporated techniques are stooping, squat, and semi-squat, with the first technique adopted by the majority of farmers and linked with low-back disorders in the agricultural sector [20]. There is a remarkable debate pertaining to the best lifting technique, as trying to alter lifting habits may lead to even worse ramifications, as underlined by Del Vecchio [21]. Apart from the above indicative studies, there are some others dealing with multiple-task manual material handling, such as those of Harari et al. [22,23], involving continuous box removing, carrying, and depositing, who investigated spinal and shoulder moments and kinematics. Harari et al. [24] also measured spinal moments as well as trunk and knee kinematics for the above experimental procedure.

Another MSD, which is usually disregarded in agricultural operations and can be provoked or aggravated by the cumulative mechanical stresses during heavy and repetitive lifting, is osteoarthritis mainly in the regions of hip and knee joints [25–27]. This arduous task was identified as an activity that can increase significantly knee moments, hence, indicating potential gonarthrosis-inducing hazards, as stated by Sahlström et al. [28]. Overall, osteoarthritis, as well as the other MSDs, can undermine a worker's quality of life and are considered to be among the primary causes of absence from work. Thus, substantial expenses may arise for farm owners pertaining to health care, disability, compensation, and other socioeconomic costs [29–31]. Consequently, MSDs constitute a principal source of socioeconomic costs, while their prevalence tends to increase with age [32]. Taking into account that the average age of farmers is steadily increasing [33] and the fact that agriculture employs a considerable number of workers, the problem seems to be reaching epidemic proportions on a global scale [25]. Policies supported by organizations, like the International Labour Organization (ILO), are increasingly seeking to prevent MSDs by promoting an Occupational Safety and Health (OSH) culture so as to alleviate hazards inherent in agricultural working environments.

Considering that MSDs are progressive in nature, the investigation of the connection between MSDs and non-neutral postures can be problematic. The majority of the relative studies in agriculture are driven mainly by special questionnaires [11], where the participants usually have to answer to yes-or-no questions or mark, approximately, the most affected body parts [34,35]. On the one hand, the questionnaires can help, to some extent, to filter the reported MSDs. On the other hand, they cannot be purely employed for a medical diagnosis, due to the above-mentioned progressive feature of MSDs. In contrast, direct measurement methods have the potential to provide more efficient evidence. A key aspect regarding the agreement between questionnaires and physical examination is pain intensity [36]. Consequently, while direct measurement methods can provide unbiased information by measuring the absolute structures and tissue performance, self-reported symptoms typically rely on sensation affected by pain perception [37]. Based on the technological progress in Information and Communication Technology (ICT), experimental measurements concerning manual agricultural tasks can exploit a wide range of sensors. Indicatively, ICT, used for these kinds of measurements, usually involves dynamometers [38], electrocardiograph [39], optical markers [40], electrogoniometers, electromyography (EMG), and accelerometers [41,42], as well as fusion of different sensors [43].

Focusing on load lifting and carriage, some ergonomic interventions have been proposed for agricultural operations such as "easy lift" and "ergo bucket carrier", which can reduce the risk of low-back disorder by 55% and 41%, respectively [44]. Furthermore, exoskeletons (also known as weight transfer devices) have been tested as an intervention strategy to reduce the risk of back pain. These devices are wearables structures which mechanically support the workers during flexed postures by storing the static energy of their weight in torsional springs and facilitating return to the upright position [45]. Although the results of using exoskeletons during farming lifting tasks are encouraging, more follow up field studies need to be carried out to verify their long-term potential benefits, as stated in several studies such as [42,46–48].

Interestingly, Unmanned Ground Vehicles (UGVs) have been suggested in order to carry crops, like apples, to be stored at the end of the row [49]. More specifically, a UGV or a fleet of UGVs can follow the farmers as they harvest the crops, while the worker can place the crates onto the upper surface of the UGV. Certainly, this is a versatile and multidisciplinary problem [50], since it requires optimal contribution of several challenges associated with Human-Robot Interaction (HRI), including Artificial Intelligence [51], Internet of Things (IoT) [52], and ergonomics [53]. For the purpose of providing a sustainable and feasible solution, each factor should be examined independently, at a preliminary stage, before a holistic handling is implemented [54].

The present study pertains to an integral element of such kind of HRI, namely the health prolepsis of the worker in agriculture, which is of major importance in the human-centered design of collaborative systems [43,53]. In particular, the subject of this paper is the physical examination of the symmetric lifting task, by means of direct measurement methods, at three different deposit heights representing possible alterations of the available UGV. To this end, the recording of both kinetic and kinematic data at hip, knee, and ankle joints, as well as that of the activity levels of different muscles, took place at an experimental physiology laboratory. In addition, the majority of the relevant studies usually involved inexperienced participants in manual material handling [15,22,24]. This fact can cause limitations in relation to the generalizability of the results, since they can lead to misleading conclusions regarding the joint loading and muscle activation patterns, as has been highlighted by relevant studies [15,19]. To address this limitation and assure the reliability of the results, only seasonal workers having experience in crop harvesting and crate lifting took part in our study. To our knowledge, no similar investigation exists in the relative literature, which focuses mainly on the lower extremities for this particular human–robot collaborative application, by considering a comprehensive combination of direct measurement methods and involving experienced workers.

