A multibody approach applied to the study of driver injuries due to a narrow-track wheeled tractor rollover

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Abstract

This paper proposes the use of the multibody approach to evaluate the severity of the injuries to the driver associated with rollover of an agricultural tractor. A simple rollover accident of a narrow-track wheeled tractor was simulated in the multibody-FEM Madymo environment and the biomechanical damage to the operator with and without 2-point pelvic restraint was analysed. The structure of the tractor was considered to be unbendable, whereas i) infinitely rigid, ii) clay-based and iii) sand-based soils have been studied. The obtained results highlight the important role played by the seat belt in confining the farm operator within the safety volume maintained by the rollover protective structure (ROPS) of the tractor so that the injuries are reduced. The deformation of the soil produces lower acceleration and velocity values than those obtained with a rigid soil. On the other hand, as soil plastic deformations increase, the penetration of ROPS into the soil also increases, thus reducing the safety volume of the tractor and increasing the probability of interactions between the operator and the soil.

Introduction

The statistics on accidents with farm tractors highlight that rollover has been the main cause of fatal agricultural tractor accidents, followed by collision/crushing during the last five years (INAIL, 2014). It actually emerges that tractor rollover has been responsible for more than 70% of fatal accidents over the years 2009-2013; well below the frequency of collision/crushing, which has accounted for about 10% of the total events (INAIL, 2014). Agricultural tractors are particularly susceptible to rollover for a wide range of reasons, linked to tractors' peculiar characteristics (centre of mass position, mass distribution, narrow track, *etc*.) and to external working conditions (configuration of the terrain, tractor-implement combinations, work on extreme slope, *etc*.) (Hunter and Owen, 1983; Cole *et al*., 2006). On the other hand, the tractor is a versatile vehicle and operators sometimes stretch the use of the tractor beyond what the machine can safely manage (Spencer *et al*., 1985; Fabbri and Molari, 2004; Melvin *et al*., 2009). This means that there are numerous potential tractor rollover scenarios, and that rollover victims are tractor operators of all ages and experience on a variety of terrains (Liu and Ayers, 1996). According to EU directives (European Commission, 2003, 2005) manufacturers fit tractors with a rollover protective structure (ROPS) (European Commission, 1979, 1986, 1987; OECD, 2014) and a seat belt anchorage (European Commission, 1976; Molari and Rondelli, 2007; ISO, 2013). During tractor rollover, this 2-point pelvic restraint system holds the driver movements inside the safety volume maintained by the ROPS (Nichol *et al*., 2005; Silleli *et al*., 2008) and protects him also when involved in head-on collisions (Myers, 2002). In addition, narrow-track wheeled agricultural and forestry tractors generally have ROPSs consisting of two fixed or completely foldable front mounted posts (Mashadi and Nasrolahi, 2009; Silleli *et al*., 2007). The foldable type of ROPS is widespread in Italy because when folded down, it allows the tractor to work under trees or in greenhouses (Baldoin *et al*., 2008). Fatal accidents have recently occurred in Italy also involving narrow-track wheeled tractors equipped with two front mounted ROPS posts in the safety position (Pessina and Facchinetti, 2011; Laurendi *et al*., 2010). ROPS introduction has led to a sharp decrease in fatalities (Baker *et al*., 2008; Springfeldt *et al*., 1998), but serious injuries and some deaths due to failure of the ROPS still occur, and tractor rollover is still of interest in research to gain an understanding of the processes involved (Pessina and Facchinetti, 2011; Guzzomi *et al*., 2009). In this area of great interest for worker safety, the Author is carrying out a research aimed at extending the use of multibody techniques to the field of workplace accidents and farm tractor safety. The aim is to simulate tractor rollover scenarios in order to predict and assess the severity of ensuing damage to tractor operators and then to plan and implement a range of feasible countermeasures. The study is carrying out by evaluating the biological injuries to drivers (NHTSA, 1998; Ambrósio, 2001) using the multibody-FEM code Madymo (*MAthematical DYnamic MOdels*) (TNO, 2010). This software can simulate the dynamic behaviour of bodies systems emphasizing crashes between vehicles and evaluate injuries suffered by the occupants of the same vehicles (Euro NCAP, 2015; Bambach *et al*., 2013). Therefore, it is commonly used for safety problems concerning road vehicles and several types of numerical dummies of different complexity are available, and also models of seat belts and airbags.

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This paper reports the original results of using this approach to the rollover of an agricultural wheeled tractor with narrow track, on sloping soil, where the resultant weight forces falls outside the supporting convex polygon. The tractor composed of rigid bodies was equipped with ROPS and a 2-point pelvic restraint for the operator, simulated using a numerical dummy. During the overturning the tractor was considered stationary, even if this condition very frequently does not correspond to the real one. Firstly, the soil was also considered as infinitely rigid, leading to a pure multibody scenario; in these conditions the analysis compared biological trauma to the operator when i) he was restrained by a 2-point pelvic restraint or ii) unrestrained. The simulation model was then improved by considering real stiffness values and a constitutive material model, detailed in a following section, of two different types of soil: clay- and sand-based soils. Finally, considering only an operator restrained by a 2-point pelvic restraint, the results from the tractor-soil impact simulated dynamics obtained with these two soil types were compared with the results obtained in the case of rigid soil.

