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Design and Crashworthiness Analysis of Rear Underrun Protection Device

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Abstract

Collision between passenger car and heavy vehicles are one of the most dangerous accident type because of the size difference. Rear underrun protection device installed in the rear of the truck consisting of a horizontal beam and structural support members, is used to prevent penetration of passenger car. In this paper, a new rear underrun protection device was designed. Three different support bracket thicknesses that vary with 4-6 mm whereas investigated and their crash performance and structural integrity were compared to each other. RUPD finite element models were created and analysed for Dodge Neon (1996) collided at 63 km/h vehicle impact speed under full overlap crash scenario. Abaqus/Explicit dynamic analysis that is special tool for highly non-linear Dynamics phenomenon was used for the analyses. The results showed that the new RUPD design with 6 mm support bracket thickness reduced both axial deformation of RUPD by %56.3, penetration of passenger car by %20.7 and enhanced CFE by %7.92. The optimum support bracket thickness was determined for the new developed RUPD against vehicle collision.

Keywords: Abaqus, Economic Commission Europe Regulation-58 (ECE R58); Finite Element Analysis (FEA), Rear Underrun Protection Device (RUPD)

Research Article

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1. Introduction

Heavy vehicles have mainly been used in many countries for trucking. Since heavy vehicles and cars use same road, their collision causes tragic losses of life. Height and size difference between passenger cars and heavy vehicles causes penetration of passenger cars underneath of heavy vehicles in rear-end crashes as shown in Figure 1. Passenger compartment intrusion due to penetration leads to severe injuries and deaths. Every year thousands of people pass away because of rear-end collisions. Table 1 shows the number of fatalities in accidents involving heavy vehicles. More than 10% of the fatalities are due to rear-end crashes. For this reason, rear underrun protection devices are installed in the rear of heavy vehicles to prevent penetration of passenger cars in rear-end crashes.

Fig. 1. Passenger vehicle collision with rear-end of truck. [1]

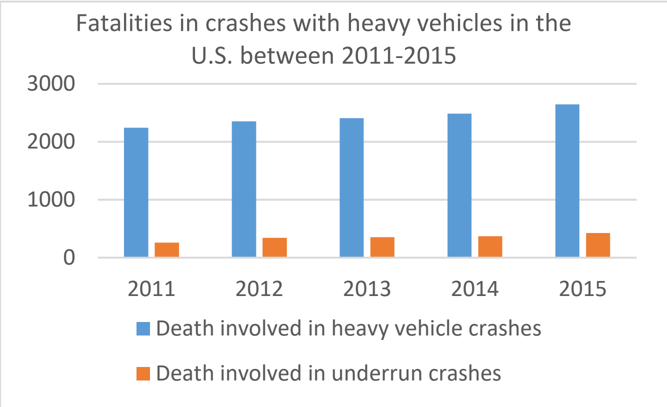


Table 1. Fatalities in crashes with heavy vehicles in the U.S. between 2011-2015 [2]

Many researches have been made by researchers for many years to improve new RUPDs; which supply impact energy absorption of cars as specified in regulations.

A study of RUPD design [4] is based on morphological analysis to generate various RUPD types. They proposed three potential RUPD designs to investigate their structural strength. They performed explicit FE analysis according to ECE R58 Regulation. Results showed that tubular cross-section bar has highest energy absorption and double box section has highest strength-to-weight ratio.

The mechanical behavior of RUPDs [5] installed on tank vehicle at different impact speeds was analyzed by FE analysis and the results were compared. Results showed that low impact speed fulfill maximum deformation law of regulation. Additionally, at 35 km/h impact speed vehicle interior parts seriously damaged.

In another study [6], a new RUPD was developed according to FMVSS 223/224 regulations. They performed explicit FE analysis with LS-DYNA at various vehicle impact speeds. Results showed that, new design with additional structural members and crashbox enhanced absorption of energy nearly 70% and reduced passenger car deceleration about 66%.

A new RUPD was designed to prevent underrun and absorb more crash energy and angle and separation distance of support structure of RUPD was also investigated [7]. They performed explicit FE analysis with LS-DYNA according to FMVSS 223 regulation. Results showed that, 20 degree support structure angle has optimum displacement and energy absorption.

