Engineering in Agriculture, Environment and Food
published by AABEA
Research Article

EAEF 16 (1) : 37−42, 2023

The minimal exoskeleton, a passive exoskeleton to simplify pruning and fruit collection

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Abstract

Terracing allows cultivation even in hilly regions but does not permit the use of conventional heavy machinery. Olive trees, grown on terraced lands, are harvested with a handheld long-shafted harvester that shakes the branches of the trees and makes olives fall over nets arranged around the trees. This relatively heavy and unbalanced hand-hold tool causes fatigue and articular-muscular disease to the operators. This paper presents a lightweight exoskeleton developed to help in the carrying and operating of such tools, reducing human effort and the incidence of long-term pathologies to the operators. This work describes the kinematics and design of the proposed exoskeleton, which is passive and “minimal”. A prototype of the exoskeleton has been produced and tested in the field.

[Keywords] exoskeleton, olive trees, agriculture, outdoor, service automation

1. Introduction

History is full of situations in which new technology is used to execute an ancient job, sometimes completely revolutionising some of its aspects. This paper refers to one of these cases. Olive harvesting is hard work, carried out for hundreds of years; one process required is that of shaking the branches to drop down the fruits, today on a net placed at the base of the tree. In the past, this was completed using long sticks to hit and move the branches. Today, vibrating olive harvesters, powered by electric or pneumatic actuation, are used. These new instruments (Fig. 1) are much heavier than the formerly used sticks, and all their weight is carried by the arms and trunk of the operator.

During the harvesting, the prolonged effort associated with the intense vibration of the device causes lumbar and cervical pain and fatigue in the upper limbs and neck muscles (Cecchini et al., 2018; Mammone et al., 2007). The harvesting operations can be partially automated, adopting elevating platforms or reducing some wearisome operations by using collaborative robots (Elkins et al., 2010; Thamsuwa et al., 2020; Vásconez et al., 2022), but this is not a realistically viable option today in the field and for the farmers. The transport of the olives collected is another problem related to the harvesting procedure; autonomous vehicles (Bergerman et al., 2015; Cepolina et al., 2015; Cepolina and Cepolina, 2021) can be successfully used to reduce human effort. Commercially available large machinery exists, which can completely automate olive growing activities. However, this equipment cannot easily reach narrow lands typical of hilly regions.

The idea of a wearable device emerged while searching for a tool able to assist the user during the olive harvesting campaign that, at the same time, is not difficult to carry and operate on steep and irregular terrain. Some exoskeletons for overhead tasks have been preliminarily assessed by attempting to replicate the motion of olive harvesting operations. These tools have a significant limit; they transfer the vibrations and loads to the shoulders and wrists of the user. For this reason, an ad-hoc wearable solution has been studied.

2. Materials and methods

2.1. Design constraint

The Italian Association of Farmers (CIA) launched a research and technological initiative aimed at reducing the overall effort of manual olive harvesting operations. The University of Genoa, to address the problem, has introduced a system able to compensate for the forces, torques and vibrations caused by manual harvesters. Exoskeletons (Bergamasco et al., 1994; Bogue, 2009; Brown et al., 2003; de la Tejera et al., 2020; Rosen and Ferguson, 2019; Gull et al., 2020) offer a possible solution to the harvesting problem; wearable robots can be used in a wide range of fields (Schiele, 2008; Shi et al., 2022), such as physiotherapy (Tsagarakis and Caldwell, 2003). The proposed system leads to a different redistribution of the loads on the operator’s body, thus “unloading” the upper part of the trunk and reducing the effort generated by working above the shoulder line. This condition produces considerable problems

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Fig. 1 Olives harvesting, instrument and procedure

relating to joint fatigue, which can cause severe traumas and occupational bone-muscle diseases (Walker-Bone and Palmer, 2002; Davis and Kotowski, 2007). Preliminary assessments are carried out to exclude all those design alternatives that might result as unsuccessful from the beginning. For this purpose, the focus falls on two main aspects: engineering and body constraints. The engineering constraints include the evaluation of the outdoor environment and the duty cycles. The olive cultivation environment frequently exposes the exoskeleton to dust, sand and other substances that could lock sliding mechanisms and bearings. Furthermore, humidity can cause problems for electronics and sensors. Finally, exposure to UV light can cause the fragilisation of polymers (Cepolina et al., 2023).

