Design a biomimetic disc using geometric features of the claws

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Abstract: This study presents a numerical investigation regarding the stress distribution on the new designed disc harrow using the ANSYS software. A conventional disc, notched disc, and a biomimetic design inspired by the claw of the leatherwing were analyzed in two conventional plowed and unplowed soils and three tillage depths (4, 7 and 10 cm). Stress analysis for all treatments showed that the highest stress was imposed at the disc-stem junction. Meanwhile the highest deformation occurred at the lowest and the most external part of the discs (land line). The results obtained in this study indicated that the maximum stress exerted from tilling soil to discs increases linearly with tillage depth in both plowed and unplowed soils. Given these results, the maximum stress also at the disc-stem junction changed linearly with tillage depth for all of the three geometric shapes. For the conventional examined harrow in unplowed soil at a depth of 10 cm, the highest maximum stress was 484 MPa and the maximum deformation was 1.84 mm. Using the new geometry for discs in plowed soil, the highest maximum stress and the maximum disc deformation were obtained equal to 130 MPa and 0.92 mm at the same tillage condition, respectively. For all treatments in plowed or unplowed soil, the lowest stress occurred with the biomimetic harrow. The soil- disc interaction stresses exerted on the notched harrow was lower than the conventional disc.

Keywords: stress, disk harrow, finite element, resistance, biomimetic

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1 Introduction

Tillage is an agricultural infrastructure operation requiring the highest energy consumption in compare to the other agricultural operations. The primary tillage operations require approximately 75% of the total energy spent in the farming, therefore draft and power requirements are important in order to determine the size of the tractor that could be used for a specific implement. The draft required for a given implement will also be affected by the soil conditions and the geometry of the tillage implement (Naderloo et al., 2009; Olatunji et al., 2009). In this way, disc harrows are one of the energy consuming implement in tillage operation, which are used to break up soil for seedbed preparation before planting. An appropriate seed bed is composed of soft soil that allows root expansion and plant growth. It should be free of large clumps that prevent adequate contact between the seed and the soil. Meanwhile, rotating disc harrows can be used as primary and secondary tillage implements in some specified conditions. A disc harrow considered for the secondary tillage crushes large clumps, smoothing and compressing the soil (HarriganandRotz, 1994). On the other hand, disc harrows can prepare the seed bed between the cultivator and roller harrows (Sommeret al., 1983). In dry farming systems of Southern Portugal, offset disc harrows were used as a conventional primary and secondary cultivation tools (Serrano et al., 2003).

The stress on disc is affected by factors such as the group angle, disc weight, disc type, speed and depth of tillage, and tension. However performance tests and field experiments for design and development of agricultural tools are time consuming. Therefore precise modeling of tool-soil interaction is the key factor for achieving an optimal design of tillage tools (Shmulevich

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et al., 2007). In this way, the finite element method is a powerful numerical technique usefully applied for analysis of the complex engineering problems (Topakciet al. 2010;Gebregziabheret al.2007; Abo-Elnor et al., 2004 and 2003).

FEM is a numerical technique for analyzing the complex engineering problems, especially for dynamic systems with large deformation and failure (Rosa et al., 2002). This method has been used by numerous researchers to analyze problems related to soil mechanics and the interaction between soil and tillage tools (Topakci et al., 2010;Gebregziabher et al. 2007; Abo-Elnor et al., 2004 and 2003). However for an accurate modelling of soil working implement, important physical and mechanical properties of soil should also be taken into account. Soil is a complex material consisting of three phases, namely solid, liquid and gaseous phases, within which a number of different physical, biological and chemical processes control the soil mechanical behavior (Richards et al., 2009).

Researches have addressed improvement of performance of the disc harrow by decreasing the tensile strength and dish friction by surface hardening operations or anti-friction coatings, see e.g., Tong et al., (2009). They also tried to improve function in soil containing vegetation residue at higher speeds using the biomimetic modeling technique.

