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Development of exoskeletons and motion measurement to reduce olive harvesting labor

Francesco CEPOLINA [1, *], Francesco CRENNA [2], Gabriele REVERBERI [1], Matteo ZOPPI [1]

Abstract

This paper focuses on the evaluation of passive exoskeletons designed to reduce farmers' fatigue during harvest. A preliminary infield test identifies typical harvesting, and then these motions are reproduced and analyzed under controlled conditions in the laboratory. Here, we present some biomechanical results obtained with and without two exoskeleton prototypes. The high repeatability of the recorded motions proves the consistency of the experimental procedures. Data analysis supports an objective evaluation of the exoskeleton prototypes and aids design optimization. This study has demonstrated the effectiveness of the designed exoskeletons in reducing workload in olive harvesting.

[Keywords] exoskeleton, agriculture, biomechanics, harvesting, ergonomics

1. Introduction

1.1. Olive harvesting development

Olive trees have been common in several areas of the Mediterranean Sea basin since the 28th century BC. In the presence of flat lands, such as in Morocco or Spain, it is possible to create intensive cultivation; highly automated machines greatly reduce the timing of the various processes (i.e., pruning, harvesting, and treatments).

On the other hand, heavy machines cannot be used in steep areas (Quaglia et al., 2014), and manual work using hand harvesters is the main method (Gobattoni et al., 2015). The most widely used method for olive harvesting is to "beat down". This technique originated in the traditional harvesting systems that use bamboo canes to perform harvesting operations. Today, the branches are beaten with a harvester equipped with a vibrating comb. The long rigid rods that support the comb can have telescopic extensions that reach branches 3−4 m in height. The first beating harvesters developed were powered by compressed air (Ghonimy et al., 2021). Newer models adopt DC motors (Ibrahim, 2018) that are located on the terminal head. The electric harvesters consume less energy and do not require a fixed power source, but, of course, they are heavier and rather unbalanced. However, the lightweight advantage of pneumatic harvesters is gradually being replaced by high-performance electric drive systems, and the most used harvesting systems today rely on electric drives.

1.2. Exoskeletons in agriculture

A passive upper extremity exoskeletal vest can reduce the muscle activity of shoulder muscles (Kim et al., 2018; Maurice et al., 2019). The adoption of occupational exoskeletons is still limited (Crea et al., 2021): large field studies are necessary to allow the stakeholders to better evaluate costs and benefits (Yin et al., 2020). Some examples of upper limb exoskeletons designed to accomplish agriculture tasks are now recalled.

An upper limb exoskeleton has been developed for oil palm harvesting (Hazreen et al., 2021): the prototype allowed the task to be performed, but the comfort still needs to be optimized. More efficient tools can also improve oil palm harvesting (Mohamaddan et al., 2021). A wearable passive upper-limb exoskeleton has been developed for orchard farming (Wang et al., 2021). The device, which uses a gas spring and a four-bar mechanism, assists in arm-lifting motions and reduces the risk of developing work-related musculoskeletal disorders.

Vine cultivation needs a very large quantity of man-hours. Upper limb active devices (Inoue et al., 2023) and passive exoskeletons (Exoviti, RB3D, France) have been developed to assist farmers in viticulture. Exoviti is a commercial product that uses two springs for passive actuation.

1.3. Research objectives

The olive harvesting operation is performed outdoors in the country in an unstructured environment. The first objective of our research is to define a standard protocol of cyclic movements, which mimics the action of the farmer during olive harvest by using motion sensors attached to the farmer's body. Thanks to this schematization, it is possible to replicate the harvesting operation inside the laboratory under controlled conditions. The second objective of the research is to evaluate the performance of exoskeletons by analyzing the operator movements obtained with and without two exoskeleton prototypes. This paper offers an original approach to how to correlate

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[1] PMAR Robotics Group, DIME, University of Genova, Italy
[2] Measurement and Biomechanics Lab, DIME, University of Genova, Italy
[*] Corresponding author: francesco.cepolina@edu.unige.it

operator fatigue with body motion. All of the exoskeletons used in this study have been designed, patented, and prototyped by the authors, specifically to carry out olive harvesting operations.

2. Materials and methods

2.1. Recording and monitoring of harvesting motions in the field

This study wishes to identify the motions that characterize the olive harvesting process (Harano et al., 2012; Fu et al., 2011). The world reference system, used to describe the motions, is defined by the vertical direction and the plane of the force plates. The operator is placed facing the X-direction with the Y-direction toward the left (Fig. 1).