Several materials have been evaluated. Carbon fibre composites have been rejected due to production cost and environmental reasons (i.e., recycling issues). The customers of the exoskeletons are micro-enterprises looking for a cost-effective and easy-to-use tool requiring very minimal maintenance and care. Injection moulding of plastic has also been excluded due to the high cost of the moulds. Moreover, as already mentioned earlier, polymers exposed to the outdoor environment tend to lose mechanical and surface properties.

The body interface evaluation regards the contact points between the exoskeleton and the operator's body (Alami et al., 2006). It includes both quantitative parameters, such as the number of degrees of freedom required for a correct harvester usage, and qualitative parameters, such as the comfort and agility for the user.

A family of six exoskeletons has been designed, prototyped and tested on the field. The performance of the different prototypes has been evaluated by a panel of final users to find the exoskeleton that best fits agricultural needs. For each solution, first, the kinematic is recalled, then the physical prototype is described, and finally, advantages and drawbacks are discussed. This paper introduces and analyses the performance of the so-called "minimal" prototype, the first exoskeleton developed; this exoskeleton provides the user with good freedom of movement while having a basic design.

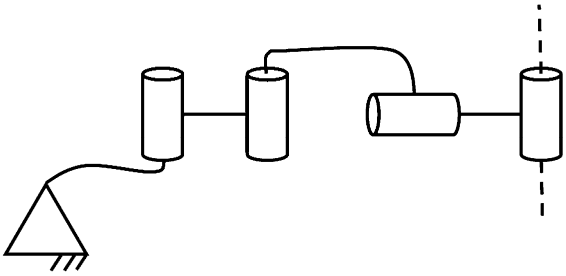


Fig. 2 Kinematic chain of the exoskeleton

2.2. Kinematic and dynamic evaluation

Screw theory is used to choose the mechanism architecture to use and the geometry to adopt. A 3D motion tracking system (Xsens Technologies B.V., Netherlands) is used to analyse the gestures of the same operators performing the task with and without the exoskeleton. The "minimal" exoskeleton resolves the basic need of transferring the load from the arms and shoulders to the torso of the operator; the load of the olive harvester is transferred by a serial chain of three revolute and one cylindrical joints (Fig. 2). The cylindrical joint is modelled as a revolute and a prismatic joint of the same direction. Elastic elements are positioned along the chain following the results of kinematics and dynamics simulations. These analyses also attain information about the geometry of the chain (i.e., the relative spacing and orientation of the joint invariants) for proper freedom and mobility that guarantee an adequate range of motion to the harvester. This chain of the exoskeleton is connected to the harvester in parallel with the human arm, imagined as a 7-DOF fully actuated mechanism; the mobility of the torso of the operator, between the shoulder and the pelvis, is not considered as not used when the operator uses the exoskeleton.

The joints in the chain are modelled, as in Fig. 3.

$$\dim T_1 = 5 \tag{1}$$

$$\dim W_1 = 1 \tag{2}$$

$$\mathrm{Span}\, T_1 = \rho_1, \rho_2, \rho_3, \rho_4, \tau_4 \tag{3}$$

$$\mathrm{Span}\ W_1 = \varphi_1 \tag{4}$$

Where T_1 is the system of all feasible end-effector twists, and W_1 represents its reciprocal wrench system (the structural constraint applied by the chain between the pelvis and the harvester) spanned by all the wrenches that cause no motion to the chain when applied to the harvester, with all the joints free to move. The chain structural constraint is the wrench φ_1 (force), coplanar to the pure rotations ρ_1 and ρ_2, coplanar to