The present study deals with the biomimetic engineering technique to design a novel disc for disc harrow. The novel disc was then analyzed for stress using ANSYS software and its results were compared to the conventional and notched discs.

2 Materials and methods

Design of the new disc has been formed based on the physiology of claws of the leatherwing. This idea was first proposed by Mo et al., (2013) and remodeled in the current study as shown in Figure 1. In this figure, profile of outer and internal toes together with the extracted profile of cutting edge of toe are presented.In most mammals, the front legs grow toward one another but in the leather wing, they grow away from each other. As it digs, the front claws of the leather wing move like a rotary shovel (Ji et al., 2010), cutting the soil, breaking the soil stream, and throwing out. Studies have shown a significant effect of the geometric shape of the leg on the soil cutting performance (Ji et al., 2010). The leather wing digging mode is similar to a rotating cutting disc and the geometric features of the claws can be used to design a biomimetic disc.

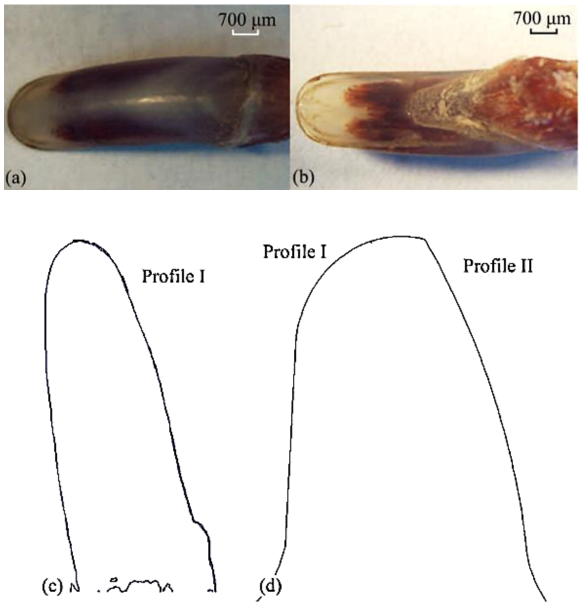

Figure 1 (a) Profile of outer toe; (b) profile of internal toe; (c) the extracted profile of cutting edge of toe; (d) the configuration of biomimetic cutting tooth

The shapes of a disc notched and disc harrow with a curved profile that imitate a leather wing claw were designed in Solidworks (Figure 2) and subjected to stress analysis along with conventional and notched harrows). The parameters of disc including disc diameter, disc thickness, and curvature radius were assumed to be constant for three disc designs for examining the influence of geometric parameters (Figure 3). In the current research, the disc diameter, disc thickness, and curvature radius were equal to 30, 3 and 53mm, respectively. Six notcheds were assumed for the notched and biomimetic harrows. Geometry of the novel disc was transferred to the ANSYS software for stress analysis. In ANSYS software, material of the disk was assumed to be tempered steel (ASTM-514) with the ultimate strength, yield strength, modulus of elasticity, density, Poisson's ratio, and shear modulus of 760, 690 MPa, 20 GPa, 7.8 g/cm3, 0.3, and 76 GPa, respectively.