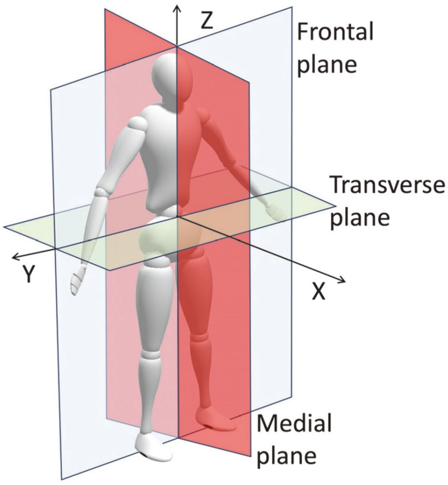
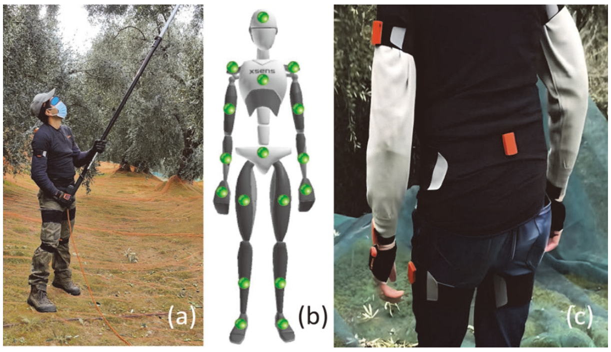


Fig. 1 Arrangement of the reference planes

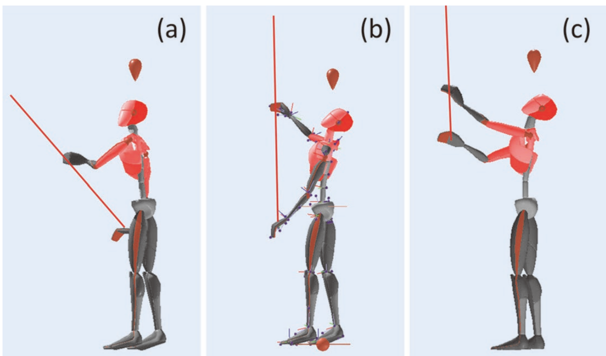
Some operators were equipped with an IMU-based 3D motion capture system (Xsens MVN Awinda, Movella Inc, USA) while working in the field (Fig. 2). Sensor positioning and operation were recorded according to Xsens protocol: the operator wore 16 inertial units, while one sensor was placed on the harvesting tool. The overall sampling frequency is 60 Hz.



(a) standing operator, (b) locations of the 17 Xsens sensors, (c) sensors positioned on the operator body

Fig. 2 Olive harvesting

The processing of the experimental data to reconstruct the movement is carried out by the Xsens environment MVN Analyze. First, three hours of recording were performed to study the basic movements without interrupting the operator. Then, the recordings were cut into 30 s segments representing the key motions. A 30 s sampling time has been chosen because the operator, during this time, performs at least five complete cycles of movements. The authors estimate that five complete cycles are sufficient for minimal statistical characterization. The recorded dataset is used by Xsens software to create a mannequin that mimics the operator's motion. The on-field tests revealed that three main harvesting movements are performed (Fig. 3).



(a) operator bent forward, (b) operator harvesting middle-level olives, (c) operator harvesting highest olives

Fig. 3 Movement of the operator in the medial plane

The vertical tilt of the harvester ranges from a few degrees near horizontal, when harvesting lower trees, to about 80° upwards. Most of the harvesting work is undertaken by maintaining the harvester at approximately 45° with respect to the ground (Fig. 3 (a)). Due to the size of the harvesting tool, the farmer cannot place the whole harvester in front of his body; he needs to keep it to one side, about 10−20° from the frontal plane, by adjusting his torso position. The other two movements are performed by keeping the harvester at 90° with respect to the ground (Figs. 3 (b) and (c)). These two movements seem to minimize the operator's fatigue. The farmer, without the aid of the exoskeleton, needs both hands to sustain the long tool. The farmer places the tool as close as possible to his body to better counterbalance the long and heavy tool. The movement in Fig. 3 (c), used to reach the highest fronds of the olive tree, is tiring and can only be performed for a limited amount of time.