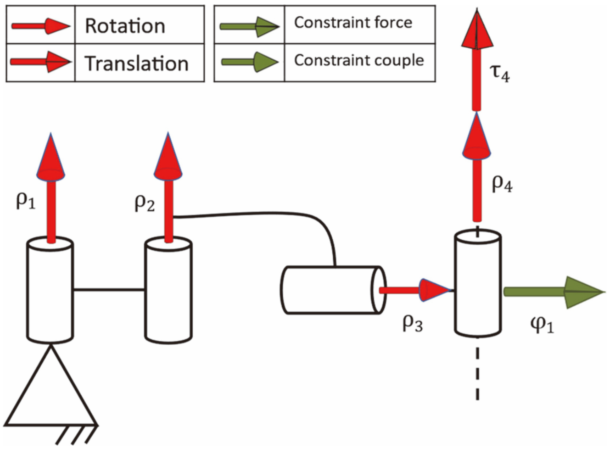


Fig. 3 Constraint analysis

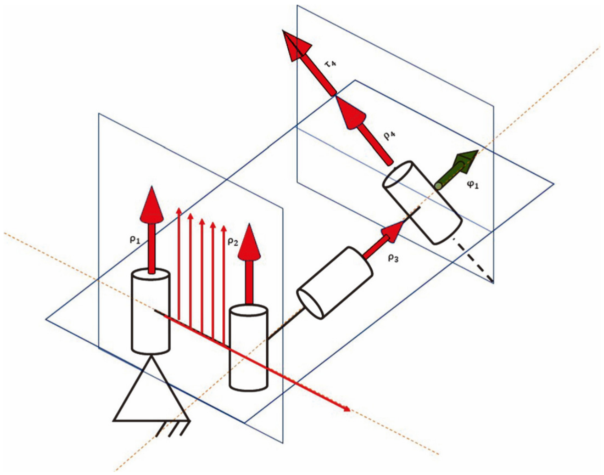


Fig. 4 Geometric constraint visualization

ρ_3 and ρ_4 and orthogonal to the velocity of translation τ_4. Figure 4 shows another configuration of the kinematic chain 1 to better show the geometric setup of the twists and wrenches.

According to the Denavit-Hartenberg parametrisation, displayed in Fig. 5, Table 1 can be obtained: the angles of rotation of joints 1 and 2, denoted as $\theta_1$and θ_2, respectively, are set to zero. This also simplifies the modelling and symbolic description of the mechanism.

For ease of explanation, the final results are presented while the intermediate steps are omitted. The rotation matrix of each reference frame, with respect to the following one and starting from the base frame, is calculated. A geometric Jacobian is assembled from the projections of the joint twists in the base reference frame. The Jacobian matrix relates the velocity of the joints to the harvester twist. The vector ϕ is obtained by transposing the Jacobian and multiplying it by the external wrench ζ_e acting on the harvester. The components of ϕ are the forces and torques to be applied at every joint to maintain the balanced kinematic chain. Since ζ_e has the weight of the harvester only along the Z-axis of the base frame, we have the following.

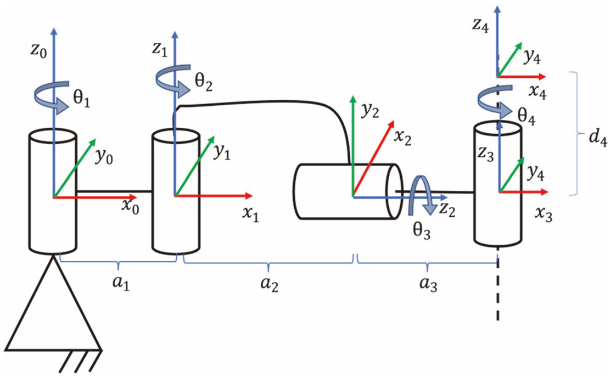


Fig. 5 Denavit-Hartenberg convention

Table 1 Denavit-Hartenberg parametrization

	JOINT 1	JOINT 2	JOINT 3	JOINT 4
TYPE	revolute	revolute	revolute	cylindrical
θ	0	0	θ_3	θ_4
d	0	0	0	d_4
a	a_1	a_2	a_3	0

