Turning stability analysis of a 12-kW self-propelled riding-type automatic onion transplanter to ensure user safety

M Chowdhury\textsuperscript{1,2}, M A Gulandaz\textsuperscript{2}, S Kiraga\textsuperscript{3}, M Ali\textsuperscript{1}, M N Reza\textsuperscript{2}, H J Kwon\textsuperscript{3}, D H Lee\textsuperscript{1,2} and S O Chung\textsuperscript{1,2}

\textsuperscript{1}Department of Agricultural Machinery Engineering, Graduate School, Chungnam National University, Daejeon 34134, Republic of Korea
\textsuperscript{2}Department of Smart Agricultural Systems, Graduate School, Chungnam National University, Daejeon 34134, Republic of Korea
\textsuperscript{3}Tonyang Moolsan Co., Ltd., Iksan 54576, Republic of Korea

E-mail: sochung@cnu.ac.kr

Abstract. The lateral turning stability analysis of the self-propelled riding-type upland crop machinery is an important issue as the cultivation lands are usually uneven, and cause severe work-related injuries, even death. In this study, the lateral turning stability of a 12-kW self-propelled riding-type automatic onion transplanter was analyzed for ensuring the operator’s safety during transplanting operation. To evaluate turning stability, the center of gravity (CG) of the developed onion transplanter was determined theoretically. Then, a simulation was carried out to identify the lateral turning stability angles using the RecurDyn software, and the results were validated through tests. Rollover angles in the loaded and unloaded conditions were also checked. The statistical significance of the replications was determined by a one-way analysis of variance (ANOVA). According to the physical dimensions of the onion transplanter, the mathematical rollover angle was 34.5°. The average simulated rollover angles were 43.9°. Due to the symmetrical structure, a 4.5° turning difference was observed between the right and left side turning, and a 3° angle difference was occurred due to the variation of load conditions. The rollover angles fulfilled the ISO (International Organization for Standardization) standard. The findings of this study would be helpful for the manufacturers to ensure operator safety during the upland crop machinery operation in uneven and sloped lands.

1. Introduction
Onion (\textit{Allium cepa} L.) is one of the major industrially marketable crops widely cultivated in different countries of the world [1]. It contains several types of functional components such as carbohydrates, proteins, vitamin C, B6, folic acid, sugars (glucose, fructose, galactose, and arabinose), minerals (Ca, Fe, S), flavonoid, antioxidant, and polyphenol components, which act as an alternative of medicines and promotes health [2, 3]. It can be consumed as a raw and also in cooked condition. The cultivation area of onion was 2.4 million ha in 1996, which became 4.9 million ha in 2016, and the production increased from 60 to 90 million tons by this 20 year [4]. Despite this, the cultivation rate of onion is decreasing in many countries, such as Korea (1.41 million tons in 2010 to 1.17 million tons in 2020) [5], due to labor intensiveness, aging of the farmers, high labor cost, and low mechanization rate. The conventional method of onion transplantation needs 185-260 man.hr.ha\textsuperscript{-1}, which is very labor-intensive and non-efficient [6]. The semi-automatic and automatic transplanting mechanisms are also...
developed. Semiautomatic transplanter are mounted by an external machine (i.e., tractor) and the growers manually put the seedlings to the planting device manually [7]. Contrariwise, onion seedlings are feed mechanically into the hopper of the planting device according to the self-propelled mechanisms of the automatic transplanter. An automatic onion transplanter might be driven automatically or by an operator, or can be mounted by another machine (i.e., tractor) [8]. The operator-driven or self-driving automatic onion transplanter are getting popular in recent times.

Turning stability of an automatic upland crop transplanter needs to be considered seriously as upland crop (i.e., onion, cabbage, or radish) farms are usually rough and inclined, which often caused accidents and injuries, even death of the operators. These farming accidents cover a large portion of agricultural machinery hazard statistics. The rollover tendency of the onion transplanter depends on the stability, which is affected by the static, dynamic, and operational variables of the transplanter. Wheelbase, tread width, and center of gravity are considered as static and dynamic factors, and the operational speed, turning radius, land inclination, and surface roughness are considered as operating parameters [9]. The lateral and longitudinal stabilities of any transplanter are determined by either calculating the center of gravity (CG) and stability angles theoretically or measuring the rollover angle practically. The CG depends on the physical properties, and the rollover angle relies on the vertical height of the CG of the transplanter. According to the ISO 16231-2, 15 to 45° stability angle is allowable based on types of agricultural machinery [10]. The maximum 15° slope is recommended for agricultural machinery operation in Korea and Japan to minimize the rollover risk with sufficient farming efficiency [11]. The stability angle is also affected by the operator weight and the carrying load [12]. Moreover, the internal fluids (fuel and lubricant) affect the steadiness of the CG. However, several studies were conducted and marked it as a negligible issue [13].