2. Materials and Methods

2.1. Experimentation Setup

The proposed synergistic task involves a worker whose job is to harvest the crops and place them in a crate. Once the crate is full, a UGV approaches the worker and stops in front of him/her. Then, the worker lifts the crate from the ground and places it onto the UGV, which, in turn, carries the crate to the desired site. In this context, an available UGV, namely Thorvald, may be used that can perform a lot of labor-intensive and repetitive agricultural tasks in different production systems, like open fields and greenhouses [55]. A schematic representation of the above description can be seen in Figure 1, showing Thorvald utilized in a recent pilot study in Thessaly, located in central Greece, for carrying walnuts in the framework of the SYNERGIE research project [56]. In this fashion, it should be mentioned that for the purpose of establishing a safe coexistence of humans and UGV, human activity "signatures" should be identified by the latter, as presented in [43,57].

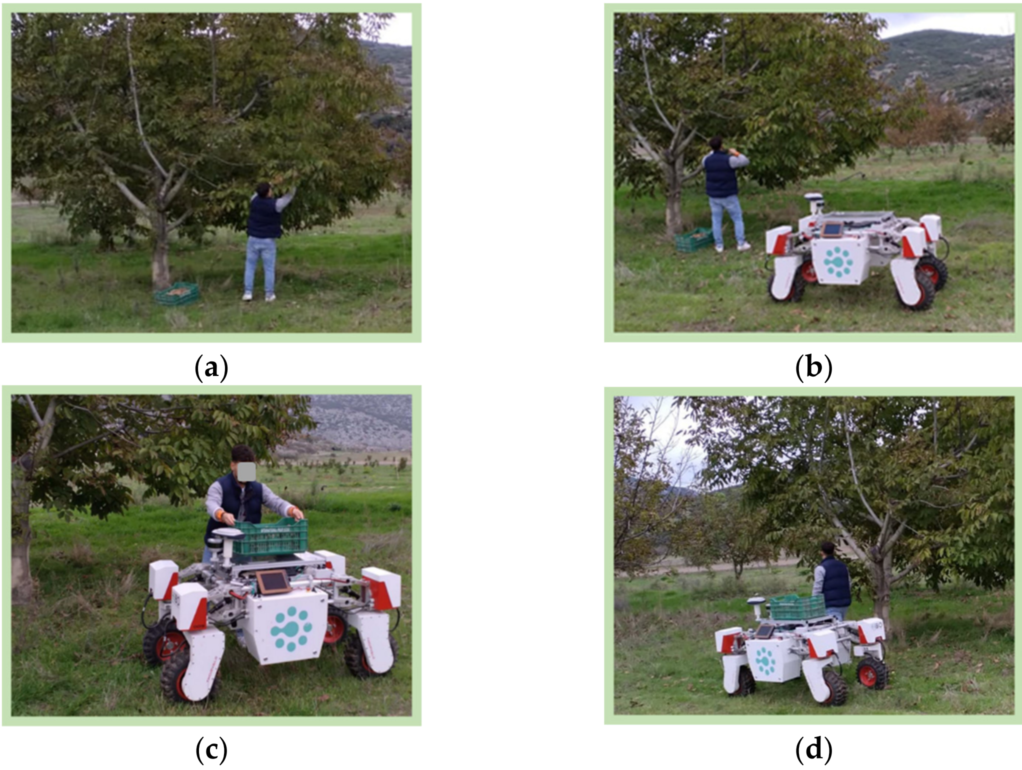


Figure 1. Images taken from a pilot study showing: (**a**) The worker harvesting walnuts, (**b**) the UGV approaching the worker, (**c**) the worker lifting the crate onto the UGV, and (**d**) the UGV carrying the crate towards the desired site.

The present study focuses on the symmetric lifting task depicted in Figure 1c. Specifically, as a means of acquiring the required kinetic and kinematic data from the participants, the lifting task was carried out in an especially equipped physiology laboratory with a custom-made shelf instead of the real UGV to avoid visual occlusion problems related to marker-based optical technologies [58]. Finally, marker trajectories, Ground Reaction Forces (GRFs) and EMG data were synchronized, recorded, and pre-processed by using a modelling and processing software appropriate for that kind of scope. A graphical abstract of the present concept is provided in Figure 2.