$$\zeta_e = \begin{pmatrix} 0 \\ 0 \\ -mg \\ 0 \\ 0 \\ 0 \end{pmatrix} \tag{5}$$

Where g is the gravitational acceleration and m approximates the weight of the olive harvesting tool. Applying the principle of virtual work, as highlighted earlier, we obtain the following.

$$\phi = \begin{pmatrix} 0 \\ 0 \\ -mg(a_3 \cos\theta_3 - d_4 \sin\theta_3) \\ -mg\cos\theta_3 \end{pmatrix} \tag{6}$$

The vector ϕ shows that only the third joint and the translational component of the fourth joint must be equipped with springs to counterbalance forces and torques that are applied by the harvester during its use. The prototype, described in the next section, has a spring on the third joint, while the translation at the cylindrical joint is compensated directly by the user.

2.3. Prototype design and testing

The articulated arm, connected to the belt at the height of the pelvis of the user, has two parallel rotational joints with axes perpendicular to the ground. These two axes enable the translation of the instrument on the horizontal plane, while transmitting the weight and the torque of the harvester on the operator's body. A third rotational joint, positioned at the tip of the arm, perpendicular to the previous two and equipped with a spring, enables the harvester to tilt. The torsion spring creates a torque to balance the weight of the harvester. The harvester is free to slide along a cylindrical guide to reach the highest branches of

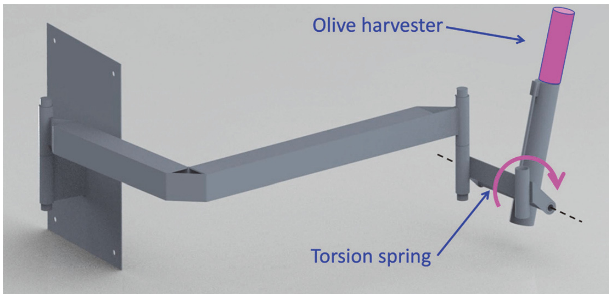


Fig. 6 Prototype 1, 3D model

Fig. 7 Harvester 3D models

the trees. The prototype is made of soft textile in contact with the human body, while the arm is made of metal (i.e., steel and aluminium). A 3D simplified model of the "minimal" prototype is given in Fig. 6. The exoskeletons prototypes, developed by the authors, are tested on a virtual mannequin (Fig. 7).

The "minimal" exoskeleton prototype is built by connecting to the torso a rigid steel plate, curved to follow the shape of the lumbar spine, held in position by two belts with a Velcro fastening. On the centre of this plate, a steel hinge is connected with an offset of approximately 100 mm, parallel to the spine of the user. The lower knuckle of the hinge is welded to an "L" shaped rigid arm obtained from a square steel tube (with dimensions (40 × 40 × 2) mm); the longer and the shorter parts of the "L" measure are 350 mm and 200 mm, respectively. At the end of the L-shaped arm, a second hinge is welded parallel to the first one. On the lower knuckle of the second hinge, a pre-loaded hinge is welded in an orthogonal position with respect to the axis of the previous one. The spring contained in this mechanism is loaded to withstand the momentum caused by the harvester. While the belts of the exoskeleton can dress farmers of various body sizes, the rigid arm has a single size that is optimal only for a "standard size" user. The architecture of the arm, without a body interface and tool support, is displayed in Fig. 6. The harvester, inserted into the exoskeleton, tends to tip forward. The torsion spring, positioned along the rotation axis, counterbalances this movement.