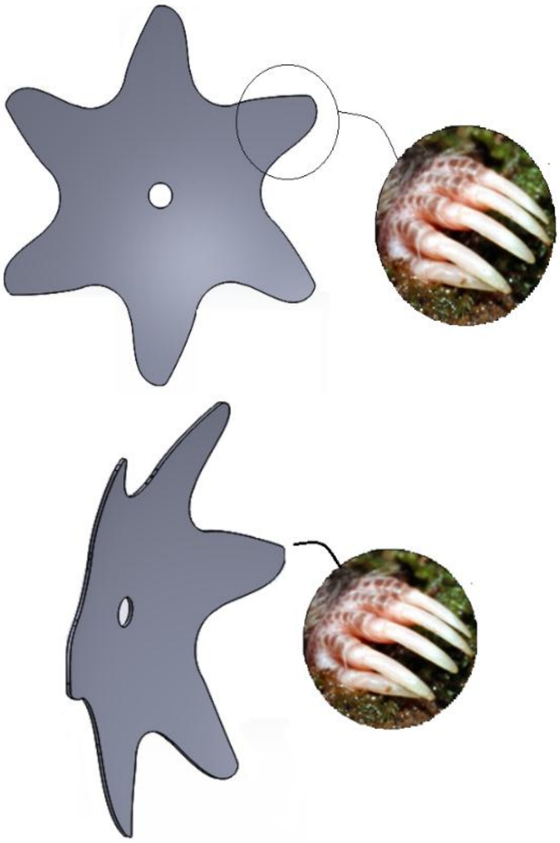

Figure2 3-D view of the disc, designed in the current study: the front view (up), an isometric perspective view (down)

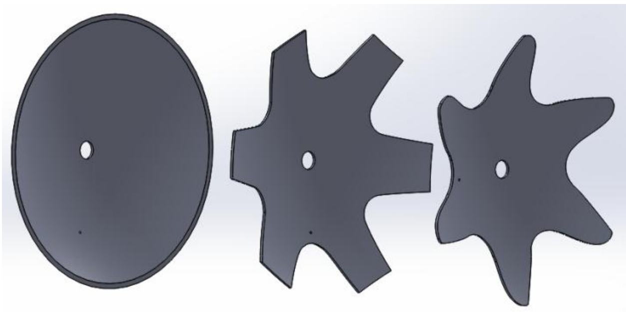

Figure 3 3D model of the examined discs: common disk (left), notched disc (middle) and biomimetic disk (right)

The designed three-dimensional disk was meshed using triangular elements. The total number of nodes and elements used respectively for conventional disc 34007, 16735, notched disk 22356, 10754 and biomimetic disk 34432, 17102 (Figure 4).

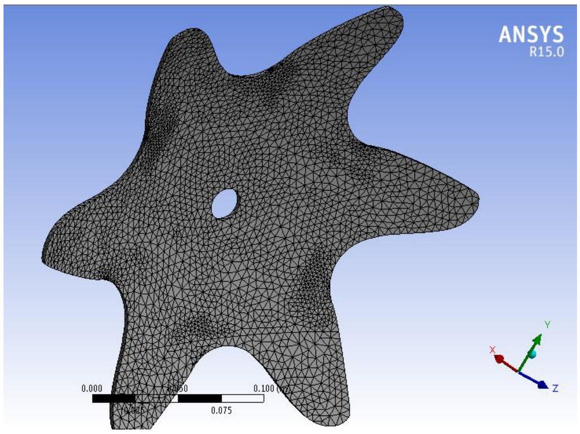

Figure 4 Meshing the designed biomimetic disk using triangular elements

The disc-axis junction was assumed to be a fixed anchor; thus the fixed support command was used. Previous research conducted by Nartov (1985) indicated that a conventional disc with a diameter of 30 cm, an inclination angle of 0°, and head angle of 15° has a specific working resistance of 0.64 kg/m^2 in unplowed soil and 0.45 kg/m^2 in plowed soils (Nartov, 1985). The soil- tool interaction stress was applied to the disc at the depth of tillage equal to 4, 7 and 10 cm (Figure 5).

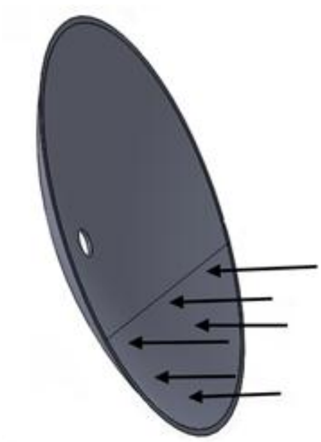

Figure 5 Soil-resistant exerted onto the disc in working tillage depth of 10 cm

3 Results and discussion

Once the boundary conditions were applied, stress distribution analysis based on the von Mises criteria, force-generated deformation, and the confidence coefficient were obtained. Figure 6 shows an instance of stress distribution and the resulting disc deformation. The highest stress on the disc occurred at the disc-stem junction and the greatest deformation by these forces occurred at the lowest and the most external parts of the discs at tillage depth (land line).