A new improved RUPD consisting of aluminum tube crash boxes filled with metallic foam was investigated [8]. In the study, dynamic FE analysis to simulate different types of impact was carried out. Results showed that, new design with aluminum tube crash boxes filled with metallic foam has better energy absorption and deceleration reduction.

RUPD simulation under crash scenario was performed by LS-DYNA [9]. They focused on RUPD bar thickness effect on crash energy absorption. Results showed that, 3.5 mm bar thickness has highest energy absorption.

In the one of the another RUPD design study [10], crash performances with varying ground clearances between 300 mm and 600 mm. They performed explicit FE analysis with LS-DYNA at two different impact speed 48 km/h and 64 km/h. Results showed that, optimum ground clearance of RUPD is 400 mm for occupant safety. Additionally, 400 mm ground clearance has highest kinetic energy absorption.

It is seen that researchers have been tried to obtain the best RUPD design. There is a need to make more efforts for the best RUPD design. In this study, a new RUPD design was introduced. Effect of the thicknesses of the RUPD parts on the RUPD design was achieved. Maximum axial displacement and maximum equivalent plastic strain of the RUPD were investigated.

1.1 RUPD Regulations

There are various types of RUPD regulations, which are used in the U.S.A., Canada, Europe and other countries. UNECE R58 regulation has been used in European countries.

Requirements of UNECE R58-03 are;

•RUPD has to be fitted to vehicles categories M, N and O

•The minimum section height of the RUPD beam should not be less than 120mm.

•The loads P1, P2 and P3 are applied at the location shown in Figure 3.

•Maximum elastic + plastic deformation must not exceed 400 mm.

•P1 = 12.5% of the gross vehicle weight (GVW)but not more than 100 kN

•P2 = 50% of the GVW but not more than 180 kN

•P3 = 12.5% of the GVW but not more than 100 kN

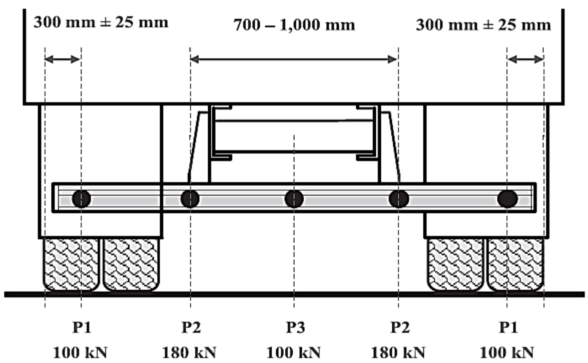


Fig. 2. UNECE R58-03 load locations and magnitudes. [3]

1.2 RUPD Design

Bar is the first part of RUPD which contacts with vehicle during an impact. Bar is connected to support brackets, which provide bending strength for RUPD when it encounters with bending load caused by impact force. Support brackets must be supply sufficient strength during impact otherwise, underrun occurs and accidents can be fatal for passenger car. In this study, effects of support thicknesses were evaluated under virtual crash scenario and proper thickness was determined according to results. In this study, a new RUPD design was proposed as shown in Fig.3. This design has pipe section bar and triangular support members due to increasing bending moment towards to chassis.

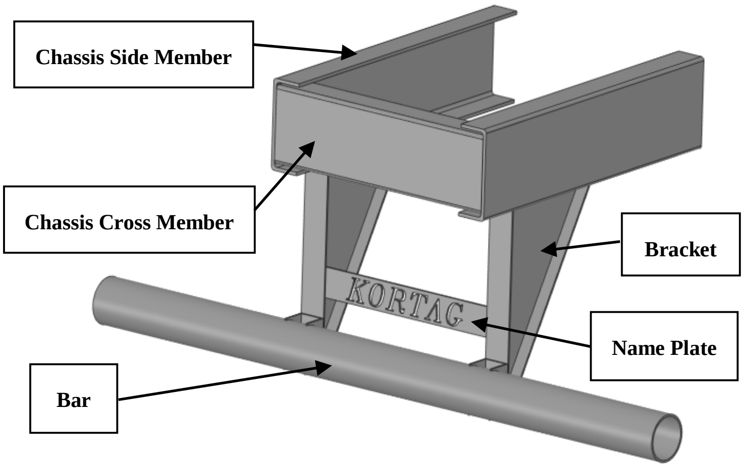


Fig. 3. RUPD solid model.

