Safety and ergonomics enhancement of the foldable rollover protective structures

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Abstract

For the agricultural tractors, the risk of loss of stability is limited when passive safety devices, the so-called rollover protective structures (ROPSs), are installed. In the case of limited height coltures, such as vineyards or orchards, the tractor is often equipped with a two-posts foldable and front-monuted roll-bar ROPS (FRB). The main advantage of FRBs consists in the possibility to use the tractor with a low operative overall height, keeping the rollbar folded down. However, FRB's conventional solutions underestimate the operators' risk-taking behavior and their widespread misuse due to the efforts needed to operate them. This study aims at reducing the problem by providing the FRB with aided systems to facilitate the FRB raising and locking. In particular, the ergonomics issues related to the raising and lowering phase were investigated and the technical characteristics of aided systems were detected. This led to the development of a novel automatic system to lock the FRB in a safety configuration to support the tractor's operator.

Keywords
Machinery safety, Ergonomics, Agricultural tractors, Roll-over protective structure (ROPS), Reverse engineering.

1. Introduction

The most relevant risk related to the use of agricultural tractors consists in the tractor roll-over (Vita et al. 2021). Focusing on the Italian situation, as shown in Figure 1, the average value of fatalities due to in-field roll-over in the period 2010–2018 is 74.7% (Figure 1). Similar situations can be found in other countries (Pinzke et al. 2018; Myers et al. 2010).

Additionally, it has to be considered that most fatalities occurred when the roll-over protective structure (ROPS) was not installed, or when it was disabled, as in the case of foldable front-mounted roll-bar ROPS (FRBs). The frequency of these cases is very large as demonstrated by the extant literature, which has shown that from 30% to 50% of fatalities are related to incorrect use of foldable protective structures (Silleli et al. 2007; Ballesteros et al. 2013). Numerous initiatives have been promoted to tackle this diffused problem: for instance, in different countries were organized retrofitting campaigns, i.e. fostering the installation of ROPSs by means of incentives and/or technical guidelines provided by public authorities. However, retrofitting campaigns do not solve the problem of the FRB's misuse during cultivation activities characterized by a low clearance between the tractor and the vegetation. Actually, to operate in these environments farmers usually unfold the ROPS and they keep it unfolded even when the operations in narrow spaces are completed. This unsafe attitude is very diffused and it is usually motivated by the excessive effort needed to fold/unfold the rollbar (Micheletti Cremasco et al. 2020).

To reduce such a phenomenon, several innovative solutions have been proposed in the literature: for instance, an automatically deployable anchor mechanism to prevent continuous rolling during sideways roll-over was presented by Silleli et al. (2008). Another solution is represented by the automatically deployable front-mounted ROPS presented by Ballesteros et al. (2015) that can be deployed both in height and width, and locked in its operative position. Other studies have analysed the problem from the ergonomics point of view, mainly focusing on the efforts needed to operate the rollbar (Facchinetti et al. 2021; Micheletti Cremasco et al. 2021). These studies brought to light the need to reduce the operator's stress when folding/unfolding the rollbar, making these operations more comfortable.

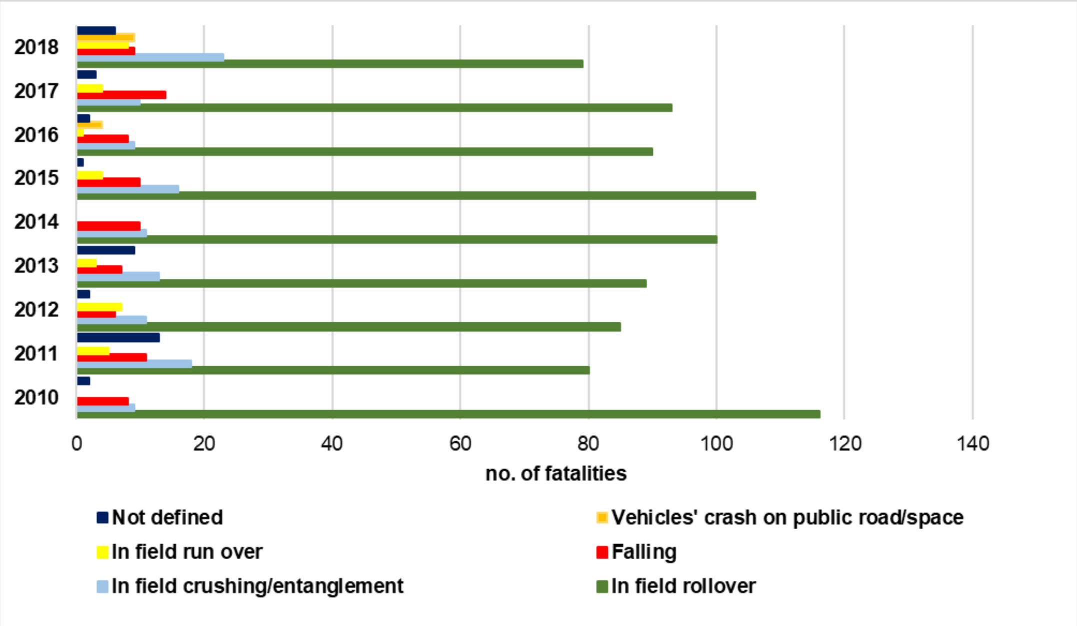


Figure 1. Occupational fatal accidents that occurred in Italy in agriculture (data elaborated from INAIL 2022).