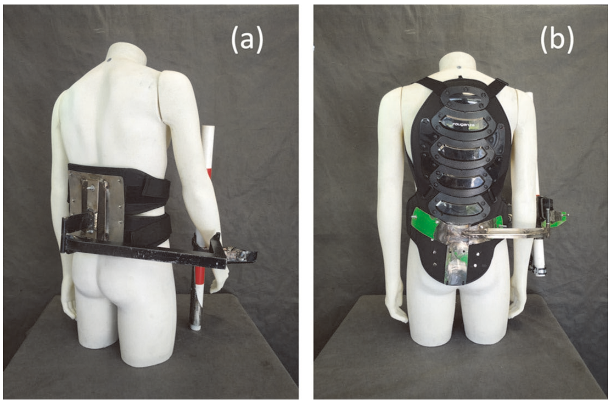
The Xsens motion capture system has also been successfully adopted to accomplish a similar agriculture study: to investigate the musculoskeletal risks in banana harvesting (Merino et al., 2019).

2.2. Design and prototyping of exoskeletons

In field trials, operators have also tested several existing commercial exoskeletons to validate their olive harvest support. These exoskeletons are designed to handle heavy tools in repetitive industrial work but are not suitable for managing such long harvesters. For this reason, it is necessary to develop a task-specific exoskeleton tailored for harvesting olives. A careful observation of operators' positions and their harvesting techniques revealed the most important design areas. The main idea is to provide the farmer with a "third arm" that can support the weight of the harvester and balance the torque due to the harvester's length.

Although today's technology allows for the creation of sophisticated, active robotic arms to create reliable devices for agriculture, we chose to develop frugal exoskeletons with no motors or sensors (Molfino et al., 2023). Passive exoskeleton prototypes were developed by the authors to address issues highlighted by operators during testing. Fiberglass material is sensitive to sunlight and wear (Cepolina et al., 2023). For this reason, the exoskeleton frame has been made of metal.

The exoskeletons, discharging harvester load through an arm fixed on the rigid back, allow the user to harvest even with a single hand. A series of laboratory tests were performed to compare the type-1 and type-2 exoskeleton (Fig. 4). The exoskeleton type-1 is secured to the body using two belts (Fig. 4 (a)). A rigid metal arm, having two hinges at its extremities, is linked to the trunk of the operator. The tip of the arm carries the olive harvester. A torsion spring balances the olive harvester tilt. The exoskeleton type-1 weighs approximately 3.5 kg (Reverberi et al., 2023). The exoskeleton type-2 has a safety shield for trunk protection (Fig. 4 (b)). Similar to the exoskeleton type-1, it has a rigid metal arm carrying the olive harvester. The arm of this exoskeleton has only one hinge, close to the olive harvester. The exoskeleton type-2 weighs approximately 3.0 kg and has two springs: one to balance the olive harvester tilt and the other to compensate for vertical movement.



(a) Type 1 (b) Type 2

Fig. 4 Harvesting exoskeletons

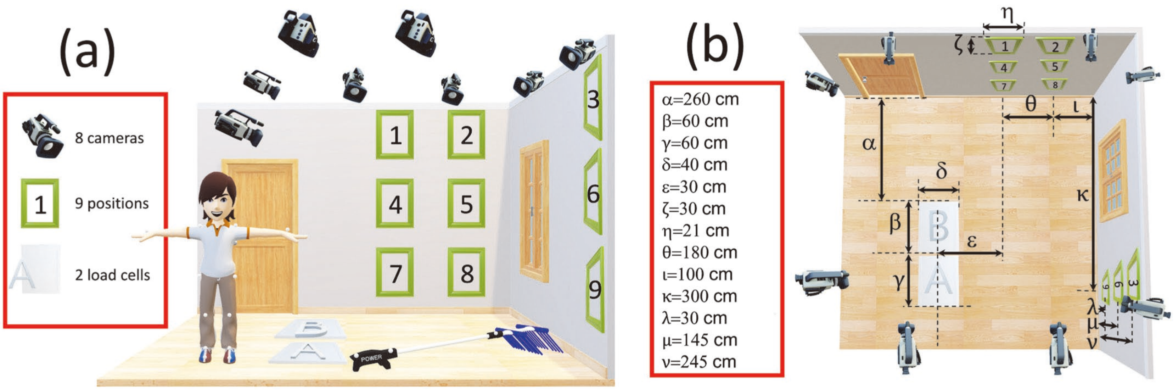
2.3. Laboratory measurement campaign

A laboratory testing campaign, under controlled conditions, was designed according to information obtained in the field (Crenna et al., 2015). The main purpose of the experimental protocol is to assess user motion with and without an exoskeleton and to identify the exoskeleton contributions. The laboratory tests were based on an optoelectronic motion capture system (MoCap, Vicon Motion Systems Ltd., Sweden), which has eight IR cameras operating at a 100 Hz frame rate to capture worker motions (Fig. 5 (a)). The eight cameras track the operator and harvester positions in real time. Two RGB cameras, not shown in Fig. 5 (a), record the medial and frontal views.