Space Claim was used to design RUPD. Solid model was converted to shell model to simplify analyses and geometry was meshed with shell elements in Abaqus as shown in Fig.4.

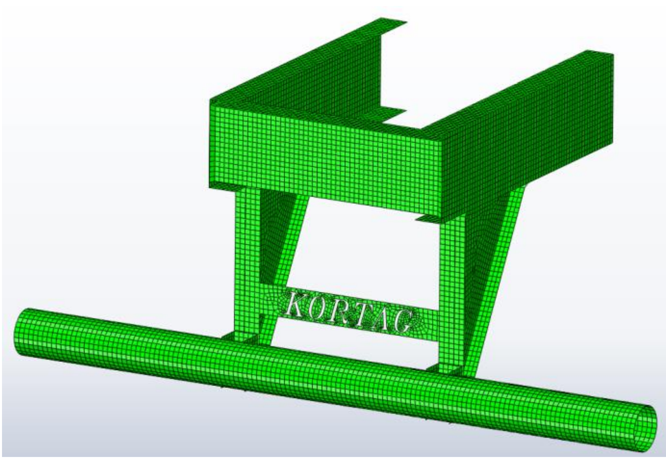


Fig. 4. Meshed geometry of RUPD.

2. Finite Element Analysis of RUPD

FEM is used to solve partial differential equations with numerical approach. General equations of motion are solved by FEM. There are two approaches for time domain; implicit and explicit methods. The explicit dynamics analysis procedure in ABAQUS/Explicit is based upon the implementation of an explicit integration rule together with the use of diagonal or "lumped" element mass matrices. [11]

Finite element method (FEM) is a suitable method for structural analysis. FEM is used to solve partial differential equations by numerical approach. It is especially preferred for complex analysis. It is based on discretization of whole structure into finite elements, obtained solutions of these elements individually then combined all the solutions of these elements, which gives the solution of the structure. The equation of motion for a general dynamical system is defined by Eq. (1). Since the problem considered in this study is dynamical, our analysis focused on this equation of motion.

$$[M]\{\ddot{u}\}_i + [C]\{\dot{u}\}_i + [K]\{u\}_i = \{F\}_i \quad (1)$$

Where [M] mass matrix, [C] damping matrix, [K] stiffness matrix,{F} force vector, {u} displacement vector and its derivatives.

There are two approaches for time domain; implicit and explicit methods. The explicit dynamics analysis procedure in ABAQUS/Explicit is based upon the implementation of an explicit integration rule together with the use of diagonal or "lumped" element mass matrices.[11] The equations of motion for the body are integrated using the explicit central difference integration rule as in Eq. (2-3)

$$\dot{u}^{(i+\frac{1}{2})} = \dot{u}^{(i-\frac{1}{2})} + \frac{\Delta t^{(i+1)} + \Delta t^{(i)}}{2}\ddot{u}^{(i)} \quad (2)$$

$$u^{(i+1)} = u^{(i)} + \Delta t^{(i+1)}\dot{u}^{(i+\frac{1}{2})} \quad (3)$$

All parts were modelled as deformable. Elastoplastic high strength steel material model was used for the all parts. Material properties of HSS steel are given in table 2.

Table 2. Material properties of HSS Steel

Young's modulus (GPa)	210
Poisson's ratio	0.3
Density (Kg/m^3)	7890

The chassis members were created with 10 mm thickness. The bar was created with 6 mm thickness. Name plate and bracket thicknesses were created with 5 mm thickness as shown in Fig.3. Bracket thickness was chosen as the design parameter that will be varied between 4-6 mm. three different FE analysis were performed for each thickness value. All parts of RUPD were meshed with S4R reduced integration quadrilateral elements with 4 nodes which is suitable for large strain analyses as shown in Fig.4. 5 thickness integration points were used to see bending effect. Average mesh size is 10 mm for RUPD parts [12]. Total simulation time is 0.1s. Finite element model of vehicle is 1996 Dodge Neon passenger sedan as shown in Fig.5 adopted from the National Crash Analysis Center (NCAC) [13] was utilized in this research as the car model.