In line with this issue, Gattamelata et al. (2021) proposed the implementation of partial assistance systems (PASs) capable of reducing the physical effort of the operator when raising/lowering FRBs. This solution can improve the FRB's correct use since the loads needed for the lowering/raising operations are reduced by the PASs. However, it should be noted that to achieve a safe configuration the operator needs to manually lock the FRB by means of two pins (one for each side of the ROPS) before using the tractor: this condition can be dangerous for the operator since it can lead to errors or to the misuse of the system. To solve such a problem, the current study aims at augmenting the research of Gattamelata et al. (2021) by means of the development of a locking system capable of automatically locking the FRB when it is fully raised while facilitating the unblock when the operator has to fold the FRB.
With this goal in mind, the procedure for the correct dimensioning of the partial assistance device was revised to determine the characteristics of the locking system. Practical tests were carried out in collaboration with a group of operators to define the position and movements of the folding/unfolding operations. Then, the design of both the PAS and the automatic locking device (ALD) was implemented and tested virtually. Finally, a physical prototype was developed and tested in the laboratory.

2. Materials and Methods

The research approach implemented in this study consists of the following main phases:

- Ergonomics analysis, which was based on experiments with a group of operators dealing with folding/unfolding a two-posts front-mounted rollbar installed on a track-laying tractor.
- Design of the PAS: following the procedure proposed by Gattamelata et al. (2021), the partial assistance system was redesigned to integrate it with the locking system.
- Design of the automatic locking device (ALD).
- Prototyping: the whole system integrating both the PAS and the ALD was developed virtually to test its features and then a physical prototype was developed to test its operability.

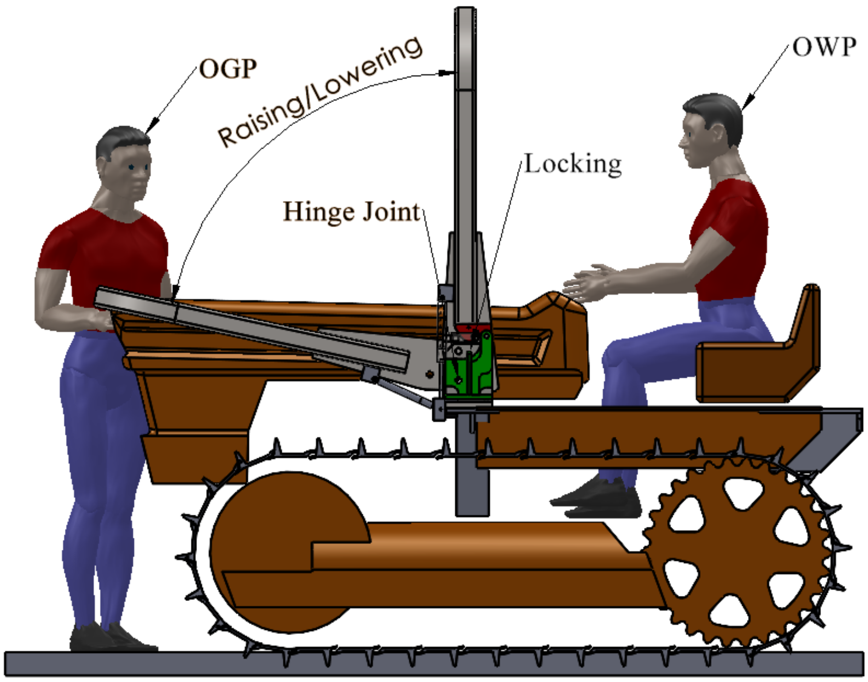
3. Ergonomics analysis

A group of five operators was involved in determining the features of folding and unfolding operations of a two-posts rollbar installed on a tracklaying tractor. Actually, the analysis of the behavior of operators was needed to determine the handling points, i.e., the position of the operator's hands and body when raising and lowering the bar. Then, from these data, it was possible to determine also the load needed to operate the rollbar. This represents a non-repetitive task since the frequency is less than once per minute for the adult working population and professional use as noted by Pessina et al. (2016). They also underlined the ineffectiveness of technical standards

for the ergonomics design of ROPS, since the 100 N limit of OECD Codes exceeds a large number of rollbars usually used to retrofit tractors. Accordingly, the OECD limit can be satisfied only by fitting an aiding device.
In practice, there are two main operating conditions to operate and lock the FRB and maneuver the tractor. As shown in Figure 2, there are two operating conditions:

- Operator on the ground (OGP);
- Operator in the working place (OWP).