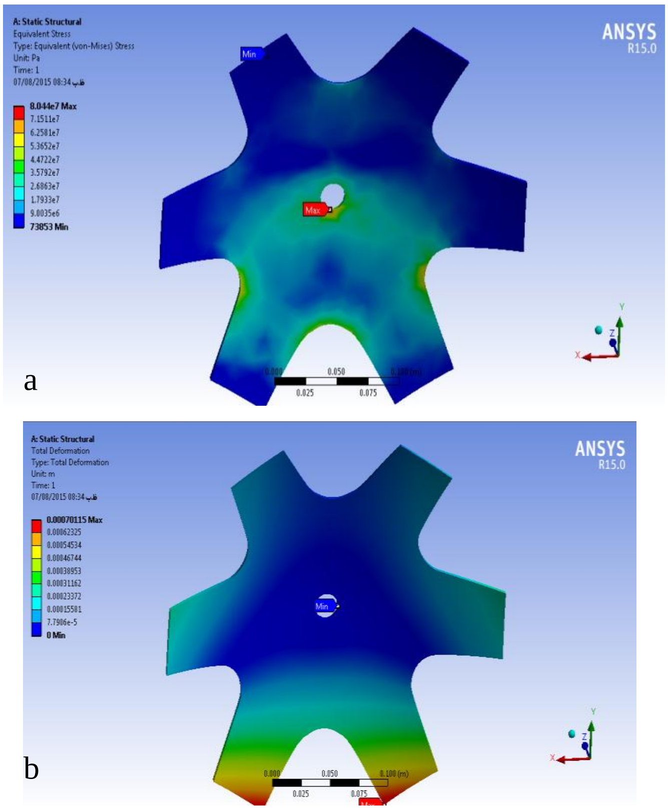

Figure 6 The maximum tension applied to the disc (b) and the maximum deformation (a) at a depth of 4 cm in the ground plowed disc notched

Tables 1 and 2 present the maximum and minimum stresses, maximum disc deformation, and the lowest confidence coefficient at the two working strengths in plowed and unplowed lands at depths of 4, 7 and 10 cm for the three geometric designs.

Results presented in Table 1 for all three geometric designs indicate that increasing the tillage depth yields increasing the maximum stress and deformation, whereas decreasing the confidence coefficient. In all treatments, the stress on the conventional/notched discs was higher than that of the biomimetic disc. The si1milar qualitative results have been obtained for the unplowed soil, see Table 1.

Figure 7 shows decreasing the dish area and the maximum stress for the notched disc in compare to the conventional and biomimetic discs. The relative reduction in the maximum stress and dish area has been computed using the following expression (Equations 1 and 2)

$$\lambda_{\sigma_{ij}} = \frac{\sigma_{\max,i} - \sigma_{\max,j}}{\sigma_{\max,j}} \times 100 \quad (1)$$

$$\lambda_{A_{ij}} = \frac{A_i - A_j}{A_j} \times 100 \quad (2)$$

Table 1 Maximum and minimum stress as well as the maximum deformation created on the disk plow in the plowed soil

Soil-resistant 0.45 kg/cm^2	Depth , cm								
	10			7			4		
	Conventional	Notched	Biomimetic	Conventional	Notched	Biomimetic	Conventional	Notched	Biomimetic
S.max,MPa	304	179	130	222	143	87.1	107	50.5	27.9
D,mm	1.15	1.09	0.92	1.02	0.92	0.71	0.59	0.44	0.3
S.f, min	2.26	3.84	5.27	3.09	4.8	7.91	6.43	132.66	15

Table 2 Maximum and minimum stress as well as the maximum deformation created on the disk plow in the unplowed soil

Soil-resistant 0.45 kg/cm^2	Depth , cm								
	10			7			4		
	Conventional	Notched	Biomimetic	Conventional	Notched	Biomimetic	Conventional	Notched	Biomimetic
S.max,MPa	304	179	130	222	143	87.1	107	50.5	27.9
D,mm	1.15	1.09	0.92	1.02	0.92	0.71	0.59	0.44	0.3
S.f, min	2.26	3.84	5.27	3.09	4.8	7.91	6.43	132.66	15

where i and j stand for each of notched, biomimetic or conventional discs.