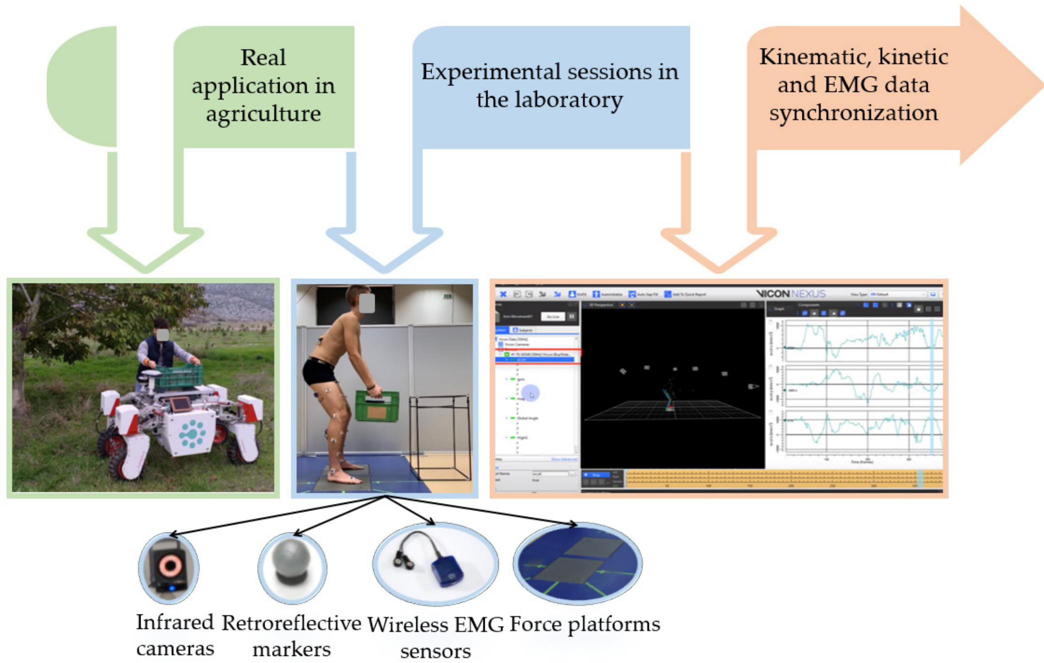


Figure 2. Schematic representation of the real application in agriculture and the emulation of the lifting task in a laboratory along with the utilized equipment, and the Vicon Nexus software used for synchronizing the collected data.

2.1.1. Participants

Thirteen (n = 13) moderately active seasonal workers aged between 20–30 years old volunteered to participate in this study. The mean height and body weight of the participants were 177.5 ± 4.9 cm and 77.6 ± 9.2 kg, respectively. The participants had to meet two basic eligibility criteria:

- To be free from any MSD (e.g., low-back discomfort, knee or hip pain, ankle sprain) 6 months prior to participating in the study.
- To have had experience in agricultural material handling (for at least two years).

All participants were informed about the testing procedures and potential risks and signed a consent form, which was approved by the Institutional Ethical Committee.

2.1.2. Data Collection

A modified marker set was employed consisting of twenty-four retroreflective markers positioned bilaterally over selected anatomical landmarks and locations of the pelvis and lower limbs [59], based on Schwartz and Rozumalski [60]. Lifting kinematics were captured by using 10 infrared cameras (Vicon T-series, Oxford, UK), sampling at 100 Hz, whereas lifting kinetics were captured by two force platforms (Bertec 4060-10, OH) embedded in the laboratory floor and sampling at 1000 Hz. EMG data were collected at 1000 Hz with a Myon MA-320 wireless EMG system (Myon AG, Switzerland) from the Vastus Medialis (VM), the Biceps Femoris (BF), the Medial Gastrocnemius (MG), and the Erectus Spinae (ES) of the same side.

The dominant limb was defined as the participant's preferred limb when kicking a ball [61]. The skin was shaved and meticulously cleaned with alcohol before placing bipolar surface electrodes (Noraxon USA, Scottsdale, AZ, USA) on the selected muscles (2 cm interelectrode distance) based on the SENIAM guidelines. Finally, kinematic, kinetic, and EMG data were synchronized utilizing Vicon Nexus software.

2.1.3. Experimental Protocol

Prior to data collection, anthropometric measurements (body mass, height, leg length, knee width, and ankle width) were recorded according to the Plug-in-Gait lower body model [62]. Additionally, the participants were familiarized with the symmetrical lifting task (Figure 2). This task can be simply defined as the action of grasping a crate (or an object in general) by using two hands and moving that crate vertically without mechanical assistance. Subsequently, the participants performed a standardized warm-up that included 7 min of jogging (2.5 m/s) on a treadmill (Technogym, Italy) and 3 min whole-body stretching exercises. The lifting task was executed, while the participants stood on the two force platforms (each limb on a separate platform). In particular, the participants were asked to lift symmetrically a commonly used agricultural crate (31 cm (height) × 53 cm (width) × 35 cm (depth)) with handles on both sides at 28 cm height above its base, similar to [43]. Additionally, the crate was positioned 10 cm in front of the participant's toes with both feet fixed on the platforms (shoulder width) to a custom-made shelf with three adjustable heights (70, 80, and 90 cm). These heights correspond approximately to the deposit heights that Thorvald can have depending on possible adjustments [43].

No specific instructions were given to the participants regarding the lifting technique (e.g., stoop, squat, semi-squat) and speed [14]. The load magnitude during the lifting test was set equal to 20% of each participant's body mass [16,43]. A total of 9 trials (3 per height destination) was performed in a randomized order. Each trial was separated by 30 s of rest to avoid neuromuscular fatigue.