The raising/lowering FRB phases push the operator to overcome the weight force of the bar in the lifting phase and support the rollbar in the lowering one. This can stress the operator, especially when this operation has to be repeated several times in a working day, leading to the misuse of the FRB: i.e., the operator intentionally does not raise the bar when in-filed works with limited clearance are ended. In these situations, the rollover risk is very high. Additional risks are related to the locking/unlocking operations: actually, the operator operates the FRB and inserts the pins from the OGP. Such a circumstance involves additional physical efforts, risk of entanglement, as well as a waste of time (since the operator has to walk around the tractor and manage the pins on both sides) that often leads the operator to do not raise the FRB or to do not lock the bar correctly.



OGP – operator ground position
OWP – operator at working place

Figure 2. Operator positions and handling of the ROPS.

In line with the provisions of Vigoroso et al. (2020), a system to support capable of facilitating the FRB's raising and lowering can reduce the above-mentioned risks and unsafe behavior.
Hence, in this context providing a human-centered solution capable of reducing the effort and stress of operators to avoid FROPS misuse while working consists in:

- Designing an assistance system, to reduce the force to operate the rollbar from the OGP, or to automate the raising/lowering phase from the OWP;
- Designing an automatic locking device, to ensure safety in the use of the rollbar and save time for inserting the pins.

In both cases, the design constraints concern the use of technologically sustainable components, which can be fitted or retrofitted on the FRB without exceeding the average cost of the ROPS. Moreover, the technical parts and assembly shall be easy to check and maintain, having a lifecycle (duration) compatible with the ROPS itself. These motivations push toward traditional materials and mechanical assemblies, which are widely used in agricultural and industrial machinery and are described hereinafter.

4. Design of an assistance system

According to the components and mechanical systems available on the market, the assistance system can be a linear or a rotating actuator, which acts on the FRB facilitating its rotation with respect to the hinge joint (see Figure 2).

Considering the retrofit ROPS and the ergonomic requirements of OECD codes [15], the calculation methodology proposed by Gattamelata et al. (2021) can be used to evaluate the forces involved in the operation of folding frames with gas spring linear actuators. Following such an approach, the forces involved in the raising and lowering tasks have can be estimated by taking into account the following moments:

- M_w, which is the moment of weight force of the rollbar: this moment varies depending on the horizontal distance of the centre of gravity (GC) from the axis of the hinge joint.
- M_{ACT}, i.e. the moment of the actuator, which varies based on the actuator type and the forces it can exert on the roll-bar, considering the distance between the anchorage points and the hinge axis to determine the arm lever.
- M_{RAI} represents the moment generated by the operator force in the raising phase.
- M_{LOW} represents the moment generated by the operator force in the lowering phase.

Accordingly, the moment the actuator/s has/have to deal with can be expressed by means of the following balance equations, distinguishing between the raising, in equation (1), and the lowering operation, in equation (2), tasks:

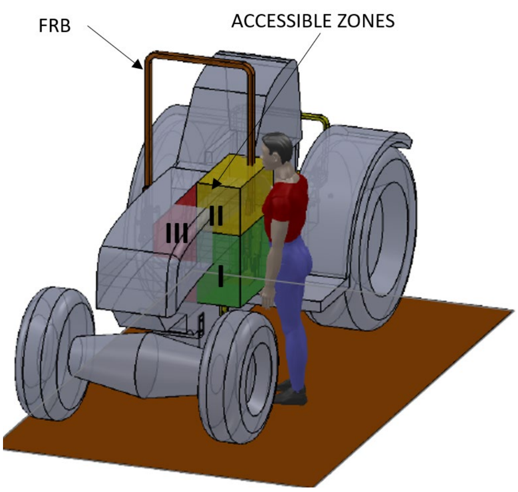
$$M_{ACT} = M_W - M_{RAI} \qquad (1)$$

$$M_{ACT} = M_{LOW} - M_W \qquad (2)$$

In the case of completely assisted systems, with the operator in OWP, the M_{RAI} and M_{LOW} are equal to zero and the actuator has just to overcome the Mw, so that equation (2) is the same as equation (1).

In the case of the operator at OGP, it should be considered that the weight force assumes the maximum value (M_{WMAX}) in the rest configuration of the rollbar: such a force represents the force to be countered by the operator supported by the actuator to raise the FRB. This is the reference value to select a proper assistance system, whose force is aimed to balance the weight force and reduce the operator's efforts in handling the rollbar. To properly define the value of this force, one should keep in mind that: a low force value makes the use of the actuator ineffective. Conversely, the choice of an actuator capable of exerting an excessive force on the rollbar can have a negative impact on the operator, mainly in the lowering phase (i.e. starting from the safe configuration when the FRB is unfolded). In this situation, in fact, the operator can be hit or can be entangled by the rollbar. Hence, its proper dimensioning is crucial from both the ergonomics and safety points of view.

The M_{RAI} and M_{LOW} maximum values can be derived considering the maximum force the operator can exert on the FRB, in a comfortable manner, according to the OECD Code no. 6 (OECD 2016), which indicates the limits of the acceptable force for the actuation of the rollbar. In Figure 3 the different zones foreseen by the OECD code and the related acceptable forces are reported.



Acceptable force limits established by the OECD Code no. 6 for raising/lowering operations.