Fig. 5. The detail of FE model of 1996 Dodge Neon. [13]

Free edges of the chassis side members were constrained in all translational and rotational degrees of freedom as shown in Fig.6. RUPD parts were tied each other assuming welded connection. For the interaction between all the parts General contact (Explicit) was used. 0.3 coefficient of friction was used as contact property using friction formulation [12]. Initial vehicle speed was chosen 63 km/h [12]. It is very common speed value for physical and virtual tests regarding braking time and distance of passenger car. RUPD has 450 mm ground clearance.

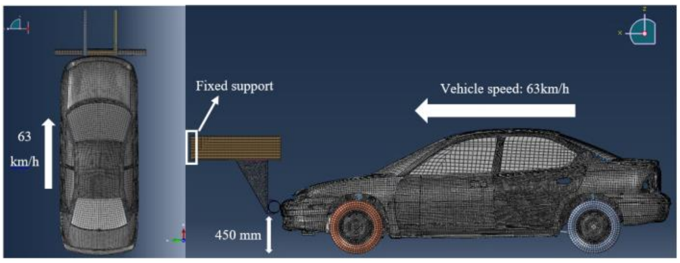


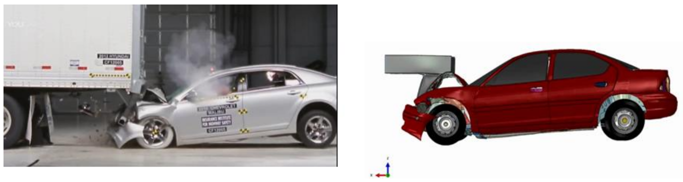
Fig. 6. Locations and magnitudes of the loads applied according to ECE R.58 regulation.

Three simulation tests were performed for rear-end impact. Model 1 has 4 mm support bracket thickness, model 2 has 5 mm support bracket thickness, model 3 has 6 mm support bracket thickness. The simulation results corresponding to the results of ref [13], which are real rear-end crash tests, are given in Fig 7. Although crash speeds are different a little bit, as it is seen, the deflected patterns on the car obtained from the FEM simulations match completely with those obtained from ref [14]. It states that the FEM simulations are correct and its accuracy is enough.

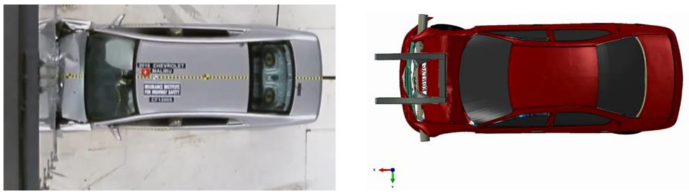
Global energy plots are very important to check accuracy of FE analysis results. Total energy remains constant and kinetic energy converts into internal energy with time as it is supposed to be as shown in Fig.8.

It can be observed from Fig.9, 5mm and 6 mm models have same crashworthiness and they are better than 4 mm as it was expected. However, after 0.09 s some internal energy of 6 mm model converts to kinetic energy due to rebound effect.

Reaction forces of three models have similar behavior but 6 mm model has higher crash force and behaves more rigidly than others until rebound time 0.09s as shown in Fig.10.



(a)



(b)

Fig. 7. (a) IIHS 56 km/h full overlap crash test side view (left) [14] and 63 km/h full overlap crash simulation side view (right), (b) IIHS 56 km/h full overlap crash test top view (left) [14] and 63 km/h full overlap crash simulation top view. (right)

Crash force efficiency (CFE) which is ratio of mean force to peak force, is nearly same for 5 and 6 mm models whereas 5 mm bracket weighs less as shown in Table 3.

According to FE analysis results as shown in Fig.12, 4 mm and 5 mm bracket thicknesses do not meet the requirements of ECE R58 [3] that limits maximum deformation of RUPD to 400 mm as shown in Table 4.

Even though all of models are strong enough to prevent penetration of vehicle beneath of chassis as shown in Fig.11, RUPD with 4 mm support bracket thickness has 1027.6 mm axial deformation of vehicle which is considered so much deformation especially for small to medium sized vehicles. It has nearly 215 mm higher deformation than RUPD with 6 mm support bracket thickness. This distance can be vital if RUPD is placed inner side of chassis. Results show that, bracket support thickness is important for load distributions that arises from crash energy.