2.2. Data Analyses

The hip joint center and knee joint flexion axis were determined by applying the symmetrical center of rotation estimation (SCoRE) [63] and the symmetrical axes of rotation approach (SARA) [64], respectively. This approach was combined with the Plug-in-Gait model [62] to calculate joint kinematics and kinetics according to the Vicon Nexus Advanced Gait Workflow (Nexus 2.10, Vicon Metrics Group Ltd., Oxford, UK). The kinematic and kinetic data were lowpass filtered using a 4th order Butterworth filter with cutoff frequencies of 6 and 25 Hz, respectively [65]. Standard inverse dynamics calculations were performed combining inertial properties of the segments, GRFs, and kinematic data to extract the maximal joint moments of the dominant lower limb during the execution of the symmetric lifting task. Vertical GRFs were calculated as a percentage of body weight, whereas the hip, knee, and the ankle internal joint moments, and power were normalized to body mass. The lifting task employed in this study was separated into three phases, according to the literature [66]. More specifically:

- The first phase was defined between the initiation of the trial and the completion of the forward bending motion to reach the agricultural crate.
- The second phase lasted from the latter time point until lifting-up the crate.
- The third phase was defined between the completion of the second phase and the landing of the crate on the custom-made shelf.

Selected vertical GRFs along with kinematic and kinetic variables of the dominant limb (described in Table 1) were calculated for the aforementioned phases in each trial and averaged across the three trials performed at each height (Figure 3). Joint power was calculated by multiplying the net joint moment by the joint angular velocity [65]. The presented kinematic and kinetic variables are in the sagittal plane.

The raw EMG data during the lifting task were filtered using a Butterworth bandpass filter (20–500 Hz), before applying an RMS algorithm (50 ms sampling window) [67]. Afterwards, the EMG data at the three selected heights were normalized to the EMG signals recorded at the lowest destination height (i.e., 70 cm). Finally, the peak and mean normalized RMS EMG were computed during the three phases of the lifting task.

Table 1. Description of the variables used in the present analysis.

Variables	Units	Description
GRF1	% BW	Minimum VGRF during phase 1
GRF2	% BW	Maximum VGRF during phase 2
GRF3	% BW	Minimum VGRF between phases 2 and 3
GRF4	% BW	Maximum VGRF during phase 3
KNEE MOMENT 1	Nm/kg	Maximum knee extension moment during phase 1
KNEE MOMENT 2	Nm/kg	Maximum knee flexion moment during phase 2
KNEE MOMENT 3	Nm/kg	Maximum knee flexion moment during phase 3
KNEE ANGLE MAX	degrees	Maximum knee flexion angle
HIP ANGLE MAX	degrees	Maximum hip flexion angle
HIP MOMENT 1	Nm/kg	Maximum hip extension moment during phase 1
HIP MOMENT 2	Nm/kg	Maximum hip extension moment during phase 3
ANKLE ANGLE MAX	degrees	Maximum dorsiflexion angle
ANKLE MOMENT 1	Nm/kg	Maximum dorsiflexion moment during phase 1
ANKLE MOMENT 2	Nm/kg	Maximum dorsiflexion moment during phase 3
KNEE POWER 1	W/kg	Maximum knee absorption power
KNEE POWER 2	W/kg	Maximum knee generation power
HIP POWER 1	W/kg	Maximum hip absorption power
HIP POWER 2	W/kg	Maximum hip generation power
ANKLE POWER 1	W/kg	Maximum ankle absorption power
ANKLE POWER 2	W/kg	Maximum ankle generation power during phase 2
ANKLE POWER 3	W/kg	Maximum ankle generation power during phase 3

BW: Body Weight; GRF: Ground Reaction Force; VGRF: Vertical Ground Reaction Force.