Zone	Acceptable Force [N]
I	100
II	75
III	50

Figure 3. Accessible zones of the grasping area for a wheeled tractor according to OECD code n. 6.

The maximum value of the operator moments can be derived considering the grasping point position with respect to the hinge joint, which is the lever arm of the moment, in the most significant position: the rest configuration

(FRB fully folded), the safe configuration (FRB fully raised) and the intermediate configurations (at least three or four).
The M_W moment can be determined considering the centre of gravity position with respect of the hinge joint according to equation (3) and the geometrical parameters shown in Figure 4, where the geometrical features of a linear actuator are depicted.

$$Mw = P \times d \times \cos(\alpha) \qquad (3)$$

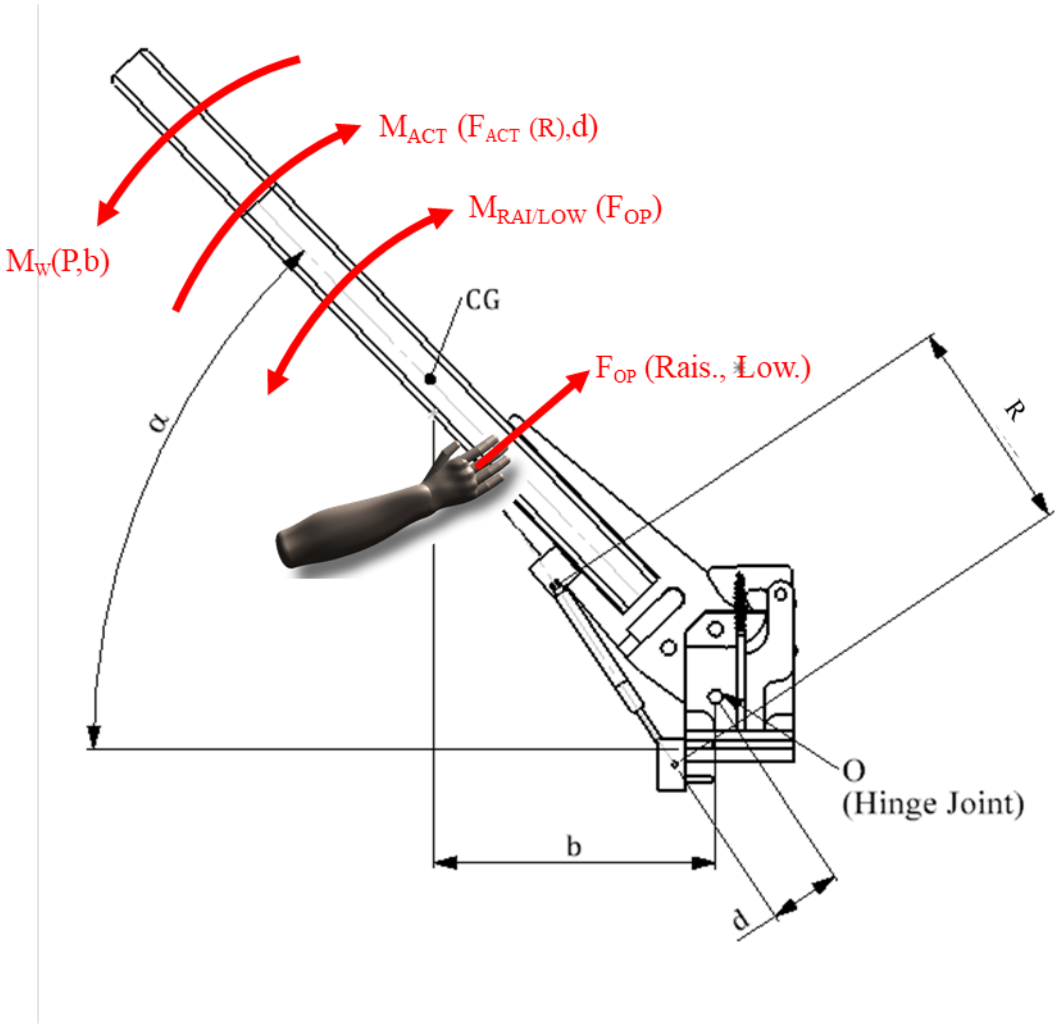


Figure 4. Geometrical features of a linear actuator and moments acting on the Hinge Joint.

Once the M_{ACT} is been defined, the nominal moment exerted by the chosen actuator $M_{ACT,Nom}$ can be calculated. In the case of a linear actuator this value can be expressed by the equation (4):

$$M_{ACT,Nom} = [F_{ACT}\,(\text{Stroke}) \times d\,(\alpha)] / (b) \qquad (4)$$

where F_{ACT} is the force exerted by the actuator (for example, a gas spring or a mechanical spring) and it depends on the actuator stroke. Finally, to achieve the ergonomics goal, the following expression must be satisfied:

$$M_{ACT,Nom} \geq M_{ACT} \qquad (5)$$

Furthermore, it has to be noted that the actuator must be compatible with the limit rotations of the rollbar, i.e., geometrical constraints. In particular, a proper stroke (*R*) and anchorage points shall ensure that the rollbar can easily reach both the folded and raised safety configurations: as shown in Figure 5, while the moving point of the gas spring has a circular and regular trajectory the gas spring dimension *R* varies. During the raising phase from configuration (1) to configuration (2) the *R* dimension passes from *R(1)* to *R(2)* with *R(2)>R(1)* and vice-versa in the lowering phase. Consequently, the minimum value of R must be greater than the minimum size of the gas spring, as the maximum value must be less than the maximum length of the same device.