Lateral turning stability analysis is essential to determine the rollover angle, operator safety along with the operational precision and accuracy. It could be determined theoretically and also by computational simulations considering the relevant factors. The considered 12-kW self-propelled riding-type automatic onion transplanter was under development. Therefore, the objective of this study was to identify the lateral rollover angles through mathematically and computational simulation process considering both loaded and unloaded conditions.

2. Material and methods

2.1. Structure and working principle of the onion transplanter

A 3-D model of the 12-kW self-propelled riding-type automatic onion transplanter was shown in Figure 1(a), which consisted of two major parts, operator-driven four-wheel vehicle and onion transplanter. The physical properties of the onion transplanter were summarized in Table 1. Like other automatic vegetable transplanter, onion transplantation process consisted of three major steps or mechanisms: seedling picking or extraction mechanism, seedling supplying or conveyor mechanism, and seedling planting or planting mechanism [14, 15, 16, 17]. The onion seedlings are extracted from the growing cell tray using the pushing pins. The picking mechanism is a combination of the pushing pins mechanism and seedling carrying assembly. Onion seedlings were transplanted in 6 rows through three separated units of seedling picking, convey, and planting mechanisms. All these units are synchronized together in such a way that each unit can supply 14 seedlings per cycle to the conveyor mechanism. So, the current transplanter is able to extract and supply 42 seedlings to 6 separated conveyors. Contrariwise, each conveyor mechanism receives 6 seedlings per cycle, which are feed into the hopper and transplanted in the soil bed through the rotary planting mechanism. Eight auxiliary pressing wheels (two for each row) pressed the soil finally to maintain the proper seedling uprightness and minimum mulch film damage.
Figure 1. 3-D model of the 12-kW self-propelled riding-type automatic onion transplanter (a), and major components of the transplanting part (b).

Table 1. Specifications of the 12-kW self-propelled riding-type automatic onion transplanter.

| Specification of 4-wheel vehicle | Specification of onion transplanter |
|----------------------------------|-------------------------------------|
| Length (mm)                      | Length (mm)                        | 875                          |
| Width (mm)                       | Width (mm)                         | 1626                         |
| Height (mm)                      | Height (mm)                        | 2036                         |
| Ground clearance (mm)            | Ground clearance (mm)              | 260                          |
| Wheelbase (mm)                   | Number of rows                     | 6                            |
| Wheel track (mm)                 | Row spacing (mm)                   | 200                          |
| Front wheel radius (mm)          | Hill spacing (mm)                  | 174                          |
| Rear wheel radius (mm)           | Power (rpm)                        | 74                           |
| Transmission level               | Transplanting speed (msec$^{-1}$)  | 0.24                         |
| Maximum power (kWrpm$^{-1}$)     | Transplanting mechanism            | Mechanical                   |

2.2. Calculation of center of gravity

Rollover stability has a significant influence on user safety among the factors that result in farm machinery hazards. Calculation of the CG coordinates, transverse rollover angle estimation, and simulation and validation of the static or dynamic rollover angles are important steps of stability analysis. A short survey of the identified static lateral rollover angle of several off-road agricultural machinery was shown in Table 2.

Table 2. Survey of the lateral rollover angle of some off-road agricultural machinery.

| Rollover angle of off-road agricultural Machinery | Lateral rollover | Reference |
|--------------------------------------------------|------------------|-----------|
|                                                   | Left             | Right     |
| Tractor mounted baler system                      | 19.5°            | 19.5°     | [18]     |
| Chinese cabbage harvester                          | 32°              | 30°       | [11]     |
| Tractor mounted onion harvester                    | 26.74°           | 38.07°    | [19]     |
| Tractor mounted Chinese cabbage harvester          | 33.2°            | 45.6°     | [20]     |
| Terrain vehicles (Honda Rubicon TRX 500)          | 41.3°            | 33.7°     | [21]     |
| Off-road utility vehicles (Polaris Ranger)         | 46.2°            | 37.7°     | [21]     |
| Lawn tractors (Kubota BX2200)                      | 40°              | 36.4°     | [21]     |
Figure 2. Schematic of model of the onion transplanter system: side view (a), and top view (b).