Two 3D force measurement modular systems (P6000, BTS Bioengineering S.p.A., Italy) capture the foot pressure of both feet. Cameras and the MoCap system were calibrated using the standard Vicon device before the acquisition. Motion tracking may be successfully improved using artificial intelligence (Cepolina et al., 2022).

The operator's feet are placed on two force plates labeled A and B. A force plate is synced to the capture system to measure the load each foot exchanges with the terrain during the motion. The experimental procedure is based on a set of positions typically assumed by the operator, reproduced to scale in the laboratory (Fig. 5 (b)).

A commercial electric harvester (Alice, Campagnola Srl, Italy) is used for the tests. A custom model was used to measure

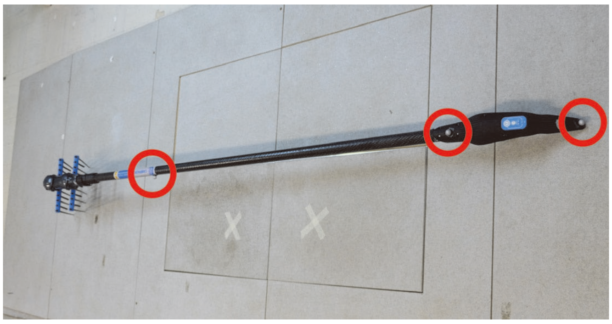


(a) MoCap and harvesting positions (b) Main dimensions of the layout

Fig. 5 The motion caption room setup

the harvesting tool movement: three IR markers were placed on the handle tip (the lowest point of the tool), below the firsthand position, on the bar above the second-hand position and at the end of the fixed part of the bar (not to move the marker when extending the bar length), as presented in Fig. 6.

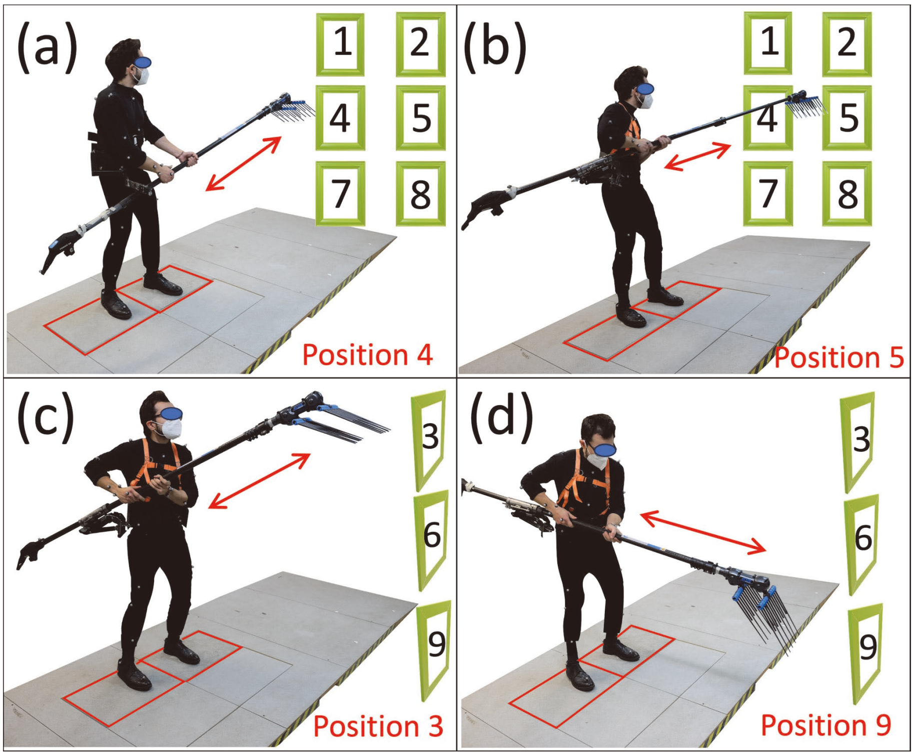
A plug-in gait full-body biomechanical model describes the subject's motions based on 35 reflective markers placed on specific anatomic points. The head has been excluded from the tracking. As mentioned before, a set of standard harvesting motions was defined to ensure the reproducibility of the experiments. The operator, while having the feet on the load cells, stands upright (position 0). Additionally, nine positions were identified: three high positions of 1, 2, and 3 at 2.45 m above the ground, three medium positions of 4, 5, and 6 at 1.45 m above the ground, and three low positions of 7, 8, and 9 at 0.3 m above the ground, as shown in Fig. 7. The lowest positions are used for harvesting while the operator stands on a terrain higher than the olive tree. The operator assumes three direction types: lateral (positions 1, 4, and 7, perpendicular to the torso), approximately 30° (positions 2, 5, and 8, slightly open position, and 30° with the torso), and frontal (positions 3, 6, and 9, almost aligned with the operator's torso). The lateral direction types are the most common, as operators can move their legs to adjust their body composition. When dealing with repeated motions, it is common in biomechanics to define reference cycles. This helps in viewing, interpreting, and checking the reproducibility of results.