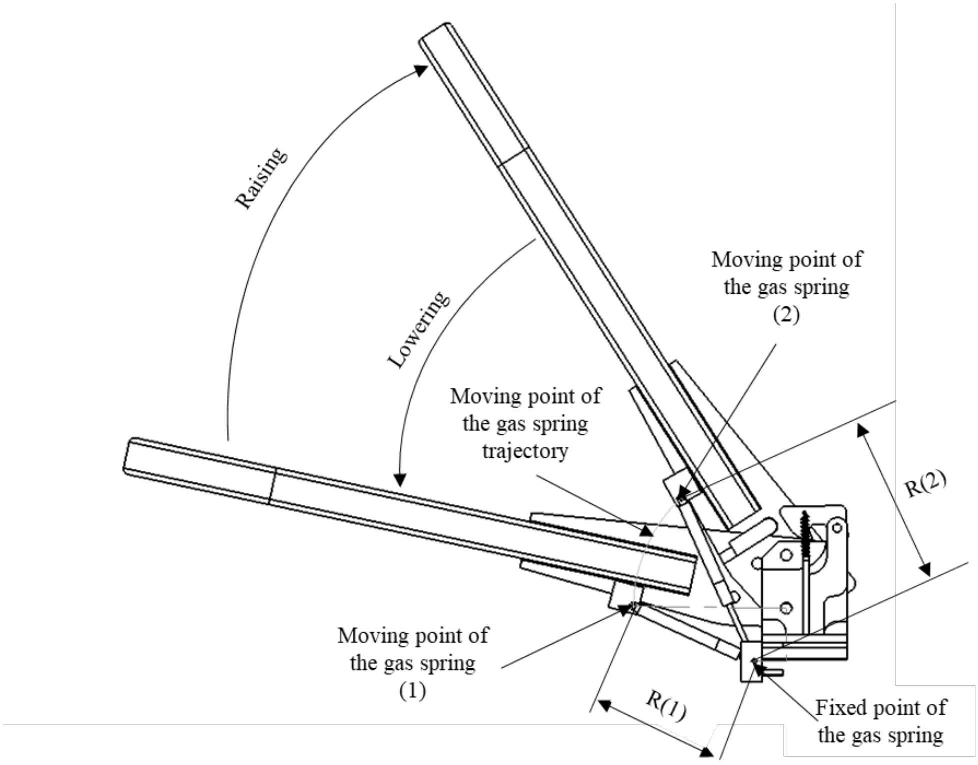


Figure 5. Geometrical compatibility and anchorage points of a linear actuator.

5. Design of an automatic locking device

The presence of an assistance system to raise the FRB minimizes the efforts of the operator when handling the rollbar, but in order to allow the operator safety in case of a rollover the rollbar shall be locked in the safe configuration. The locking phase is usually delegated to the operator, who has to insert pins in the locking holes on both sides of the tractor as shown in Figure 6.

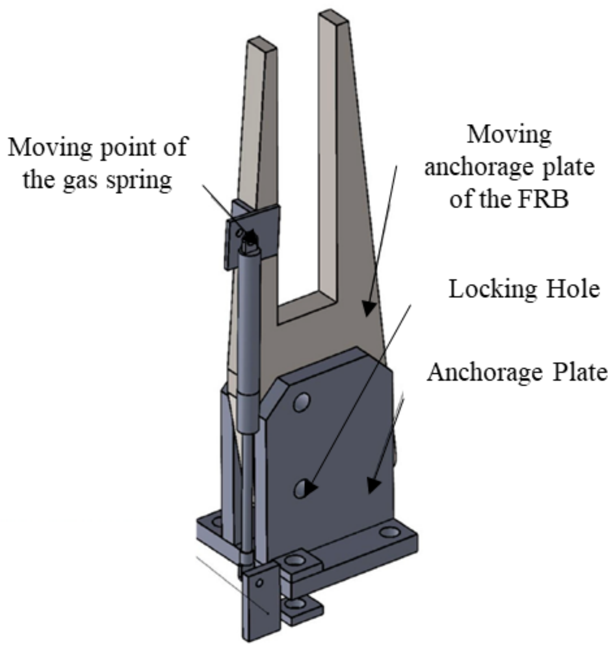


Figure 6. Details of the gas-spring assembly points and locking hole.

The implementation of an automatic locking device (ALD) can avoid these operations and the related risks. To achieve such a goal, it should be taken into account that an ALD shall be capable of preserving the operator in the OWP, as well as guaranteeing both the engagement phase and a suitable structural resistance. These requirements, together with the need of keeping the costs of the device at a feasible level, led us to implement a mechanical solution, capable of locking the rollbar automatically at the end of the raising phase and withstanding the loads deriving from the impact with the ground in case of a rollover. In Figure 7 a model of this device assembled with the PAS is provided.