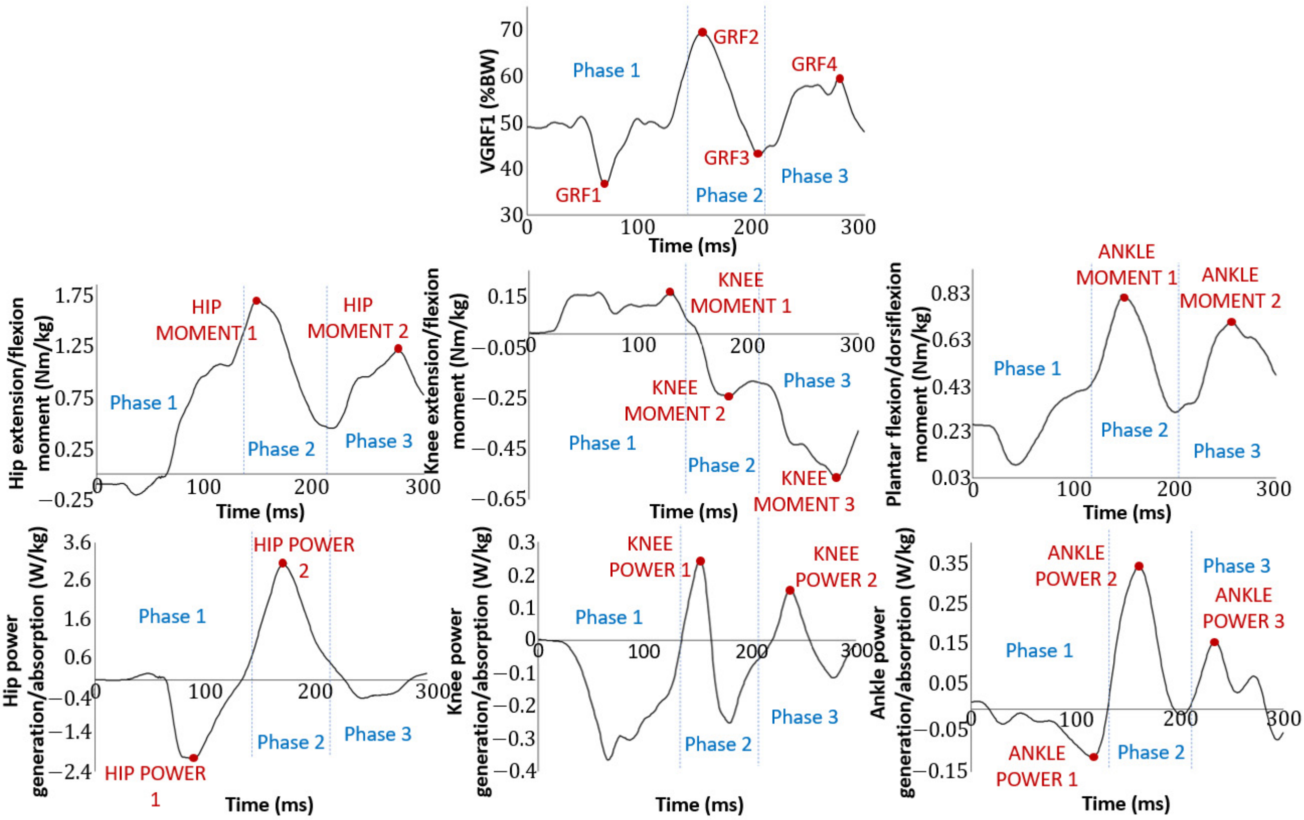


Figure 3. Selected kinetic variables during the symmetric lifting test. Please, refer to Table 1 for full variable description.

As far as the statistical analysis is concerned, the normal distribution was investigated using the Shapiro–Wilks test and did not differ significantly from normal. One-way ANOVA (three destination lifting heights) with repeated measures was used and existing significant interactions were examined using Bonferroni post hoc analysis. A significance level of $p < 0.05$ was set for all statistical tests, similar to the relative literature [15].

3. Results

The measured GRFs, kinematic and kinetic variables during the symmetric lifting task for the three deposit heights are presented in Table 2. Overall, significant interactions were observed for KNEE MOMENT 3, KNEE ANGLE MAX, and HIP MOMENT 2. In particular, post hoc analysis showed that KNEE MOMENT 3 was significantly higher while performing the lifting task with 70 cm deposit height compared to 80 cm ($p < 0.05$). This knee moment corresponds to phase 3, during which the participant leaves the crate on the custom-made shelf. As regards the maximum knee flexion angle, it was observed that it was significantly lower when performing the task with a height of 70 cm in comparison to the other two heights ($p < 0.05$). Moreover, HIP MOMENT 2 was significantly lower for the height of 90 cm as compared to the height of 70 cm ($p < 0.05$). No significant interactions or main effects were found for the remaining biomechanical variables examined ($p > 0.05$).

Table 2. Biomechanical variables during the symmetric lifting task for heights 70, 80, and 90 cm; data are reported as mean ± standard deviation. Please, refer to Figure 3 for the graphical representation of the selected variables and Table 1 for full variable description.

Variables	Height			*p*
	70 cm	80 cm	90 cm	
GRF1	34.81 ± 5.00	35.35 ± 5.55	36.87 ± 4.18	NS
GRF2	76.64 ± 7.33	77.69 ± 6.88	74.63 ± 5.73	NS
GRF3	43.08 ± 7.77	45.39 ± 5.76	44.98 ± 4.60	NS
GRF4	63.22 ± 6.58	62.39 ± 4.06	62.50 ± 5.70	NS
KNEE MOMENT 1	0.65 ± 0.34	0.69 ± 0.27	0.74 ± 0.27	NS
KNEE MOMENT 2	−0.27 ± 0.16	−0.25 ± 0.13	−0.22 ± 0.10	NS
KNEE MOMENT 3	−0.91 ± 0.32	−0.82 ± 0.26	−0.81 ± 0.24	<0.05
KNEE ANGLE MAX	88.55 ± 17.59	91.93 ± 17.94	93.44 ± 17.42	<0.05
HIP ANGLE MAX	101.45 ± 4.40	101.50 ± 4.95	101 ± 6.20	NS
HIP MOMENT 1	1.73 ± 0.20	1.78 ± 0.25	1.75 ± 0.24	NS
HIP MOMENT 2	1.34 ± 0.26	1.22 ± 0.28	1.11 ± 0.22	<0.05
ANKLE ANGLE MAX	28.26 ± 10.82	29.33 ± 11.11	29.01 ± 9.99	NS
ANKLE MOMENT 1	0.97 ± 0.16	0.97 ± 0.15	0.92 ± 0.15	NS
ANKLE MOMENT 2	0.92 ± 0.15	0.90 ± 0.14	0.89 ± 0.15	NS
KNEE POWER 1	−1.12 ± 0.51	−1.03 ± 0.40	−1.07 ± 0.63	NS
KNEE POWER 2	0.94 ± 0.81	1.03± 0.77	1.05 ± 1.10	NS
HIP POWER 1	−1.84 ± 0.44	−1.88 ± 0.58	−1.76± 0.49	NS
HIP POWER 2	3.14 ± 0.84	3.30 ± 0.91	3.11 ± 0.72	NS
ANKLE POWER 1	−0.21 ± 0.09	−0.21 ± 0.09	−0.18 ± 0.07	NS
ANKLE POWER 2	0.69 ± 0.39	0.63 ± 0.21	0.64 ± 0.29	NS
ANKLE POWER 3	0.20 ± 0.07	0.21 ± 0.09	0.20 ± 0.57	NS