Finally, a quick-release system is connected to the pre-loaded hinge to sustain the harvester; the system is obtained by plasma-cutting a 35 mm diameter pipe. The quick-release holder gently counterbalances the horizontally held harvester. The relative friction between the harvester and the quick-release system helps to keep the tool in position. The overall weight of the tool is approximately 3.5 kg. For the sake of clarity, the exoskeleton, mounted on a mannequin, is photographed in four different positions (Fig. 8).

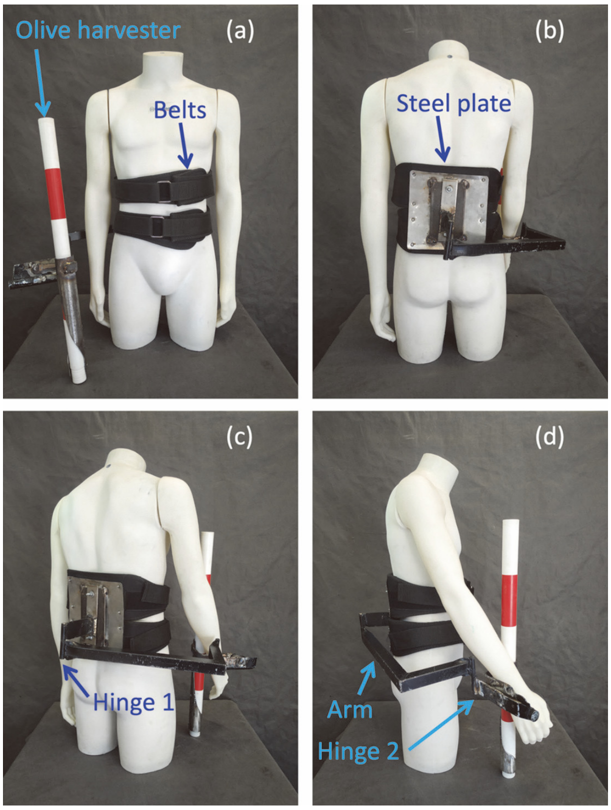


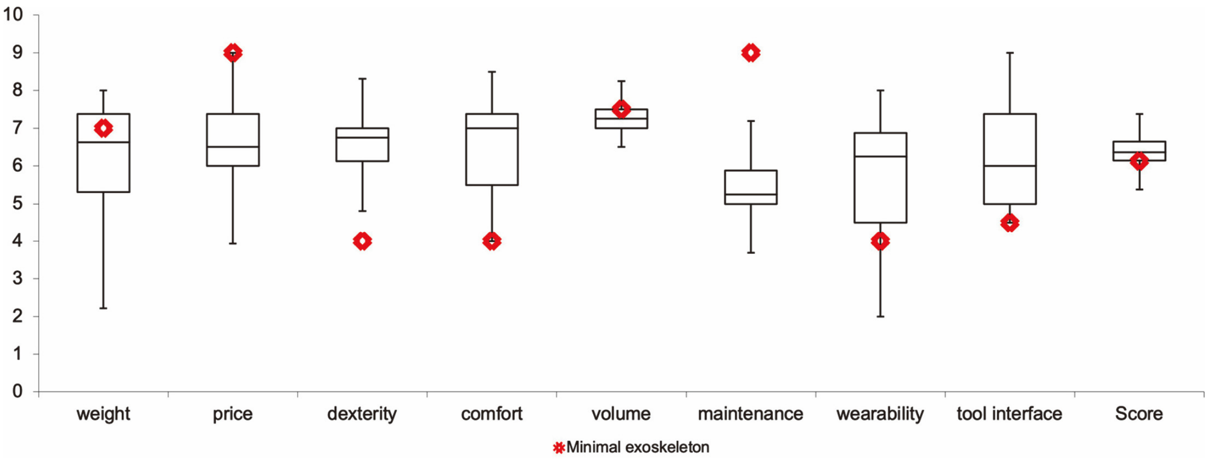
Fig. 8 Prototype minimal views: front (a), back (b), 45 ° back (c), side (d)

The prototype has been extensively tested in an olive grove in Liguria, in the north of Italy, to evaluate its comfort, wearability and dexterity. Each of the 20 farmers has harvested for an hour, using a commercial olive harvester, with and without the exoskeleton. All users have evaluated, thanks to a questionnaire, the comfort and performance of the device. The perceived effort (the Borg scale) has been recorded on a scale from 1 to 10. The questionnaire also recorded the age, weight and previous musculoskeletal condition of the user, along with free comments about the tool's possible improvements.