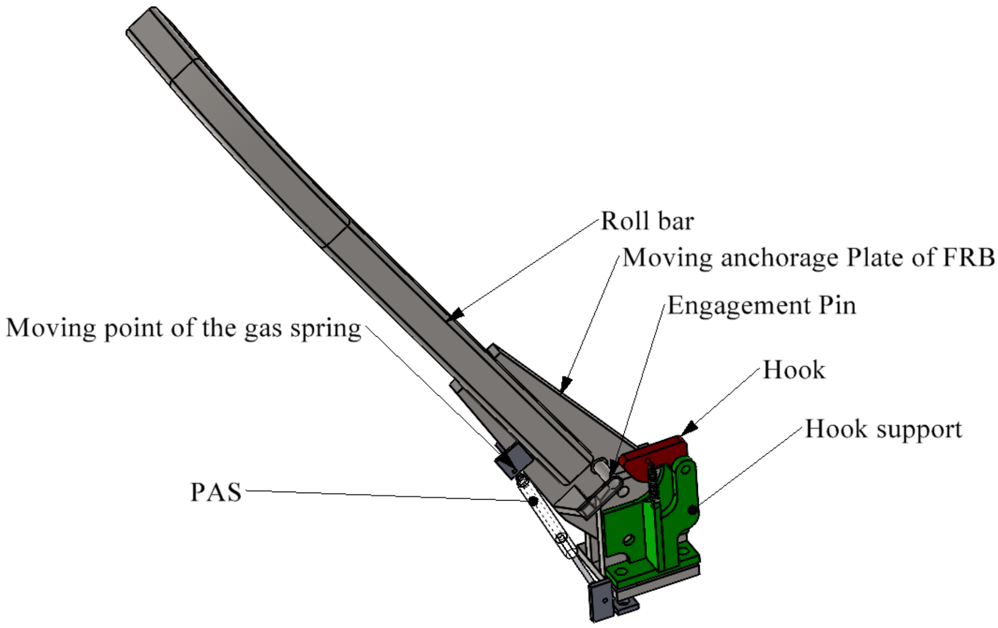


Figure 7. The FRB structural joint with the hook locking device.

Then in Figure 8, the operating phases of the locking device made of a pin and a hook are shown. In this case the locking pin (engagement pin) is fixed on the movable plate and the triggering and locking happen due to the contact with the hook.

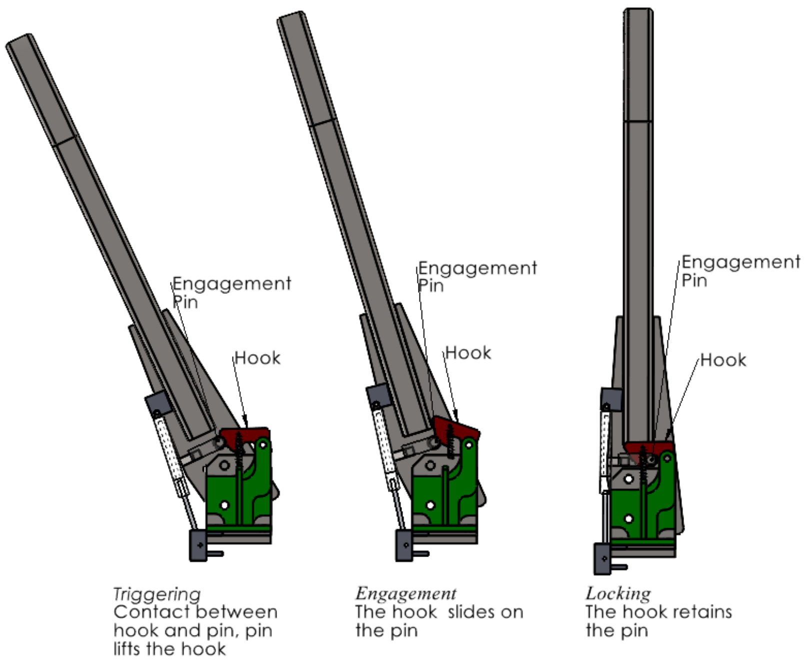


Figure 8. Operating phases of locking device.

6. Prototyping

6.1 Virtual prototyping

Once geometrical features are defined, the whole system integrating both the PAS and the ALD was developed virtually to test its kinematical and dynamic features. Actually, dynamic analyses are useful to evaluate the correct engagement of the automatic locking device (for example the correct coupling between the profiles of the hook and the circular profile of the locking pin). The structural analysis allows us to analyze if the locking device can bear the expected loads, which are calculated in accordance with the criteria provided by the OECD codes.
More in detail, the proposed locking device with hook and pin was tested with respect of the longitudinal load by means of the finite elements method (FEM). First, we considered the loads reached by a traditional structure characterized by manual locking pins: in this case, a load of about 21000 N was applied at the upper part of the rollbar, considering that:

- the roll-bar and plates material is S275 JR;
- the locking pin material has a yield strength of about 640 MPa and ultimate strength of about 800 MPa.