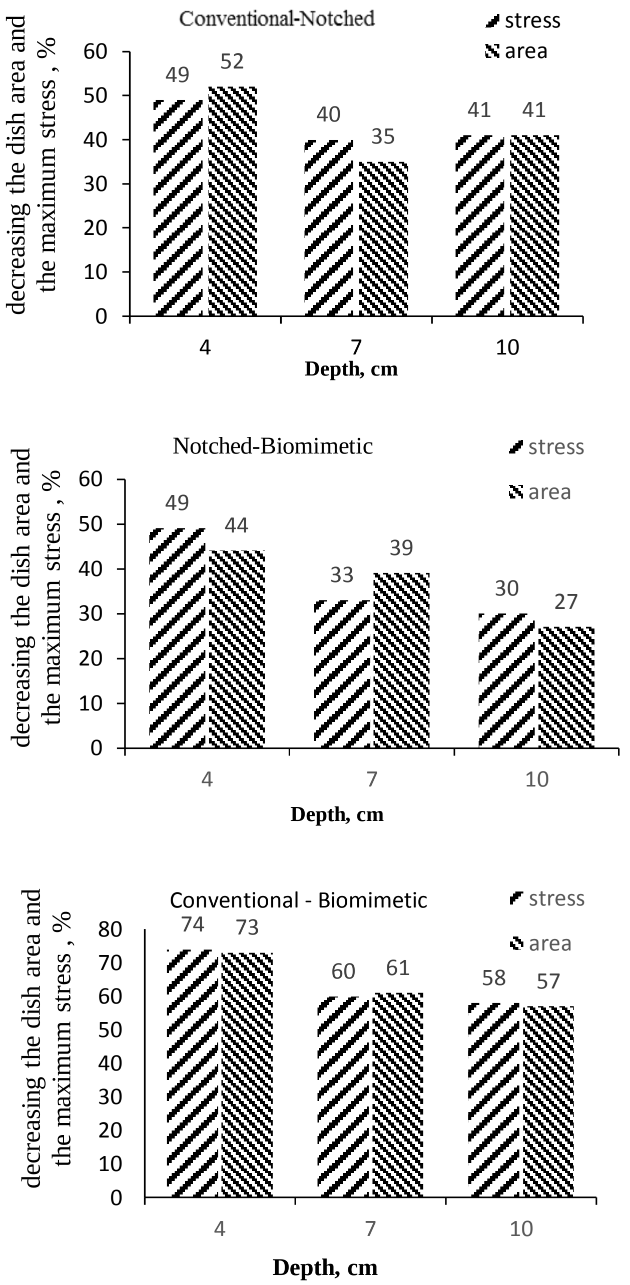

Figure7 Relative comparison between decreasing the dish area and the maximum stress for the notched, biomimetic and conventional discs

The maximum reductions were obtained at depth of 4 cm for the biomimetic-to-conventional disc.

Figures 8 and 9 present the maximum stress exerted from the plowed and unplowed soil to the examined disc, respectively. As illustrate in these Figures, the maximum stress increases linearly with increasing the tillage depth. The maximum stress exerted on the new proposed disc, i.e., biomimetic disc, is significantly lower in compare to two other examined discs.