Materials and methods

Theoretical considerations

Multibody systems

A set of bodies interconnected by kinematic joints form a multibody system, whose motion within a reference space is drawn with respect to a coordinate system (X, Y, Z) (Diana and Cheli, 1998). A kinematic joint causes a constraint load on the pair of interconnected bodies so restricting their relative motion, described by the joint degrees of freedom. A rigid body *i* is defined by the mass, the location of the centre of gravity through a body local coordinate system (x_i, y_i, z_i), and the moments of inertia and the products of inertia specified relative to an inertia coordinate system, with its origin in the centre of gravity of the body. The motion of body *i* is totally specified by the location of the origin and the orientation of the body local coordinate system (x_i, y_i, z_i) relative to the reference space coordinate system (X, Y, Z) (Diana and Cheli, 1998). A system of bodies is set out through (TNO, 2010): i) the bodies: the mass, the inertia matrix and the location of the centre of gravity; ii) the kinematic joints: the bodies they connect, the type, and the location and the orientation; iii) the initial conditions.

The evaluation of biological damages and injury parameters

The effects of mechanical loads and specially impact loads on the biomechanics of the human body are covered by the injury biomechanics (Niederer, 2010). Injury takes place when the biological system deforms beyond a recoverable limit, causing harm to anatomical structures and modifying their normal function (Holzapfel and Ogden, 2006). Injuries have been ranked and quantified through anatomical scales that reckon the injuries rather than their outcomes. The most well-known, widely accepted anatomical scale is the abbreviated injury scale (AIS), an anatomically based global severity scoring system. It classifies each injury in every body region by assigning a code ranging from AIS0 (*non-injured*) to AIS6 (*currently untreatable/maximum injury*) (Schmitt *et al*., 2014). The loading conditions during impacts on human bodies are related to the levels of the injury scale like the AIS scale through the so-called *injury criteria*, that can be delineated as a biomechanical index of exposure severity or in other words as the potential for impact induced injury by its magnitude. Injury criteria are then essential implements to evaluate the gravity of accidental loading and the associated risk of sustaining injury. The *injury severity* or the gravity of the resulting damage is then evaluated with respect to the corresponding injury criteria, which allows calculation of an injury parameter that is a physical parameter or a function of several physical parameters. This injury parameter is compared with a certain threshold value.

In this paper, the injuries suffered by the tractor driver have been studied according to the values of the injury parameters, considering both cases: i) driver wearing a 2-point pelvic restraint; ii) driver without any retention system (McIntosh *et al*., 2010a). For the particular dynamics of the accident, attention was directed mainly to the head, neck and chest and lower limbs, therefore the injury parameters and the corresponding criteria used in the paper were (NHTSA, 1998; Ambrósio, 2001; Euro NCAP, 2015): the head injury criterion (*HIC*); the neck injury predictor (N_{ij}); the 3 ms criterion (*3ms*) to evaluate the damages occurring to thorax; the femur force criterion (*FFC*); and the tibia index (*TI*).

The *HIC* is a wide-use injury criterion to estimate the head injuries and its dates back to 1961 (Gadd, 1961). It is based on acceleration response only and the current version is represented as follows (NHTSA, 1998, 1999; Schmitt *et al*., 2014):

$$HIC = \left\{ (t_2 - t_1) \cdot \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} R(t)\,dt \right]^{2.5} \right\}_{\max} \qquad T_o \le t_1 \le t_2 \le T_e \tag{1}$$

where: $R(t)$ is the resultant head acceleration measured at the head's centre of mass over the time interval $T_o \le t \le T_e$; t_1 and t_2 are any two arbitrary time points during the acceleration pulse; T_o is the starting time of the simulation, T_e is the end time of the simulation. $R(t)$ is measured in multiples of the acceleration of gravity (g) and time in seconds. The length of the time interval greatly affects the *HIC* calculation, but according to the US Safety Standards (NHTSA, 1999), the maximum time window ($t_2 - t_1$) considered to give appropriate *HIC* values must not be more than $36 \cdot 10^{-3}$ s (thus called HIC_{36}). Furthermore, the maximum HIC_{36} must not exceed a value of 1000 for the 50th percentile during an impulsive frontal shock (NHTSA, 1999). The unit of the *HIC* is s $g^{2.5}$, which is usually omitted (Henn, 1998).

In automotive crashes, the loading of the neck is generally due to head contact forces and combined axial or shear load with bending (Sances *et al*., 1984). The N_{ij} has been proposed for evaluation of serious neck injuries in frontal impacts, caused by the load transferred through the occipital condyles (Kleinberger *et al*., 1998; NHTSA, 1998, 1999). A study that was the underlying notion for the N_{ij}, suggested combining axial forces with moments for a composite neck injury indicator (Prasad and Daniel, 1984; McIntosh *et al*., 2010b), therefore the N_{ij} criterion implies a linear combination of the neck axial force F_z and the flexion/extension bending moment. The values achieved by F_z and M_y are put in a suitable dimensionless form by using critical values F_{zc} and M_{yc}, that depend on the dummy typology and on the neck loading conditions (compression/tension and flexion/extension):

$$N_{ij} = \left| \frac{F_z}{F_{zc}} \right| + \left| \frac{M_y}{M_{yc}} \right| \tag{2}$$

Four different types of N_{ij}, are achieved by evaluating the criterion for all possible load cases: N_{TE} for tension and extension, N_{TF} for tension and flexion, N_{CE} for compression and extension, N_{CF} for compression and flexion. An injury threshold value of 1.0 applies for each load case. The critical values concerning the Hybrid III 50th percentile male dummy are: F_{zc} (compression/tension) 6160/6806 [N] and M_{yc} (flexion/extension) 310/135 [Nm] (NHTSA, 1999; Schmitt *et al*., 2014).