The contour plot of the Von Mises stress is shown in Figure 9, where it is evident that the most stressed component is the pin. Accordingly, proper dimensioning was carried out. In Figure 10 the final result of the dimensioning process is portrayed.

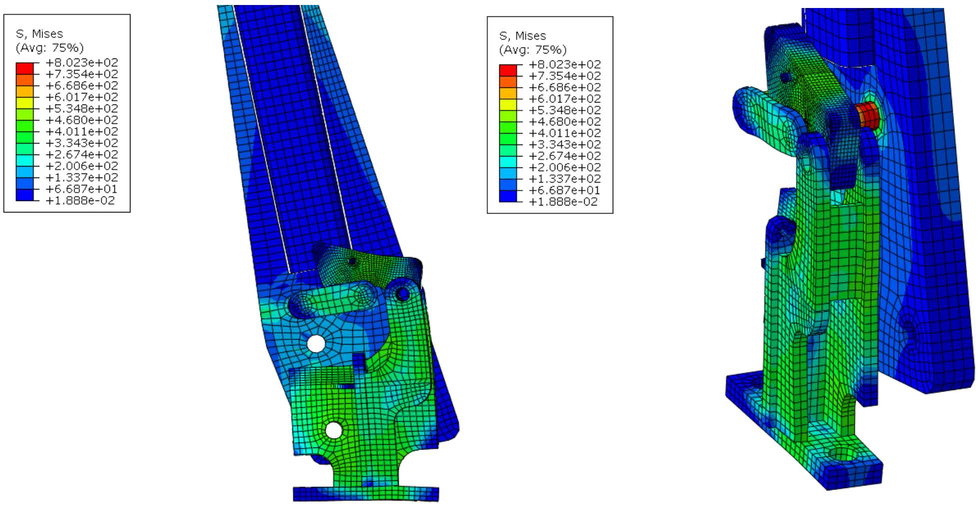


Figure 9. Von Mises stress diagram of longitudinal load, energy value 4500 Joule.

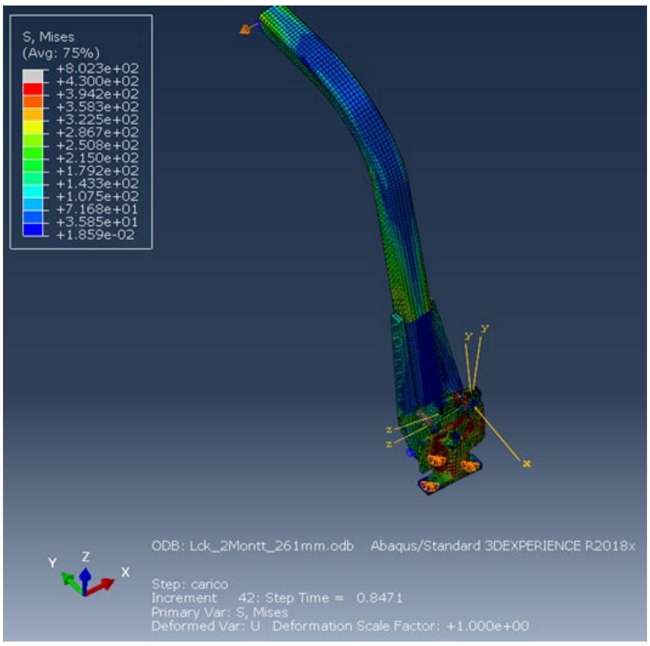


Figure 10. Final dimensioning of the system.

6.2 Physical prototyping

Finally, a physical prototype was developed in laboratory in order to practically test the feasibility of the system (Figure 11).

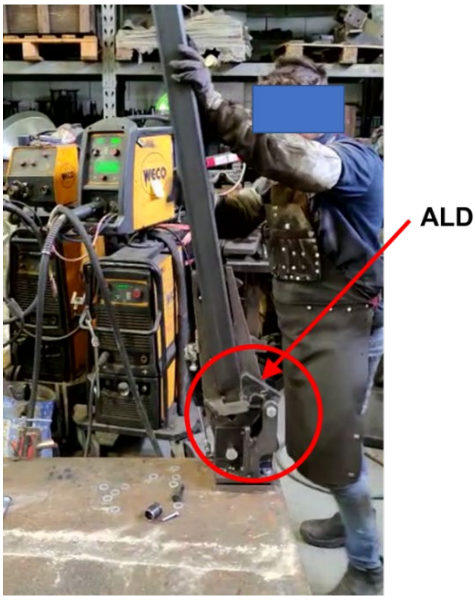


Figure 11. Physical prototype of the ALD.

This final step allowed us to better define the constructive features of the system.