The harvester is long from 185 mm (short length) to 270 mm (extended length) and weights 2.8 kg. The red circles show three IR reflective markers.

Fig. 6 The commercial harvester (Alice, Campagnola)

In this field, the branches of the trees are combed back and forth by the harvester: the operator in the laboratory mimics the harvester's back-and-forth movement. Then, from this starting position, while keeping his feet still, he extends his body forward towards position 1. The operator then returns to the starting position. The operator performs this cycle: "position 0 → 1 → 0". Then, the operator moves the tip of the harvester to reach, in sequence, the other target positions. The following cycles are performed: "position 0 → 2 → 0", "position 0 → 3 → 0", …, and "position 0 → 9 → 0". The operator performed the nine types of motion cycles by simply moving their upper limbs to guide the harvester to the desired position without moving their feet or rotating the torso toward the harvesting



(a) position 4, (b) position 5, (c) position 3, (d) position 9

Fig. 7 Operator, wearing the exoskeleton type 8, inside the motion capture room position. The operator's performance was repeated five times per position, taking a total of about 7 s.

This procedure is performed under the following conditions: operators without an exoskeleton, operators wearing the exoskeleton type-1 and type-2, and harvester in standard (185 cm) and full length (270 cm).

First, using the motion capture system, the force plate and the patient model are calibrated. After this acquisition, the data are pre-processed to obtain continuous trajectories from each marker. In this phase, markers are traced and labeled, and the model is reconstructed (Fig. 8).

3. Results and discussion

3.1. On-field tests

In collaboration with the CIA (Italian Farmers Association) and Savona C.I.P.A.T. (Italian Centre for Vocational Training and Technical Assistance) (Lizzi, 2018), several experimental field trials were carried out during harvesting without exoskeleton prototypes. A set of Xsens inertial sensors was used to record the motion. Concerning the medial plane, the orientation of the harvester is primarily determined by the tree characteristics and the operator's position under the tree. Generally, a range of 90 ° to 20 ° with respect to the horizontal (i.e., 0 °) was verified, with positions around 45 ° to 60 ° occurring most frequently (Fig. 3). The operators push and pull the harvester (dominant movement), they also work to contrast the weight and the torque exerted by the harvester. Due to these movements, the operators are exposed to shoulder and trunk fatigue.