Thorax injuries are the most critical injuries after head injuries. The following different injury mechanisms can be characterized when the thorax is suddenly decelerated due to a strong impact: compression, viscous loading, inertial loading of the internal organs, and combinations of these (Lobdell, 1973). Furthermore, injury to the thorax commonly occurs with impacts from the front and the side as well as in all impact directions intermediate to these two. Different injury criteria (Kroell *et al*., 1974; Viano and Lau, 1985; Cavanaugh *et al*., 1993) have been developed in order to relate a definite loading of the thorax to a corresponding injury risk and of these, the so-called *3ms* states that in order to not suffer severe damage, the thorax centre of mass must not undergo an acceleration over 60 g for more than 3 ms. This value is used also to assess frontal impact crash worthiness (Schmitt *et al*., 2014; NHTSA, 1999). The definition of force tolerance values is closely connected to acceleration; a force limit of 17.6 kN equates to the 60 g acceleration level, presuming an effective thorax mass of 30 kg (Cavanaugh, 2002).

The *FFC* evaluates the compression force acting on the femur as well as the duration (ms) for which the force is applied. The compression force that is transmitted axially on each femur settles the *FFC* and the criterion threshold value is 10 kN (Brun-Cassan *et al*., 1982).

The *TI* entails the bending moments as well as the axial force in the

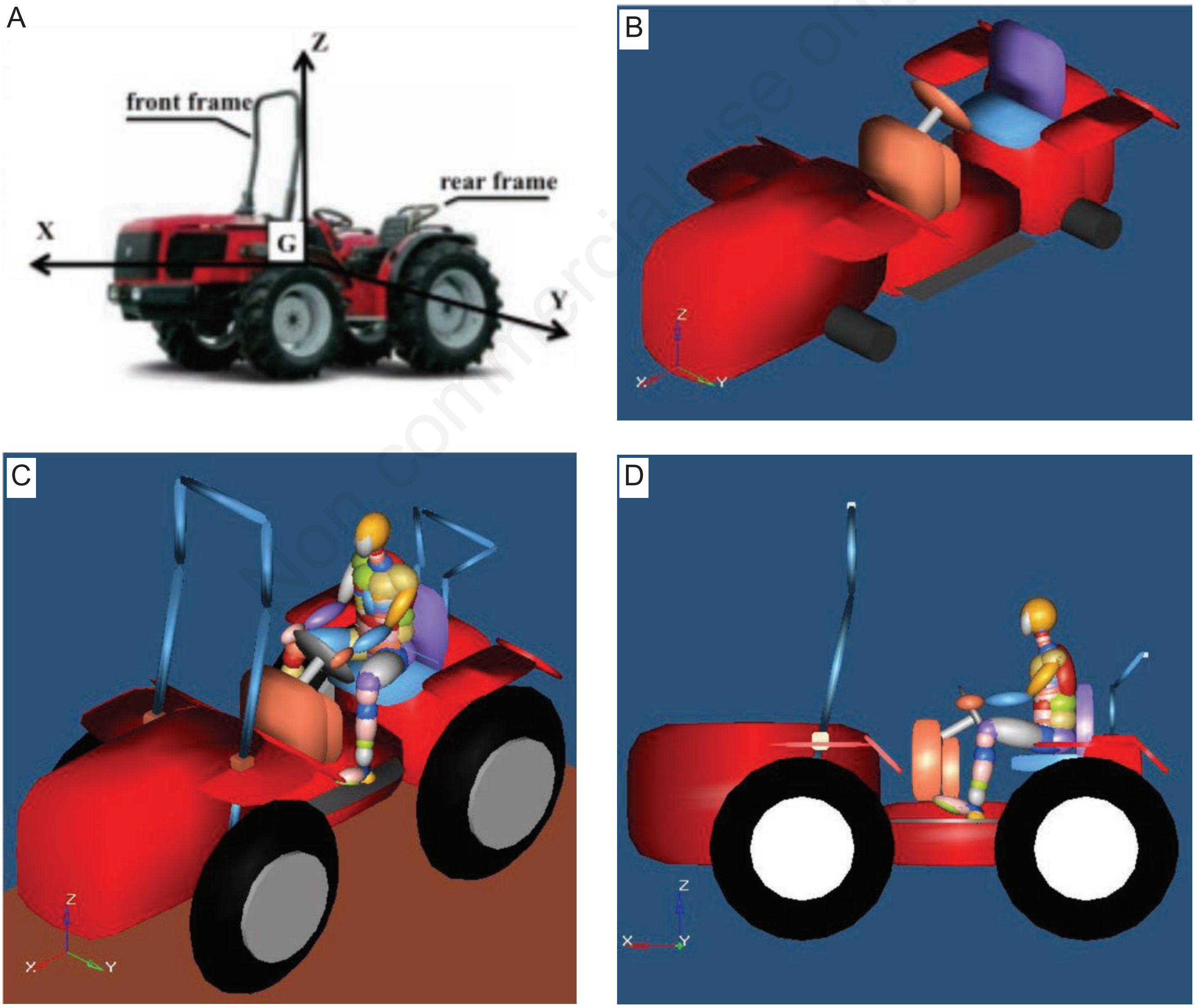

Figure 1. A) The tractor used for the study and the adopted frame of reference; B) 3D multibody model of the tractor case; C) 3D dummy-tractor model; D) lateral view of the model.

tibia with the purpose of preventing tibia shaft fractures. The *TI* is calculated by means of the following equation:

$$TI = \frac{F}{F_{cr}} + \frac{M}{M_{cr}} \qquad (3)$$

where *M* is the bending moment and *F* the compressive force. The critical values M_{cr} and F_{cr}, obtained in static bending tests of the tibia, are respectively 225 Nm and 35.9 kN for the 50th percentile male (Yamada, 1970). The maximum *TI* measured at the top and bottom of each tibia shall not exceed either location 0.4 or 1.3, respectively, for a highly secure or for a less certain estimation of the tibia injury severity (Yamada, 1970).