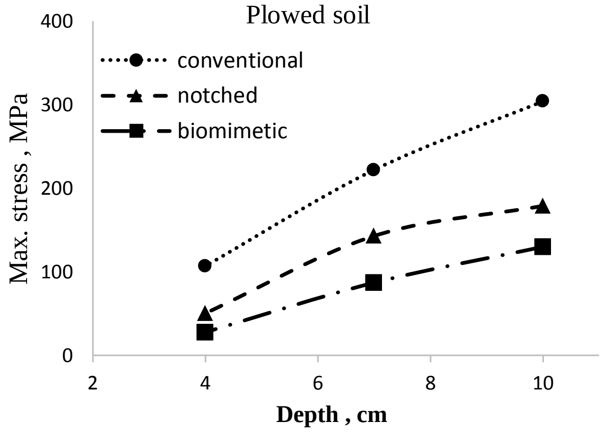

Figure 8 Comparison between the maximum stresses applied to the examined discs in plowed soil

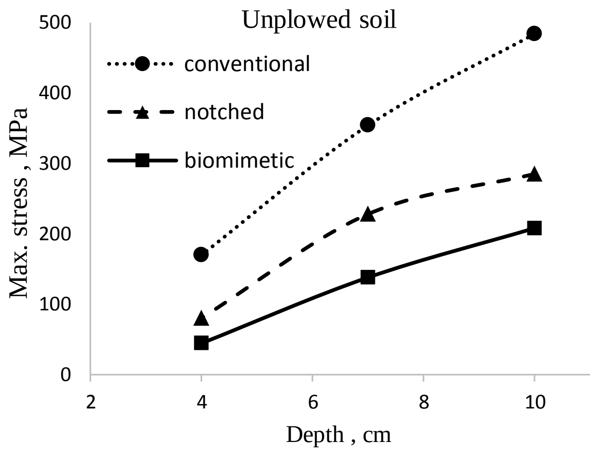

Figure9 Comparison between the maximum stresses applied to the examined discs in unplowed soil

As a final result, front row of a conventional disc can be replaced by the new proposed biomimetic design, which can reduce the draft force and the maximum stress exerted onto the disc surface and disc-stem junction. An exemplary design is illustrated in Figure10.

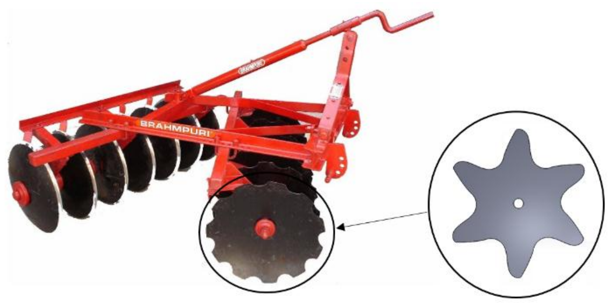

Figure 10 An exemplary design for the front row of a conventional disc

4 Conclusions

The influence of geometric parameters of three different discs has been performed in this study. The obtained results for the stress distribution indicated that the working strength generated the highest stress at the disc-stem junction in the conventional, notched, and biomimetic harrows. The greatest deformation occurred at the lowest and the most external parts of the discs (land line). The study showed that increasing the tillage depth in plowed and unplowed soil was accompanied by an increase in stress for all three geometric designs. Table 3 shows the linear correlations obtained for the maximum stress for each treatment.

Table 3 Correlation coefficient for linear equation obtained for the maximum stress as a function of depth of tillage

Treatment		Equation	Correlation Coefficient
Unplowed soil	Disk	y = 52.333x - 30.333	0.99
	Toothed	y = 34.1x - 40.9	0.94
	Rat	y = 27.25x - 60.583	0.99
Plowed soil	Dsk	y = 32.833x - 18.833	0.99
	Toothed	y = 21.417x - 25.75	0.94
	Rat	y = 17.017x - 37.45	0.99

In unplowed soil, the maximum stress was 484 MPa and maximum deformation was 1.84 mm at a depth of 10 cm for the conventional harrow. These values were 285 MPa and 1.73 cm for the notched harrow and 208 MPa and 1.46 mm for the biomimetic harrow. In plowed soil, maximum deformation and stress at the maximum working depth of 10 cm was 1.15 mm and 304 MPa for the conventional harrow, 1.09 mm and 179 MPa for the notched harrow, and 0.92 mm and 130 MPa for the biomimetic harrow.

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