GRF: Ground Reaction Forces; NS: Non-Significant.

The results regarding the EMG measurements are presented in Table 3. In brief, interactions were noted for three variables, namely Mean EMG VM during phase 1, Peak EMG VM during phase 1, and Peak EMG ES during phase 1 ($p < 0.05$). Post hoc analysis demonstrated that for the Mean EMG VM and Peak EMG ES during phase 1, the EMG activity was higher while lifting the agricultural crate with a destination height of 90 compared to 70 cm ($p < 0.05$). On the other hand, Peak EMG VM during phase 1 was higher for both 80 and 90 cm heights compared to 70 cm ($p < 0.05$). No significant differences were observed for the EMG variables during the other two phases ($p > 0.05$).

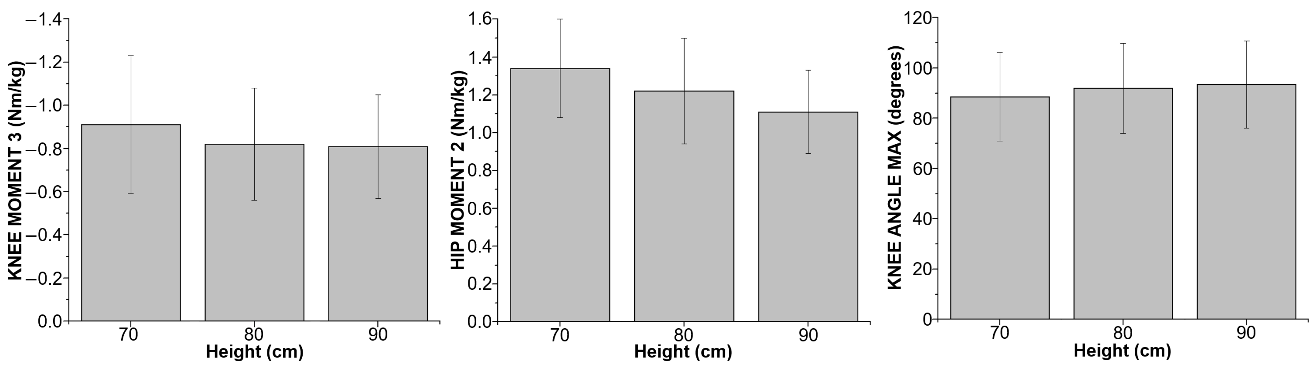
Table 3. Peak and mean normalized RMS EMG values during the three phases of the symmetric lifting task for heights 70, 80, and 90 cm; data are reported as mean ± standard deviation.

Variables	Height			*p*
	70 cm	80 cm	90 cm	
Mean EMG VM (Phase 1)	100 ± 0	114.60 ± 28.61	116.76 ± 22.41	<0.05
Peak EMG VM (Phase 1)	100 ± 0	130.14 ± 42.82	126.49 ± 36.37	<0.05
Mean EMG VM (Phase 2)	100 ± 0	109.11 ± 36.26	99.46 ± 28.44	NS
Peak EMG VM (Phase 2)	100 ± 0	122.61 ± 27.63	111.98 ± 26.99	NS
Mean EMG VM (Phase 3)	100 ± 0	97.01 ± 25.11	107.06 ± 35.99	NS
Peak EMG VM (Phase 3)	100 ± 0	86.85 ± 37.29	115.96 ± 63.73	NS
Mean EMG ES (Phase 1)	100 ± 0	98.43 ± 17.34	113.94 ± 23.35	NS
Peak EMG ES (Phase 1)	100 ± 0	118.04 ± 39.98	122.03 ± 30.31	<0.05
Mean EMG ES (Phase 2)	100 ± 0	104.10 ± 22.11	113.31 ± 24.35	NS
Peak EMG ES (Phase 2)	100 ± 0	97.52 ± 20.91	104.75 ± 19.66	NS
Mean EMG ES (Phase 3)	100 ± 0	99.20 ± 22.96	102.66 ± 24.07	NS
Peak EMG ES (Phase 3)	100 ± 0	101.59 ± 33.57	107.84 ± 34.97	NS
Mean EMG GASTRO (Phase 2)	100 ± 0	134.48 ± 63.20	120.52 ± 79.51	NS
Peak EMG GASTRO (Phase 2)	100 ± 0	143.11 ± 95.06	149.10 ± 197.03	NS
Mean EMG GASTRO (Phase 3)	100 ± 0	111.37 ± 36.05	104.60 ± 31.10	NS
Peak EMG GASTRO (Phase 3)	100 ± 0	114.00 ± 39.83	106.74 ± 21.09	NS
Mean EMG BF (Phase 2)	100 ± 0	115.22 ± 40.03	99.67 ± 30.77	NS
Peak EMG BF (Phase 2)	100 ± 0	127.06 ± 65.50	109.12 ± 44.57	NS
Mean EMG BF (Phase 3)	100 ± 0	100.93 ± 25.54	94.50 ± 24.11	NS
Peak EMG BF (Phase 3)	100 ± 0	91.60 ± 36.09	89.70 ± 31.13	NS