Simulation of tractor and accident scenario

The study used a commercial tractor model selected among those available on the market, an *Antonio Carraro* model TRH 9400 fitted with two ROPSs: a folding non-tiltable front protective structure and a rear fixed safety frame (Figure 1A). It is a narrow track wheeled tractor, also used in Apulian vineyards due its reduced size (Pascuzzi, 2013; Pascuzzi and Cerruto, 2015); furthermore its ease of manoeuvre allows its use also inside greenhouses (Blanco *et al*., 2014). By analogy to what is done in the field of automotive construction, the coordinate system reported in Figure 1A was adopted for the local reference frame of the tractor.

A variety of mechanical components compose the tractor, but from a kinematic point of view, it can be reproduced by a 3D multibody model, using native hyper-ellipsoidal Madymo surfaces, consisting of seven parts: i) the body frame; ii) the 4 wheels; iii) the front and the rear safety ROPS.

A (hyper) ellipsoid has equations of the type:

$$\left(\frac{|x|}{a}\right)^n + \left(\frac{|y|}{b}\right)^n + \left(\frac{|z|}{c}\right)^n = 1 \qquad (4)$$

where *a*, *b* and *c* are the semi-axes of the (hyper)ellipsoid and *n* is the degree. The equation describes an ellipsoid if *n*=2 and as the degree *n* increases the (hyper)ellipsoid will approximate more and more a rectangular shape (TNO, 2010).

The entire tractor model was then assembled by fixing the rigid parts each other by kinematic joints. The safety frames were fixed to the body frame by two brackets. Each of the four wheels was connected to the body frame by a cylindrical joint. The whole tractor model was then inserted into the input scenario, connected to a reference space linked to a coordinate system (X, Y, Z) by a free joint. The dynamic behaviour of the tractor is affected by the inertial characteristics of its parts and these quantities were evaluated according to the data and drawings provided by the manufacturer (Figure 2). The shape of a body is not relevant to the equations of motion except when a body contacts other bodies or its environment, but during the simulated rollover some parts of the tractor come into contact with the terrain (other body) and then it is necessary to define the shape of these parts (TNO, 2010).

Tractor case model

The tractor case reproduced the whole tractor without the wheels and the two ROPSs. The location of its centre of gravity and the inertia tensor have been evaluated according the reference frame of the tractor, reported in Figure 1A, whose origin corresponded to the location of its centre of mass. The inertial properties were evaluated through the overall scheme provided by the manufacturer, in which the tractor has been divided into a set of geometrically simple units, and the mass and the locations of centre of mass has been reported for each of these units.

The following components of the case were modelled using surfaces allowed by the software: i) block of front bonnet with engine; ii) block of the central frame; iii) block under the driver's seat; iv) rear block that includes the organs for coupling the implements; v) wheel hubs; vi) block comprising the dashboard and steering wheel support; vii) seat and backrest; viii) steering wheel and its rod; ix) platform; x) front and rear fenders.

The software provided that if two bodies come into contact, at least one of the respective surfaces must have an (hyper)ellipsoidal form. The (hyper)ellipsoidal form has been then considered for all the surfaces of the tractor that come in contact with the soil (flat surface) during the simulated roll-over. To better approximate the hyper-ellipsoidal surface to the parallelepiped form it has been considered *n*=5 in Equation (4).

The surfaces relating to the hubs and the steering rod, however, were chosen as cylindrical because this better represented the actual geometry of these components and during rollover these should not be in contact with the soil. The model concerning the tractor case is reported in Figure 1B.

Wheels modelling

The wheels of the TRH 9400 tractor have the same sizes and come into contact with the terrain. Therefore the ellipsoidal surface was chosen to model the tyres and the plane for the terrain, because the ellipsoidal surface best approximates the shape of the peripheral area of the tyre. Furthermore, a further cylindrical surface representing the rim was introduced into the model of the wheel as an embellishment.

The wheel was jointed to the case by a revolute joint, which allows only the rotation around the axis of the wheel. In actual fact, this joint did not affect the simulation since overturning was simulated with the tractor in static conditions and so the wheels did not rotate around their axis.

Front and rear rollover protective structure modelling

The drawings supplied by the manufacturer highlighted that the real geometry of both front and rear ROPS was very complex but for the aim of this work it was necessary only to define an accurate geometry of the area that could be in contact with the terrain using the hyper-ellipsoidal form. The model and the inertial frame used for the simulation are shown in Figure 1C and Figure 1D.

The soil

The threshold slope for the rollover has been evaluated according to the data and drawings provided by the manufacturer (height of the centre of gravity h_g=690 mm; track width t_r=1130 mm) using the following (Biondi, 1999):

$$\tan(\alpha)=\frac{t_r}{2\cdot h_g}=\frac{1130}{2\cdot 690}=0.819 \rightarrow \alpha=39.31 \qquad (5)$$

The technical procedures (OECD, 2014; ISO, 2008) for testing protective structures front-mounted on narrow-track wheeled agricultural tractors require preliminary tests to be carried out before the strength tests of the ROPS: these are the lateral stability test and the non-continuous rolling test. This last one executed on a 1/1.5 test slope covered with a material characterized by a fixed cone penetration index makes it possible to determine the critical ROPS height to prevent continuous roll. In this paper, the soil has been considered infinitely rigid to assess the operator biological traumas in these operative conditions and so the criteria of the aforesaid standards were not performed. On the other hand, a continuous rolling of the tractor occurred in the simulation performed by positioning the tractor on the plane with the calculated slope. Therefore, three planes with different slopes were supposed to compose the soil to give non-continuous rolling of the tractor. At the beginning of the simulated dynamics, the tractor was positioned on the plane with a slope of 40°, in such a way that the resultant weight force was able to make the tractor roll over. The intermediate plane with a slope of 20° was actually the one that the rolling over tractor finally hits. The third plane was horizontal (Figure 2).