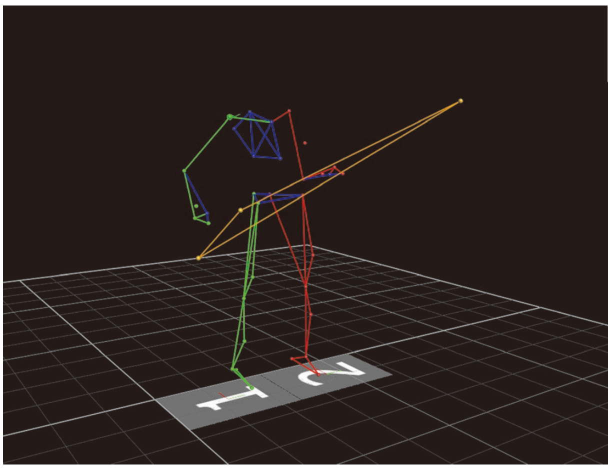
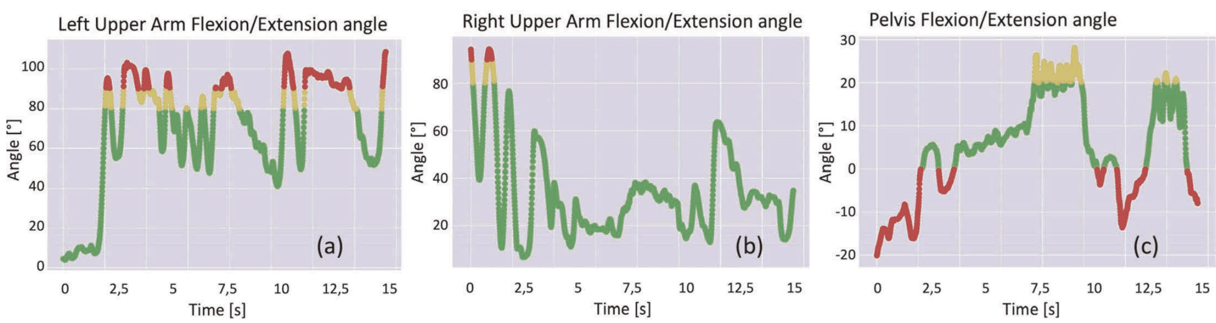


Fig. 8 Subject and harvester models

The study is focused on the most common movement: the operator bent forward (Fig. 3 (a)). The harvester is held laterally to the trunk, with the smallest possible angle between the harvester and the trunk in the medial plane. This position is kept, minimizing the annoyance of holding such a long and heavy device in one position. The flexion and extension of the arms and pelvis are analyzed (Fig. 9). The left upper arm, during the harvesting, assumes a wide range of angles from about 40 ° to 100 ° (Fig. 9 (a)): the left upper arm is kept at 54.64 % in a comfortable pose (green), 16.15 % in a slightly tiring pose (yellow), and 29.20 % in an uncomfortable pose (red). The right upper arm axis has an angle mostly between 20 ° and 40 ° (Fig. 9 (b)): the right upper arm is kept at 96.54 % in a comfortable pose (green), 1.7 % in a slightly tiring pose (yellow), and 1.7 % in an uncomfortable pose (red). The pelvis is alternatively flexed and extended. The flexion of the pelvis is uncomfortable (Fig. 9 (c)): the pelvis is kept at 54.8 % in a comfortable pose (green), 12.2 % in a slightly tiring pose (yellow), and 32.97 % in an uncomfortable pose (red).

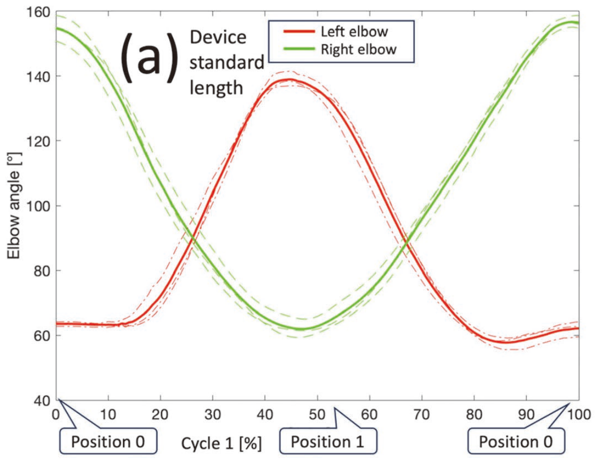
The harvesting procedure involves an active motion of the whole body. Well-organized motion parts have been demonstrated from the proximal to the distal. Operators are more likely to suffer fatigue from continuous motion, mainly in the shoulders and back. This repetitive type of operation, carried out for about 8 hours a day and even 7 days a week during the harvesting campaign, often leads to an inflammatory process requiring pain medication (Osborne et al., 2012; Cecchini et al., 2018; Van der Molen et al., 2020). The passive exoskeletons designed and tested by the authors aim to reduce the operator's