Center of gravity (CG) is an imaginary point where the whole mass of an object is acted through. A schematic model of the onion transplanter was constructed, as shown in Figure 2, to calculate and observe the transference of CG. First, the CG of the four-wheel vehicle (CGV) was calculated. Then, the CG of the system (vehicle with transplanting part) (CGS) was calculated by integrating the vehicle with the transplanting part. According to Figure 2(a), the vehicle-transplanter system is composed of the following components: left and right-sided loads of the front and rear wheels (WL1, WR1, WL2, WR2), the radius of the front and rear wheel (r1, r2), the front and rear wheelbase (W1, W2), distances between front and rear axle (L1), rear axle to three-point hitch (L2), and three-point hitch to CGT (L3). In this study, the coordinates of the CG of the four-wheel vehicle (CGV: Xv, Yv, Zv) and onion transplanter system (CGS: Xs, Ys, Zs) were calculated following the ISO 2012, and methods of previous studies [9,18].

As the onion transplanting part was mounted by the four-wheel vehicle, the whole system was considered as a single body during the calculation of the CGs. The mass distribution of the four-wheel vehicle without and with the transplant was summarized in Table 3, which was used to calculate the CG coordinates. Equations (1-3) and (4-6) were used for determining the CG of the vehicle and whole onion transplanter system, respectively. The theoretical rollover angle was determined using Equation (7) combining the CGS coordinates (Xs, Ys, Zs), wheelbase (L1), and the deflection angle (γ).

\[
X_v = \frac{(W_{VR2} + W_{VF2}) \times L_1}{W_V} \tag{1}
\]

\[
Y_v = X_v \times \tan \delta - \left(\frac{W_{(F/R)2}f_1 \times (L_1 \times \cos \delta + (r_2 - r_1) \times \sin \delta)}{W_v} \right) + W_v \times \sin \delta \tag{2}
\]

\[
Z_v = \frac{(W_{VR1} \times W_{VF1} + W_{VF2} \times (W_1 + W_2) + W_{VR2} \times (W_1 + W_2))/2}{W_V} \tag{3}
\]

\[
X_s = \frac{(W_{SR2} + W_{SF2}) \times L_1}{W_S} \tag{4}
\]

\[
Y_s = X_s \times \tan \delta - \left(\frac{W_{(F/R)2}f_1 \times (L_1 \times \cos \delta + (r_2 - r_1) \times \sin \delta)}{W_S} \right) + W_s \times \sin \delta \tag{5}
\]

\[
Z_s = \frac{(W_{SR1} \times W_{SF1} + W_{SF2} \times (W_1 + W_2) + W_{SR2} \times (W_1 + W_2))/2}{W_S} \tag{6}
\]

\[
\xi = \tan^{-1}\left(\frac{(L_1 - X_s) \times W_1 + 2Y_s \times L_1) / L_s \times (2L_1 \times \cos \gamma - 2 \times \sin \gamma + TH \times (W_1 \times \sin \gamma - 3X_s \times \cos \gamma + 2L_2 \times \sin \gamma))}{W_5} \right) \tag{7}
\]

Table 3. Mass distribution of the vehicle and vehicle with transplanting part used for CG calculation.

| Mass of four-wheel vehicle (kg) | Mass of four-wheel vehicle with transplanting part (kg) |
|--------------------------------|-------------------------------------------------------|
| Mass of left front wheel       | WVF1: 250                                             |
| Mass of right front wheel      | WVF2: 237                                             |
| Mass of left rear wheel        | WR1: 32                                               |
| Mass of right rear wheel       | WR2: 56                                               |
| Total mass                     | Wv: 575                                               |

| Mass of left front wheel       | WVF1: 250                                             |
| Mass of right front wheel      | WVF2: 237                                             |
| Mass of left rear wheel        | WR1: 32                                               |
| Mass of right rear wheel       | WR2: 56                                               |
| Total mass                     | W5: 958                                               |
2.3. Determination of the lateral rollover angles

A simulation was performed to determine the lateral rollover angles of the onion transplanter using commercial software (RecurDyn V9R4, Function Bay, Gyeonggi-do, Republic of Korea). A 3-D prototyped of the onion transplanter was drawn for this purpose according to the actual dimensions. The required parameters were specified in the software before starting the simulation, and lateral rollover angles were determined for different load conditions and rollover sides (right and left) (Figure 3). Here, the mass of the operator (80 kg) and carrying seedlings mass (40 kg) were considered as external load. Each test was conducted three times as replications.