The testing procedure refers to the 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 and filling out the questionnaire.

3. Results and discussion

The objective of the research is to create an exoskeleton that



The scale is from 0 (worst score) to 10 (best score).

Fig. 9 Performance of the minimal exoskeleton compared to the other members of the exoskeleton family

reduces the effort of the farmers during harvest operations. The agriculture world needs effective and reliable tools. The design constraints forced the research group to focus on basic solutions; the proposed tool has no sensors and no motors. The exoskeleton, linked to the body by means of two belts, provides the farmer with an additional passive arm that helps carry most of the weight of the harvester. The arm is a kinematic chain with three rotational and one cylindrical joints: a torsional spring on the third revolute joint counterbalances the weight of the harvester. The harvester mass is counterbalanced by the kinematic chain and successfully transmitted to the pelvis of the user. The field tests have shown that the "minimal" exoskeleton is easy to wear, without fragile components and with a good movement span. The farmers reported an average reduction of perceived effort (Borg scale) of 3 points (from 4 to 1) in the upper body, shoulders, and arms. From a technical perspective, the tool is easy to manufacture and is quite inexpensive; furthermore, it is easy to repair, even by non-professionals.

A list of device drawbacks is reported here. It is necessary to have good dexterity to perform the olive harvest operation effectively since the arm slightly constrains the natural movement of the operator. The exoskeleton arm, secured to the waist area, does not allow the harvester to reach the tallest branches. Only the torque generated by the non-vertical use of the harvester is counterbalanced. Whenever the instrument is in its vertical position, the entire weight of the harvester must be sustained by the user's arms.

Another issue arises regards wearability and ergonomics. After prolonged use, the body interface causes discomfort; when the "L" arm spans on one side of the rigid back plate, it creates a torque that loads the two body-interface belts. This torque, along with the physiological stiffness of the belts, causes uncomfortable stress on the ribcage.

It is interesting to compare this exoskeleton with the other five exoskeletons developed by the authors (Fig. 9). The "minimal" exoskeleton is relatively light, cheap and offers limited comfort and dexterity. The exoskeleton needs low maintenance and offers limited wearability. The tool interface needs to be improved. The overall score of this exoskeleton is 6.1 out of 10.

4. Conclusions

This research has shown that it is possible to create a basic cheap exoskeleton that is able to sustain unbalanced loads for agriculture activities. The passive exoskeleton (Maurice et al., 2019) proposed in the paper offers basic features that effectively align with agriculture harvesting needs. The torque, created by the weight of a long-shafted tool (the olive harvester), is successfully transferred by the arm to the pelvis of the user. Some operators from the Italian Association of Farmers (CIA) have tested the prototype on the field and were positively impressed. While the feedback is overall positive, some problems still need to be addressed. The arm architecture shall be changed to enable improved farmer motion dexterity. The weight of the harvester, while positioned vertically, can be compensated by adding an additional spring. Clever solutions need to be introduced to reach even the tallest olive tree branches. The human-exoskeleton interface shall be redesigned so that comfort can be improved by distributing the weight of the arm over a larger area of the user's body. To address all the mentioned issues, five more exoskeletons have been created.

The prototype created has demonstrated that the proposed solution meets some of the requirements of the final users but still must be improved.

Acknowledgements

This work was supported by the Italian regional activity: "Measure 16.1 of the Rural Development Programme 2016–2020 of the Liguria Region IEP".

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(Received: 22 December 2022, Accepted: 21 May 2023)