At first an isotropic elastic, perfectly plastic constitutive model was used (Peruzzi and Sartori, 1997). Subsequently, the simulation model was improved by considering two types of terrains with quite different mechanical properties: i) a sand-based soil; and ii) a clay-based soil. The parameter values used in the accident model are reported in Table 1 (Lancellotta, 1987).

The tractor operator - dummy

The numerical dummies allow simulation of the dynamic behaviour of the real instrumented dummies commonly used in the crash tests for road vehicles (TNO, 2010). As is well known, dummies have suitable joints calibrated on the basis of knowledge obtained in the field of biomechanics through tests on volunteers and dead bodies (Schmitt *et al*., 2014). The dummy numerical models are then multibody systems with kinematics joints and restraints, which reproduce the connections present in the instrumented dummies usually used in the crash tests. The Hybrid III 50th percentile male dummy, representing the size and weight of an *average* adult male, simulated the tractor operator in the rollover scenario (TNO, 2010). In the technical standard (European Commission, 1987; OECD, 2014) the position of the driver on the narrow track tractor is considered as prone on the steering wheel. In this study, the chosen dummy, defined by a single multi-body system, was positioned on the tractor seat with its arms holding the wheel (Figure 1C and D).

Results and discussion

The roll-over kinematics

The analysis of the kinematic parameters concerning the simulation of the tractor overturning does not highlight appreciable differences between the case of the belted dummy and the case of the unrestrained dummy, probably because the dummy mass compared with that of the whole tractor is negligible. Therefore the obtained kinematic results are reported only with reference to the belted dummy. Some kinematic quantities of main interest concerning: i) clay; ii) sand; and iii) rigid soils considered have been represented as functions of time in Figures 3 and 4, *i.e.*, the longitudinal (x-) component of the tractor body angular velocity and acceleration. The rapid variation of the components of the velocity and acceleration at the instant of time $t^* \approx 1130$ ms from the beginning of the simulation highlights the main shock to the system when hit the soil on its side (Figure 2).

As expected, the tractor bounced on the rigid soil with a series of fol-

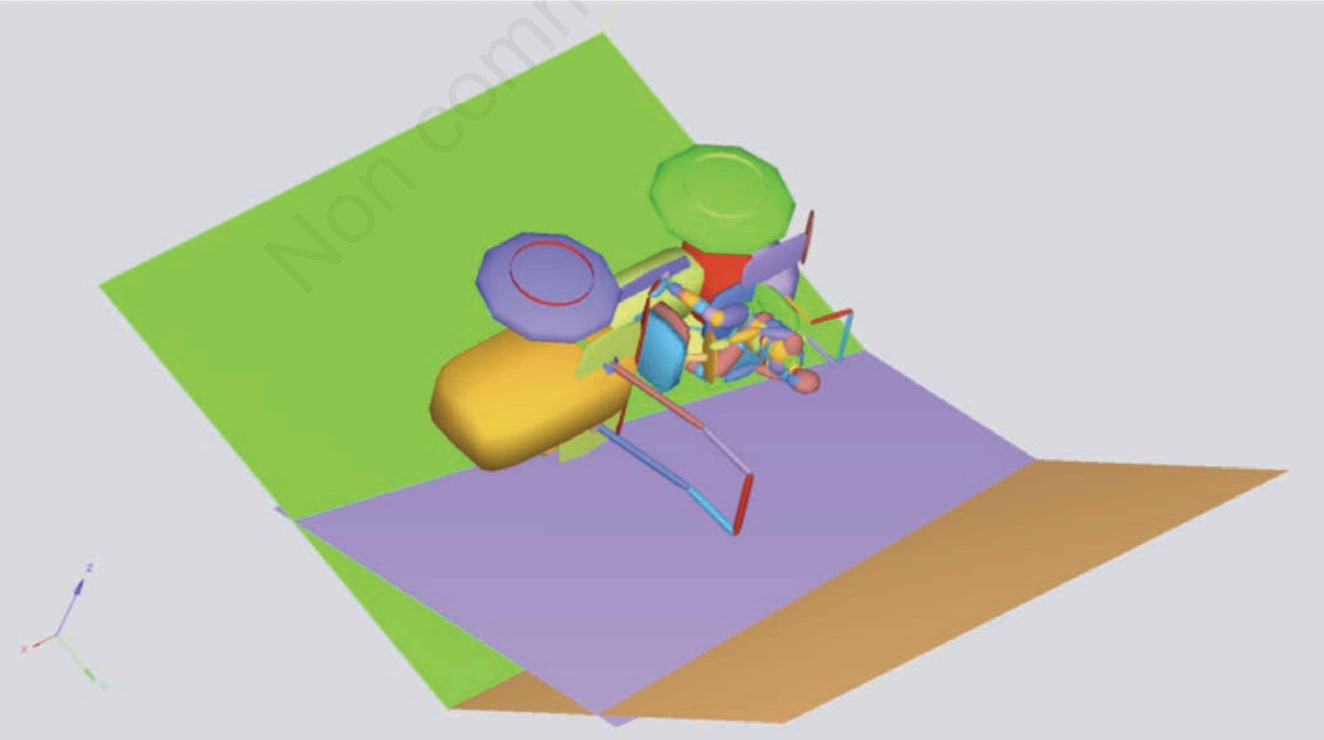

Figure 2. The instant of time in which the main shock occurs (1130 ms).

lowing shocks, each of which contained a step variation of the angular velocity vector (Figure 3) and an extremely high peak value of the angular acceleration (Figure 4). Similar considerations can be made referring to velocity and acceleration of the tractor body centre of gravity, which on average moved down along the slope. It is useful to underline that the body surfaces are supposed to have a hyper-ellipsoidal form, therefore the contact region between the parts of the system and the soil was in each case reduced to a single contact point as the body stiffness approached infinity. This behaviour is actually far from the real situation. Furthermore also the two frames were considered infinitely rigid and this is clearly a non-real situation.