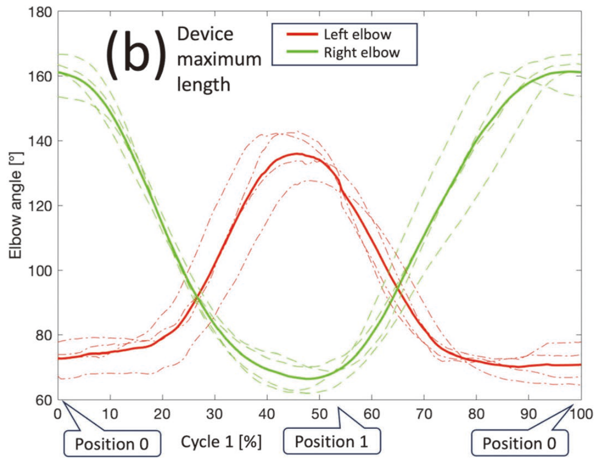
(a) Left upper arm flexion/extension (b) Right upper arm flexion/extension (c) Pelvis flexion/extension

Green lines represent comfortable poses that can be kept long time. Yellow colour lines show a bit tiring poses. Red lines represent uncomfortable body positions.

Fig. 9 On field harvesting test, raw data, operator in the medial plane bent forward



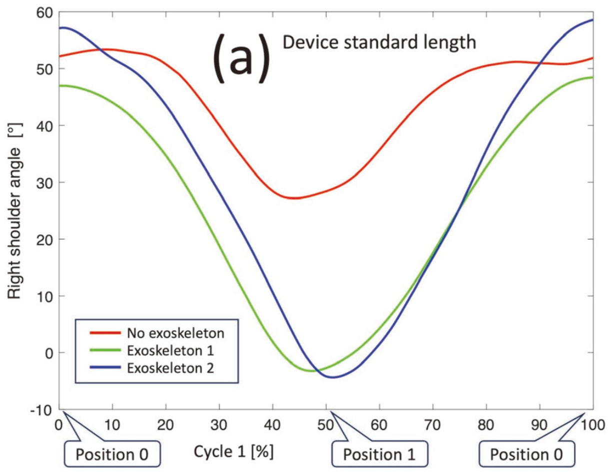
(a) With standard length



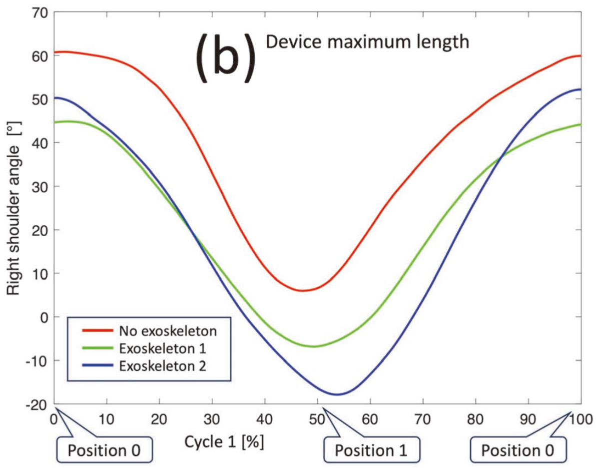
(b) With extended length

The thick lines represent the mean values, while the dashed lines represent the 5 repetitions.

Fig. 10 Elbow articular angular motion as a function of the harvesting cycle



(a) Using standard length harvester



(b) Using extended length harvester

Fig. 11 Shoulder articular angular motion in the frontal plane as a function of the harvesting cycle

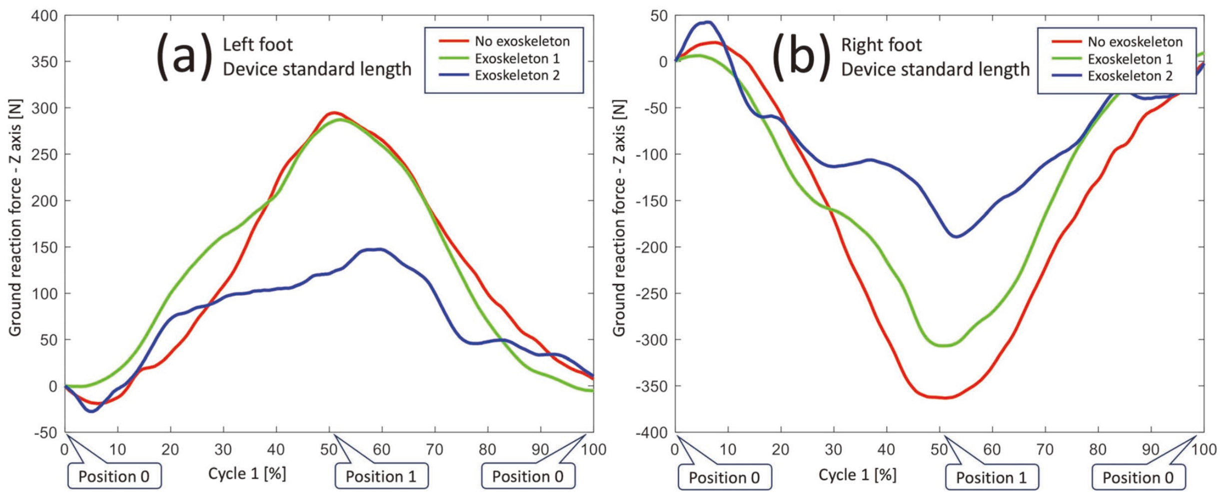
efforts.