EMG: Electromyography; NS: not significant.

4. Discussion

The findings of the post hoc analysis demonstrated some statistically important differences among deposit heights, the main ones of which are depicted in the form of bar charts in Figure 4 (kinetic and kinematic variables) and Figure 5 (EMG data). It can be deduced that when the case of 90 cm was considered, the participants tended to bend their knees more compared to the other lower heights (Figure 4c). As revealed by the results of Plamondon et al. [19], who investigated the biomechanical differences between novice and experienced workers, this can be attributed to the fact that greater knee bending can bring the worker closer to the object. This is a well-known technique for decreasing the moment at the L5/S1 spinal segment [68,69]. Hence, in contrast with novice workers, the experienced ones kneel more with the intention of avoiding possible discomfort in the lumbar region. This finding reinforces our initial assumption that specific attention must be paid to the experience of participants in such kinds of experimental measurements.



(a) (b) (c)

Figure 4. Bar charts showing the mean values (± standard deviation) of the statistically important alterations: (**a**) Maximum knee extension moment, (**b**) maximum hip extension moment, and (**c**) maximum knee flexion angle for the three different deposit heights along with the standard deviation.

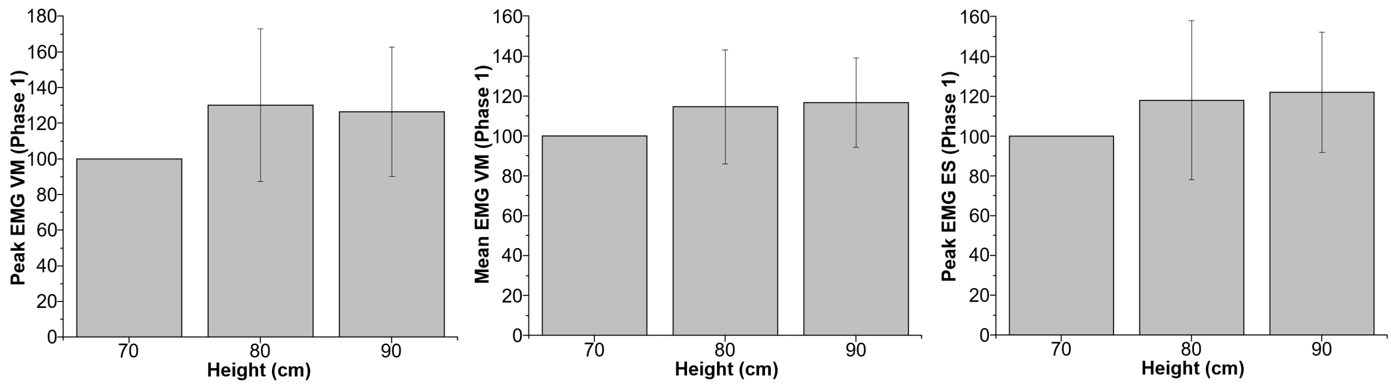


Figure 5. Bar charts showing the values (±mstandard deviation) of the statistically important alterations: (**a**) Peak EMG of VM, (**b**) Mean EMG of VM, and (**c**) Peak EMG of ES during phase 1 for the three different deposit heights along with the standard deviation.

The larger knee flexion at the higher deposit heights was accompanied, as expected, by simultaneous larger activation of VM during phase 1 (Figure 5a,b). This has also been reported by other studies like [70], who examined the squat exercise. More specifically, the muscles contract eccentrically during this phase. The increased neural activation combined with the accumulated energy while stretching the muscles possibly enhances the participants' effort during the concentric phase of the lifting task at the higher deposit heights (phases 2 and 3).

As regards the maximum knee flexion moment, this was noticed during the last phase while the participants placed the crate onto the custom-made shelf. In this phase, the higher reported values took place for the smaller height, namely at 70 cm, while their mean values were approximately 9.89% and 10.99% larger than the corresponding ones for 80 and 90 cm, respectively. This finding implies that knee loading is higher while lifting the crate at the lowest deposit height. Thus, possible knee discomfort or injury may occur, as highlighted by [28].