On the other hand, in the cases of sandy and clayey soil all the acceleration peaks reduce to realistic values and, in particular, the time interval during which the first main rebound of the tractor body becomes longer. In conclusion, a slower variation of the kinematic quantities was obtained, with a consequently more realistic representation of the rollover dynamics of the tractor.

The final time of the simulations is shown in Figure 5. The plastic deformations of the soil related to the interaction with the tractor body and mainly with the front safety frame can be clearly seen.

The biological traumas occuring to the operator

In the case of rigid soil, comparison of the values concerning the considered injury parameters regarding the operator restrained with a 2-point pelvic restraint and the non-restrained operator highlights that the biological damage in the absence of a restraining system are severe, as expected (Figure 6). The analysis of head injuries is linked to accelerations that this part of the body suffered during the simulation. The unrestrained driver was thrown from the seat and impacted with the soil; the head came into contact with the soil after 1328 ms and the contact force reached its maximum value at 1330 ms. The results emphasized an *HIC* value of 1465.4 (Figure 6), in the time range corresponding to highest resultant acceleration, that was between t_1 = 1327.3 ms and t_2 = 1331.1 ms. The restrained driver was not thrown from the tractor, and remained inside the safety volume maintained by the ROPS. However, the head suffered acceleration variations, even if the maximum value of the acceleration vector was 217.5 m s^{-2} (t = 1226 ms) corresponding to 22.2 g, which is far below the threshold value, and the *HIC* value was equal to 124.65 in correspondence with the time interval with extreme t_1 = 1223.5 ms and t_2 = 1259.5 ms (Figure 6). Therefore, in this case the risks of serious or

Table 1. Mechanical property parameters of the two considered soils.

Soil	Mass density (kg/m³)	Young's modulus (MPa)	Poisson's ratio	Yield stress (kPa)
Sand	1600	200	0.3	200
Clay	1800	40	0.3	120

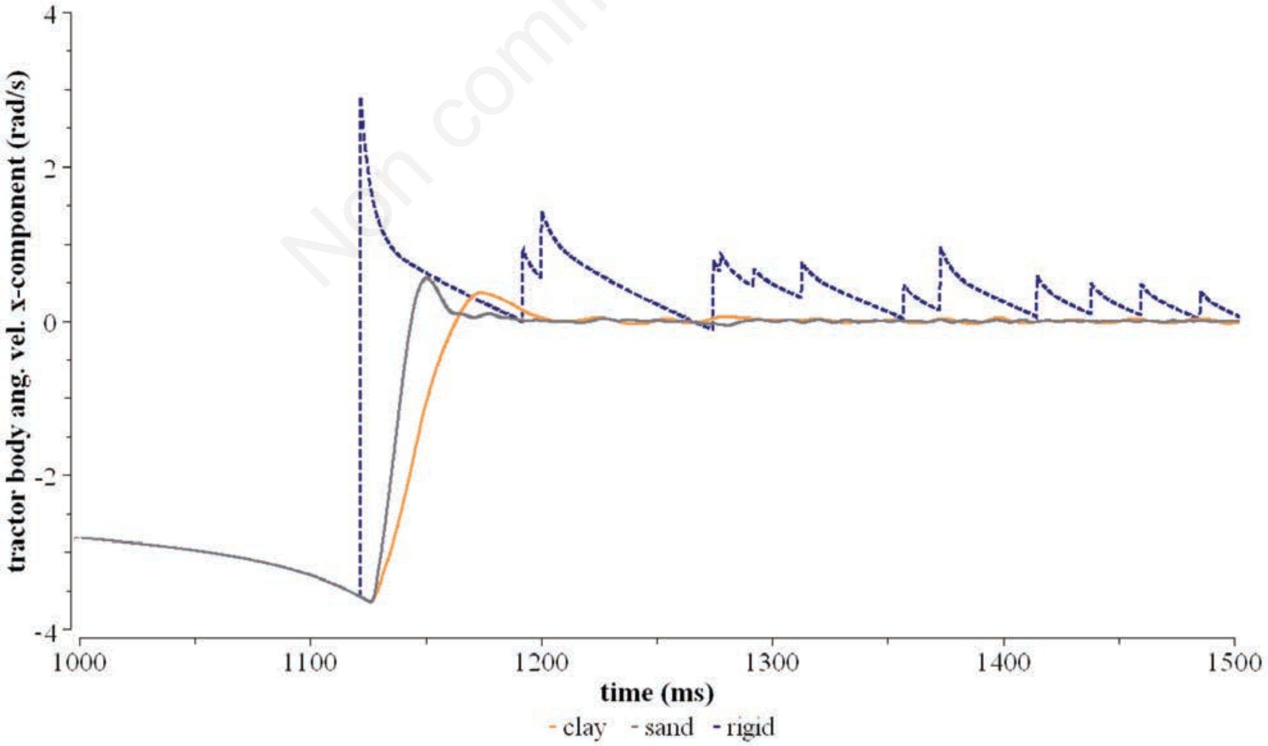

Figure 3. The x-component of the tractor body angular velocity as function of time.