![Simulation of lateral rollover stability: left side (a) and right side (b) of the onion transplanter system without load condition.](image)

3. Results and discussion

3.1. Center of gravity by mass

The CG of the four-wheel vehicle (CG\textsubscript{V}: X\textsubscript{V}, Y\textsubscript{V}, Z\textsubscript{V}) and the onion transplanter system (CG\textsubscript{S}: X\textsubscript{S}, Y\textsubscript{S}, Z\textsubscript{S}) were calculated using the Equations (1-6). The mass of the four-wheel vehicle was 575 kg, of which 84.70% and 15.30% of the mass was supported by the front and rear wheels, respectively. Front wheels carried most of the mass as the engine of the vehicle is placed on the front side. The total measured mass of the onion transplanter system was 958 kg, of which 14.82% of the mass was distributed to the front wheels and 85.18% to the rear wheels. The mass ratios between the left and right-sided wheels of the front and rear axles of the vehicle and the onion transplanter system were 51.33: 48.67 and 36.36: 63.64, 54.93: 45.07 and 50.37: 49.63, respectively, which were almost symmetrical on each axle. The CG\textsubscript{V} coordinates of the four-wheel vehicle (X\textsubscript{V}, Y\textsubscript{V}, Z\textsubscript{V}) were 495, 370, and 625 mm, and the CG\textsubscript{S} coordinates of the onion transplanter system (X\textsubscript{S}, Y\textsubscript{S}, Z\textsubscript{S}) were 587, 215, and 621 mm, respectively. After adding the transplanter part with the four-wheel vehicle the CG moved backward (near to the rear axle) and the ground clearance was reduced. Similar results were also observed in other studies where a harvester, collector, or baler part was added with a tractor \[9,18,20\].

3.2. Lateral rollover angle by physical properties

In this study, lateral rollover angles were determined through simulation considering loaded and unloaded conditions and validated through tests. Considering the physical properties of the onion transplanter, the mathematical rollover angle was 34.5°. The average simulated rollover angles were 43.9° as shown in Figure 4. Due to the symmetrical structure of the onion transplanter, around 4.5° turning difference was observed between the right and left side turning. Chowdhury \textit{et al.} \[9\] analyzed the lateral stability of a tractor-mounted radish collector for ensuring user safety and found a 5° angle difference between the simulation and validation, and an around 15° angle difference between the right and left side turning for the asymmetric structure.
Figure 4. Simulated lateral rollover angles of the onion transplanter system under loaded and unloaded conditions.

According to the ISO 16251-2 [10], the acceptable range of the rollover angle varies from 15 to 45° based on different off-road agricultural vehicles. Besides, slope less than 15° is allowed for agricultural farm machinery operation in Korea and Japan. In this study, rollover angles varied from 31 to 51°. About 4° angle difference was observed due to the variation of load conditions. Lateral rollover angles under the loaded condition were scientifically different according to the ANOVA analysis compared to the unloaded condition. Ayers et al. [21] tested the lateral stability of several off-road agricultural vehicles under loaded and unloaded conditions and observed 6 to 7° angle variation for terrain vehicles, lawn tractors, off-road utility vehicles, and zero-turn radius mowers.

4. Conclusions
This study presented the static lateral stability of an onion transplanter, where the coordinates of the center of gravity and rollover angle were calculated mathematically. Moreover, a simulation was performed to determine the rollover angle under loaded and unloaded conditions using commercial software. Based on the physical parameters and mass, the theoretical rollover angle was 34.5°, and the coordinates of the CG moved backward to the rear wheel axle after attaching the transplanting part. The average simulated rollover angle was 43.9°. Due to the symmetrical structure, a 4.5° turning difference was observed between the right and left side turning, and a 3° angle difference was occurred due to the variation of load conditions. As the onion transplanter overturned more than 45° angle, it satisfied the ISO standard also. This study would provide useful information for ensuring the safety of the upland crop machinery operating under uneven and sloped field conditions.

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References
[1] Barla S and Upasani R 2019 Study on different methods of weed management in onion (Allium cepa L.) Cur. J.App. Sci. Techn 331
[2] Sharma K, Mahato N, Nile S H, Lee ET and Lee YR 2016 Economical and environmentally-friendly approaches for usage of onion (Allium cepa L.) waste Food Func. 73354
[3] Sami R, Elhakem A, Alharbi M, Almatrafi M, Benajiba N, Ahmed Mohamed T and Helal M 2021 In-vitro evaluation of the antioxidant and anti-inflammatory activity of volatile compounds and minerals in five different onion varieties Separations. 8(5)57
[4] Hanci F 2018 A comprehensive overview of onion production: worldwide and Turkey J. Agric.