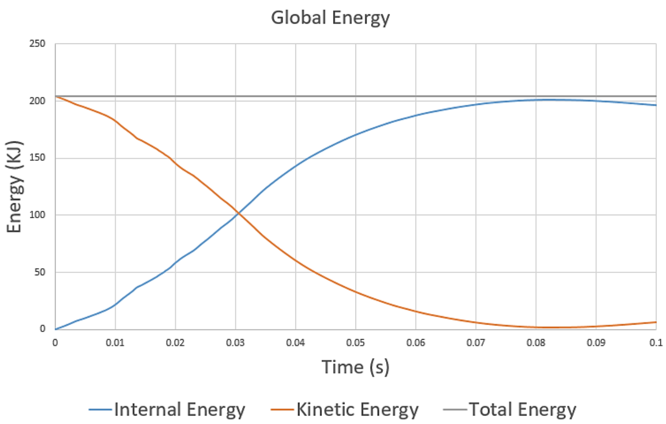


Fig. 8. Global energy plot of whole model.

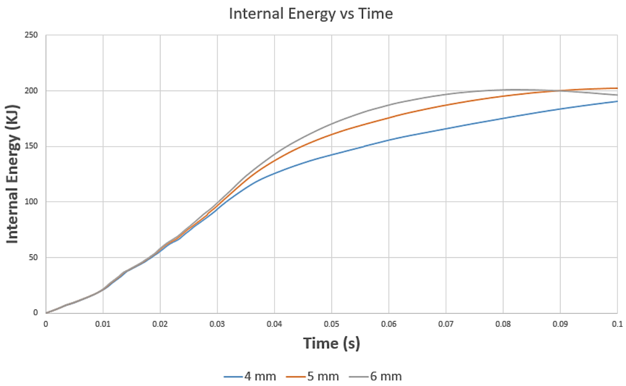


Fig. 9. Energy absorption results of RUPD

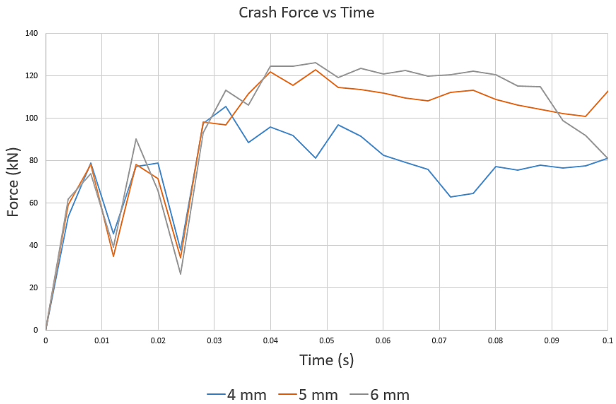
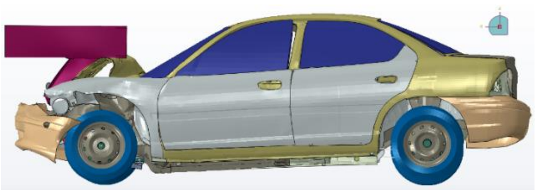


Fig. 10. Crash force results of RUPD



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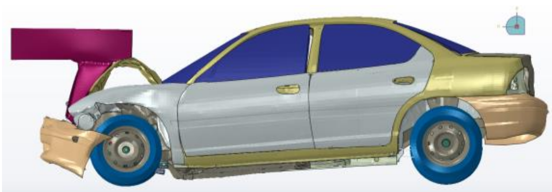