In the same vein with the knee extensors, the experimental measurements revealed some alterations for different heights regarding ES, the group of muscles extending the vertebral column. Similar to the findings of relevant studies such as [15], which focused mainly on the trunk kinetics and kinematics during symmetric load lifting, as the deposit height increases so does the ES activity (Figure 5c). This was an anticipated result, as the increase of load height causes greater trunk flexion and an additional moment contribution as a result of the upper body mass [14,69]. Concerning the maximum hip extension moment, it was larger during phase 3 for the case of the smallest load height (Figure 4b). More specifically, it was 8.96% and 17.16% larger than the corresponding moments for the heights of 80 cm and 90 cm, respectively. Finally, no noteworthy alterations were observed for the ankle joint and the remaining biomechanical variables, at least for the three examined heights.

Overall, the results of the present study were within the range of the values measured by Hwang et al. [71], who examined the differences between squat and stoop lifting with three different weights, however, by focusing only on the second phase of the lifting task (as described in Section 2.2). The present experimental findings can provide useful information when a case like the one examined here is designed. Representative agricultural applications are the cases of a UGV functioning as a "bin dog" with the aim of carrying apple bins during harvesting [49] and as illustrated in Figure 1 for carrying walnuts. Based on the above results, the deposit height of the crate is a considerable determinant not only of spine loading [14,72] but also for knee and hip joints, while ankles appear not to be particularly affected.

Arguably, there are a few limitations towards the generalizability of the present experimental results that must be stressed. First, the experimental measurements took place in a physiology laboratory so as to avoid visual occlusion problems, based on the available equipment and authors' expertise. Acquiring data from real-time application on the field would definitely have provided more realistic measurements. Second, as described in the second section, the experiments considered a load equal to 20% of each participant's body mass, similar to relevant studies [16,43]. This corresponds to an average load of 15.52 ± 1.84 kg, which might be lower than the ones required for some agricultural lifting tasks, thus, underestimating the muscle activation profiles as well as the kinetic and kinematic ones. Thirdly, the definition of an experienced worker is not clear in the literature [69]. Nevertheless, the present incorporated criterion (at least two years of experience) avoids using participants with no skills in manual material handling which can result in misleading conclusions [19].

In the light of the aforementioned limitations, future research could involve real loads at real conditions, depending on the agricultural application at hand, as a means of verifying the present findings and identifying other possible biomechanical responses. Moreover, taking into consideration the strong probability of an interaction among kinematics, kinetics, and EMG of the lower extremities and the low back (partially shown in this study via the EMG data of ES), data from the trunk could also be combined towards proposing a more comprehensive ergonomic solution. Apart from symmetric lifting, also asymmetric lifting could be investigated in future research studies, since the UGV can potentially approach the worker not only in front of them, but also by the side of them. In addition, other lifting task variables could be investigated associated with the NIOSH lifting equation, including the duration and frequency of lifting, the horizontal position of the crate relative to the body, and the asymmetry angle. Finally, possible interventions, like the use of back-support exoskeletons, could be evaluated for decreasing the biomechanical load and, hence, the risk of experiencing back disorders.

5. Conclusions

The central objective of the present study was the biomechanical assessment of the movement patterns of agricultural workers during symmetrical lifting of a crate onto a robotic platform that, in turn, carries it from the site of harvest to the required site. This scenario has emerged in modern agriculture as a synergistic task in the broader framework of HRI for the purpose of preventing farmers from musculoskeletal injuries related to load carriage. In particular, three deposit heights (70, 80, and 90 cm) were investigated that correspond to possible alterations of Thorvald, a commonly used agricultural UGV. To acquire the required kinematic and kinetic data, experimental sessions took place in a laboratory. Moreover, the muscle activation levels, originating from VM, ES, GASTRO, and BF, were evaluated by utilizing a wireless EMG system.

In brief, a height equal to 70 cm was related to higher values of hip extension and knee flexion moments. These findings indicate possible osteoarthritis-inducing occupational hazards in these body regions [28]. In contrast, when considering a height equal to 90 cm, higher activation levels of the erectus spinae muscles were observed. The higher values of VM activation at this height were attributed to the observed larger knee flexion, which is a technique followed by experienced workers to bring the crate closer to them [19]. No statistically important differences were found for the ankle joint and the activation of the other investigated muscles.

As a final note, assuring a safe and viable HRI in agriculture is a multidisciplinary problem connected with a lot of scientific and engineering aspects. However, ergonomics (or human factors), which is strongly related to fitting the task to the worker through the avoidance of risky activities and postures, constitutes a key element of human–robot collaborative systems as fostered by the ISO 9241-210 [73]. Last but not least, it is anticipated that the present attempt to quantify the biomechanical effects of the investigated synergistic task will contribute to more systematic research in the direction of developing an international strategy for ensuring a safe culture in the area of agriculture, as has been established in other sectors.

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