3.2. Laboratory tests

Joint angular motion, derived from the trajectory data, provides significant biomechanical information. Considering a harvesting cycle, the following results are discussed. A cycle starts with the harvester at its lowest position, moves toward its target position, and returns to its lowest position, where the next cycle begins. The kinematic results are now analyzed.

The elbow angle is defined by arm and forearm segments in their plane. The elbow angle is zero with the forearm aligned with the arm (i.e., the elbow is completely extended). Figure 10 shows both the elbow's angle motion averaged over 5 cycles. At the end of each cycle (100 %), the elbow returns to its starting position (0 %). The lowest dispersion was verified with the short harvester (Fig. 10 (a)), demonstrating the optimal repeatability of the measurement procedure; a slightly increased dispersion is shown when using the extended-length harvester (Fig. 10 (b)), which is more difficult to manage.

Shoulder angles have been considered in the three planes: frontal, medial, and transverse (Fig. 1). The subject position is maintained fixed during all the tests, so the planes are the same during the overall test campaign. In this case, shoulder angles correspond to the absolute angles of the arms, with values above 90° for abduction and lower for adduction. The average angle of the right shoulder in the frontal plane for standard (Fig. 11 (a)) and maximum length (Fig. 11 (b)) harvesters are shown. Each color represents a different operating state: without an exoskeleton (red), with exoskeleton type-1 (green), and with exoskeleton type-2 (blue). The use of the exoskeleton dramatically changes the motion of the shoulder when using a standard-length harvesting device (Fig. 11 (a)) and with the extended one (Fig. 11 (b)). When operating without an exoskeleton, the shoulder must manage the momentum generated by the harvester; the shoulder restricts the range of motion around the



(a) Left foot

(b) Right foot

Fig. 12 Normalized vertical Ground Reaction Force, during the harvesting cycle, using the exoskeleton standard length

most suitable position to minimize the effort. On the contrary, the exoskeleton facilitates shoulder motion as the weight and momentum of the harvester are compensated by the exoskeleton.

Dynamic measurements examine vertical ground reaction force (GRF) variation throughout the harvest cycle. Fig. 12 shows a vertical GRF for both feet of the operator. The positive or negative value of the GRF means that the operator is moving the weight from one side to the other. The blue line relative to the type-2 exoskeleton shows a reduced force variation, so the operator is more stable during the motion. This is confirmed by the displacement of such point of force application (or center of pressure (CoP)), which is by far reduced with this exoskeleton model. Further confirmation of the improvement can be obtained by an inverse dynamics analysis (Crenna et al., 2020) based on kinematics, external forces, and the harvester's accelerations obtained by differentiating its motions (Crenna et al., 2021).

4. Conclusions

This paper describes the characterization of passive exoskeletons developed for harvesting olives. Field and laboratory tests have enabled the validation of the working principle of the proposed exoskeletons. A quantitative characterization procedure allowed for a comparison of the operator's motion in different conditions while operating with and without an exoskeleton. Prototype 2 is the evolution of the exoskeleton type-1. Laboratory tests showed that this prototype outperforms prototype 1. A series of novel biomechanical and physiological tests, including surface electromyography, was performed on the final prototype to identify possible fatigue effects. Several farmers were able to appreciate the benefits of the proposed solution.

Further developments are underway to fully meet the high expectations arising in the world of agriculture. A patent has been filed to protect the proposed exoskeletons. Once some ergonomic aspects are optimized, it will become possible to enter into the exoskeleton production phase with confidence.

Disclosure statement

Ethical approval Registration No. 47 2022, the University of Genoa, session 20 October 2022. "Analysis of the performance variation induced by passive exoskeletons in olive growing operations". The data does not involve any foreseeable risk of harm or discomfort. Each subject signed an informed consent module before conducting the test. No personal information or opinion is recorded.

Acknowledgments

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