fatal injury were minimal. The neck injury predictor regarding tension and extension loading (N_{TE}) exceeded the corresponding threshold value only for the unrestrained driver. Due to its impact with the soil the head rotated rearwards and tensile force and an extension moment were applied on the neck. Tension-extension loading commonly occurs when unbelted occupants hit the windscreen or when the chin impacts on the dashboard (Schmitt *et al*., 2014). On the other hand, the compression-flexion loading (N_{CF}), which may result from a frontal impact in which the torso is restrained and the neck is meant to stop head movement, did not exceed the limit value for both the considered drivers. The non-restrained operator's thorax centre of mass underwent an acceleration of 718.92 m s^{-2}, corresponding to 73.3 g following the crash with the soil. This value was then beyond the threshold value for *3ms*, while the acceleration suffered by the restrained driver was clearly far below this limit. Furthermore, the non-restrained operator's collision with soil affected the tibia because the limit value for *TI* was exceeded; there were no consequences for the femur because *FFC* threshold was not exceeded. Finally, the possibility offered by the pelvic belt of confining the operator within its safety volume greatly reduced all injuries, as was also expected. In this case, the criteria threshold was exceeded only for the tibias, but less than in the case of a non-restrained operator. A side-bag with an opportune counter-reacting structure could be used in order to completely avoid this kind of injury. The values of several injury parameters in the case of operator restrained with a 2-point pelvic belt are reported in Figure 7, where the results from the simulated tractor-soil impact obtained considering real stiffness values and the constitutive material model of the clay- and sand-based soils are compared with those obtained in the case of rigid soil. None of the injury parameters exceeded the corresponding threshold value and this aspect has highlighted the usefulness of the seat belt, as expected. Furthermore, driver injury increased as the stiffness of the soil decreases as seen from comparison of the biological damage values obtained with the different soil simulations: the injuries assessed with a clayey soil were greater than those obtained with a sandy soil, which were greater than those obtained with a rigid soil. The distinct stiffness values clearly influenced the extent to which the ROPS penetrated into the soil and so soil deformation also affected the safety volume, which diminished as the stiffness of the soil lessened. In conclusion, the increased deformation of the soil caused a more probable interplay between the tractor driver and the soil.

Conclusions

The multibody techniques currently utilized in the automotive sector could also be used for agricultural accidents, and this paper reports an example in which this approach is used to evaluate the severity of the injuries to the driver associated with the rollover of an agricultural tractor. According to the obtained results, the seat belt plays an important role in confining the operator inside the safety volume of the tractor so that all injuries are reduced. In the simulated accident, the use of the 2-point pelvic restraint prevented the operator from being thrown out of the tractor and impacting with the soil, thus preventing damage to the head and neck. Soil deformation produced lower acceleration and velocity values than those obtained considering a rigid soil. Furthermore, the obtained results have shown that the higher the soil's plastic deformations the greater was the penetration of the ROPS into the soil, thereby reducing the safety volume and increasing the possibility of interactions between the operator and the soil. It should also be noted that with the roll-bars shaped as rigid bodies, the acceleration of the head and the stresses discharged on the neck at the time of contact between them and the soil were definitely more than the real stresses that would have occurred if the two roll-bars had been modelled as deformable bodies. The real ROPS are far from being perfectly rigid in these accidents and extensive plastic deformation of ROPS

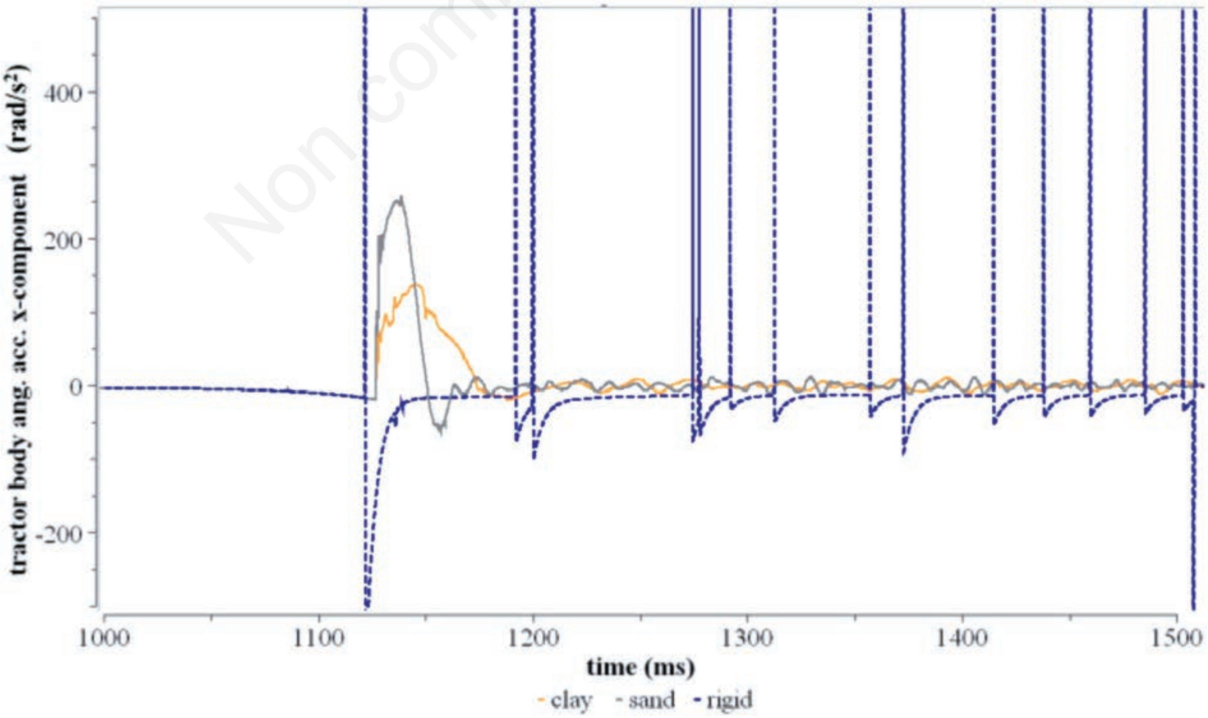

Figure 4. The x-component of the tractor body angular acceleration as function of time.