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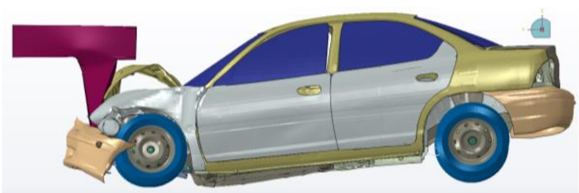
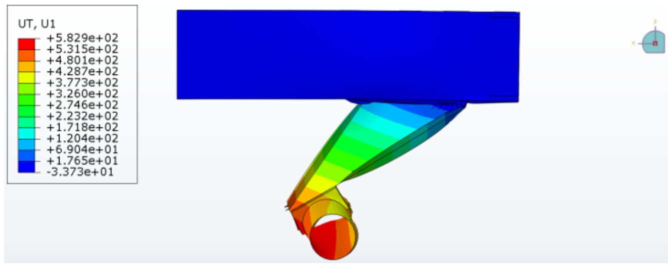
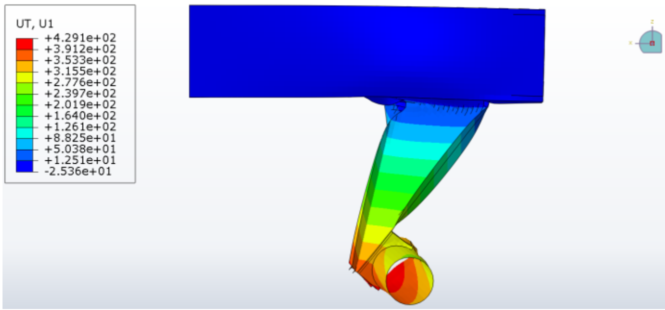


(c)

Fig. 11. Deformation of whole model after crash for (a) 4 mm bracket thickness, (b) 5 mm bracket thickness, (c) 6 mm bracket thickness.



(a)



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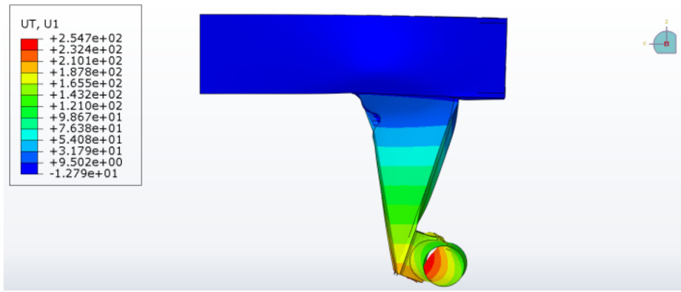

(c)

Fig. 12. RUPD axial deformation results for (a) 4 mm support bracket thickness, (b) 5 mm support bracket thickness, (c) 6 mm support bracket thickness.

Table 3. Comparison of the results for different support bracket thicknesses.

Bracket Thck. (mm)	Mass (kg)	MCF (kN)	PCF (kN)	CFE	RUPD Def. (mm)	Car Def. (mm)
4	6.785	78.180	105.8	0.738	582.9	1027.6
5	8.480	97.751	123.1	0.794	429.1	895.8
6	10.17	100.7	126.4	0.797	254.7	814.6

3. Conclusions

In this study, a new RUPD was developed and effects of thicknesses of structural parts on RUPD design were investigated. Crash analyses were made by FEM and the corresponding simulations were obtained. The results showed that:

- MCF and PCF values increased with the increase of support bracket thickness in the design.
- RUPD deformation decreased with the increase of support bracket thickness in the design.
- Vehicle deformation decreased with the increase of support bracket thickness in the design.
- Energy absorption increased with the increase of support bracket thickness in the design.
- RUPD with 4 mm and 5 mm bracket thicknesses has axial deformation higher than 400 mm which is the limit of maximum axial deformation of RUPD according to UNECE R-58 regulation.

Although a physical test according to the standard is recommended to assess the suitability of the RUPD for actual usage, FEA can significantly reduce the time and effort required to achieve the final design.

For future studies:

- Auxetic structures can be tested due to their impact resistance and high energy absorbing capacity.
- Crashboxes can be placed between beam and support members to absorb crash energy.
- Strength of RUPD components can be investigated for different vehicle speeds.
- Different materials can be considered to obtain optimum design

Nomenclature

$\{\ddot{u}\}$	:	Acceleration Vector
[C]	:	Damping Matrix
$\{\dot{u}\}$	:	Velocity Vector
[K]	:	Stiffness Matrix
$\{u\}$	:	Displacement Vector
CFE	:	Crash Force Efficiency
PCF	:	Peak Crash Force
MCF	:	Mean Crash Force

Conflict of Interest Statement

The authors declared no potential conflicts of interest in the study.

CRediT Author Statement

Sadettin Orhan: Writing-review & editing, interpretation of analyses.

Ufuk Kortağ: Conceptualization, Writing-original draft, Visualization, Formal analysis, interpretation of analyses.

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