7. Discussion of results and conclusions

The interaction between mechanical systems and the operator is a main issue in occupational safety in many sectors (Fargnoli 2021), In particular, in agricultural activities, the use of machinery such as tractors is the main cause of severe injuries and fatalities (Fargnoli and Lombardi 2020). Accordingly, the implementation of a human-centered approach can be beneficial to facilitating working activities, while reducing the risk of equipment misuse and risk-taking behavior (Micheletti Cremasco et al. 2021; Fargnoli et al. 2018). This study proposed an analysis of ergonomics issues related to the misuse of a protective structure such as the FRB, which is very diffused among operators using narrow-track tractors, providing a technical solution that can reduce their efforts and stress during working activities. Such a goal is in line with the research cues by Irwin and Poots (2018), who highlighted how relevant can be psychosocial factors, such as fatigue, time pressure, and stress in the misuse of machinery among farmers. The folded configuration of FRB is useful for specific tasks with low clearance between tractor and bushes, but it is also a dangerous one. This safety problem is strictly related to ergonomic issues, since the operator is entrusted with the raising and lowering phases of the rollbar, as well as with the locking phase. Raising and locking, or unlocking and lowering, are time-consuming maneuvers that also require significant physical effort.

Hence the risk of not raising the FRB or incorrectly locking is high, such as the risk of accidents when operating the FRB (whose weight can be more than 70 kg) without assistance.
Overall, the current study improves the results achieved by Gattamelata et al. (2021), providing more practical insights and contributing to augmenting knowledge on assistance systems dedicated to agricultural tractors' ROPSs.
In particular, the merit of the current study is twofold: on the one hand, it provides a practical solution to augment the safety level of operators, whose feasibility from the technical and economic standpoint has been verified and validated.
On the other hand, the study also proposes a methodological approach for dealing with similar problems. The main features of such an approach are illustrated in Figure 12, where starting from the ergonomics and human factors analysis, the main features of the system are defined.

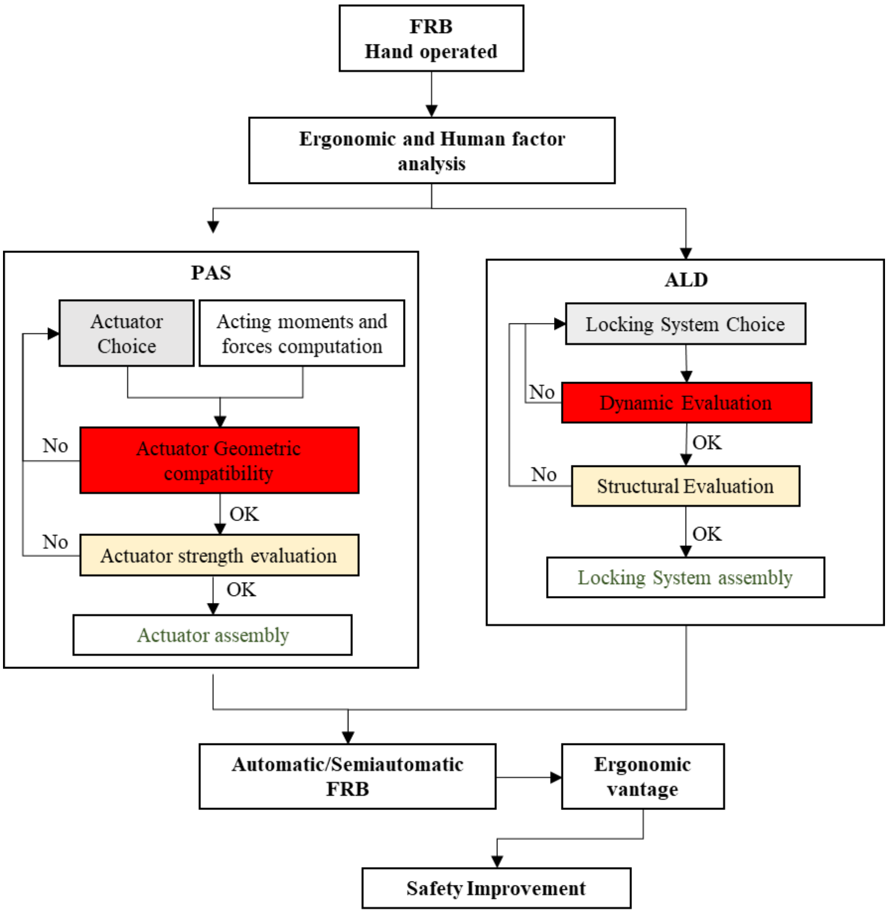


Figure 12. Flowchart of FRB ergonomic improvement method.

The latter represent the input for the development of both the PAS and ALD systems, whose implementation procedures are carried out in parallel. Then, the validation is carried out by means of both virtual and physical prototyping.
It has to be noted that the methodology considers ergonomic requirements applicable to the FRB, as the structural requirements which FRB shall comply nowadays according to European mandatory regulations. Such a procedure can be applied to both new tractor models and existing ones that need to be retrofitted, facilitating farmers in updating older tractors in accordance with mandatory safety requirements (Sorensen 2006; Caffaro et al. 2018). These criteria can be used also for other types of machinery, such as the ones used in construction and earthmoving

activities. Accordingly, further research is expected to augment the proposed methodology by means of additional practical applications.
Lastly, the study shows the important relationship between ergonomics and safety improvement, highlighting the fundamental role of human factors as a key factor in carrying out work activities safely.

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