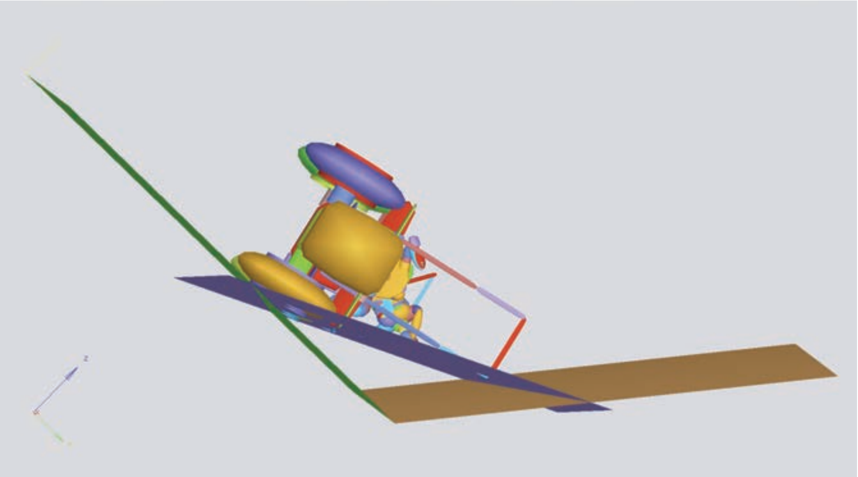

Figure 5. End of the simulation: it is possible to visualise the contacts between the dummy-tractor system and the soil.

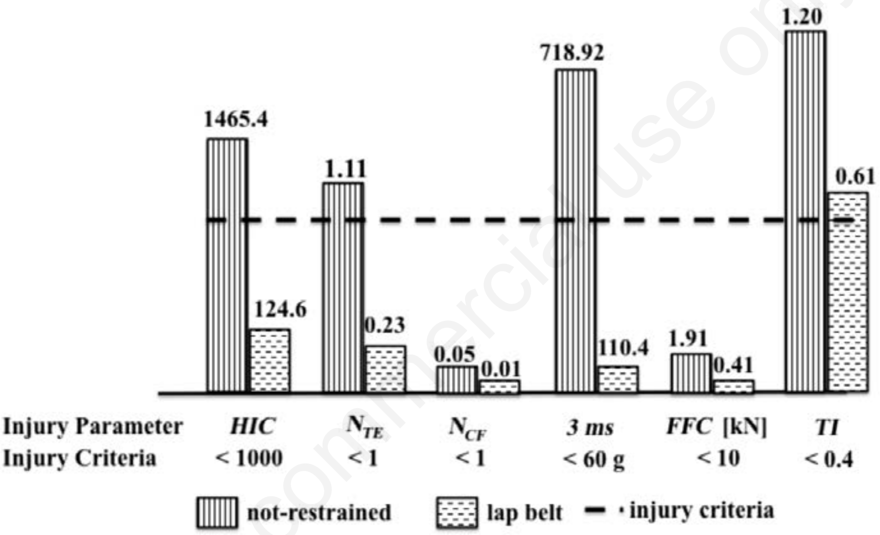

Figure 6. Comparison of the main injury parameters in the cases of: i) non-restrained dummy; and ii) dummy restrained by a 2-point pelvic belt. *HIC*, head injury criterion; N_{TE}, neck injury predictor for tension and extension; N_{CF}, neck injury predictor for compression and flexion; *3ms*, criterion for thorax injury; *FFC*, femur force criterion; *TI*, tibia index.

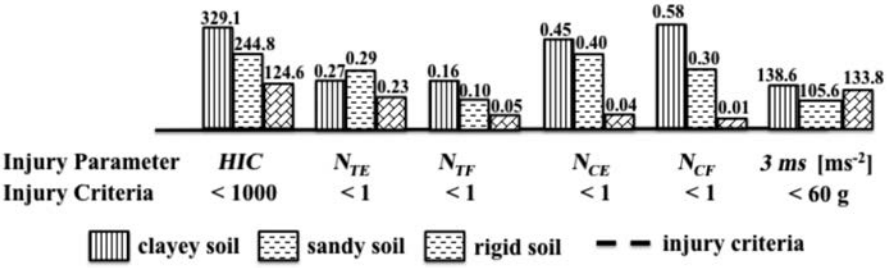

Figure 7. Comparison of the main injury parameters in the case of operator restrained with a 2-point pelvic belt considering each one of the examined soils. *HIC*, head injury criterion; N_{TE}, neck injury predictor for tension and extension; N_{TF}, neck injury predictor for tension and flexion; N_{CE}, neck injury predictor for compression and tension; N_{CF}, neck injury predictor for compression and flexion; *3ms*, criterion for thorax injury.

structures during rolling absorbs energy, lowering acceleration peaks.

Therefore, further improvement of the simulation model will take account of the deformability of the safety ROPS and a more accurate model of the agricultural soil, and will be dealt with in a study of the FEM problem. Furthermore, in addition to the finite element analysis of the arches of protection, with which to get an overview of their most truthful stresses and deformations, the deformation of the structures through appropriate discretization of the model in rigid bodies connected by junctions of various type, able to develop actions that reproduce the characteristics of resistance of the elements deformed, will be pointed out. An example of this approach might consider a plastic hinge in the attachments between strings and casing, such as to shape the plastic deformation.

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