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# Quantitative analysis of facemask-induced compressive forces on the auricle and possible implications on user health.

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**Abstract**

Mandatory use of facemask in public is a globally accepted precautionary measure to stop the spread of COVID-19. Numerous studies have highlighted the benefits of wearing facemasks, while some have raised their environmental, physiological, and psychological concerns. However, no study has analyzed the compressive forces exerted by facemasks and understood its influence as the cause for variously reported health concerns. The present study analyzes the forces exerted by different facemasks with pre-auricular head straps/earloops and determines the auricular stress and displacement fields for the extreme instance. Initially, the earloop displacement on wearing facemask is determined. An appropriate Universal Testing Machine (UTM) is then used to plot the earloop force-displacement curve. The compressive forces on the auricle were determined based on Newton's laws. It is the input data to numerically determine the auricle stress and displacement fields for the extreme condition. The force exerted by the surgical mask and the N95 respirator is 0.9 N and 2.7 N, respectively. Custom cloth masks, being non-standardized, is projected to exert force in the range of 1.5-3 N. N95 respirators exert the maximum compressive forces on the auricle among different classes of commonly used facemasks. Double masking exerts more force than any individual mask. The numerical analysis indicates that the concha is the most stressed part of the auricle while the helix experiences maximum deflection. The resultant auricular stress and displacement are conjectured to cause pressure injuries/sores, headaches, and temporary hearing loss.

***Keywords:*** Auricle, Covid, Facemask, Stress analysis, Ear displacement.

## 1. Introduction

Coronavirus disease or COVID-19 is a contagious respiratory illness caused by Severe Acute Respiratory Syndrome CoronaVirus-2 (SARS-CoV-2). The alarming spread of COVID-19 across the global population forced World Health Organization (WHO) to declare it a global pandemic on March 11, 2020 [1]. Pathogen infectivity, a defining factor in measuring the transmissibility of any respiratory virus, is quantified using basic reproduction number $R_0$ [2]. Estimated $R_0$ values for original SARS-CoV-2 ranged from 1.4 to 6.49 with a mean of 3.28 [3] whereas $R_0$ values for the Delta variant ranged from 3.2 to 8 with a mean of 5.08 [4]. This observation, coupled with the multiple transmission modes of coronavirus, underlines its highly infectious nature. Studies show that coronavirus rapidly spreads via respiratory droplet transmission, aerosol transmission, direct physical contact with the infected host, and by contact with contaminated fomites (indirect contact) [5][6][7]. To contain the spread of COVID-19, World Health Organization (WHO) recommended the use of facemasks along with other precautionary measures [8]. Based on the recommendations of the corresponding national health agencies, most countries mandated their citizens to wear a facemask in public [9][10]. Facemasks provide two-fold protection against the coronavirus by source and respiratory control, especially against airborne transmission [11]. With the discovery of even more contagious variants, countries like the US and India recommended double masking [12][13][14]. Double masking is wearing a cloth mask over a surgical mask to improve its filtration efficiency and fit around face contours, significantly reducing chances of virus transmission. Consequently, citing hygiene and safety, the use of single-use facemasks increased drastically. Estimates indicate a monthly requirement of 89 million medical masks for healthcare workers globally and 129 billion facemasks for the global population to fight against Covid-19 [15]. Facemask usage is not without adverse effects. As graphically represented in Figures 1 & 2, the concerns of the pandemic-induced extensive usage of facemask broadly branch out into environmental and facemask-user effects. Environmental concerns relate to the adverse effects affecting nature and biodiversity, including humans in general.

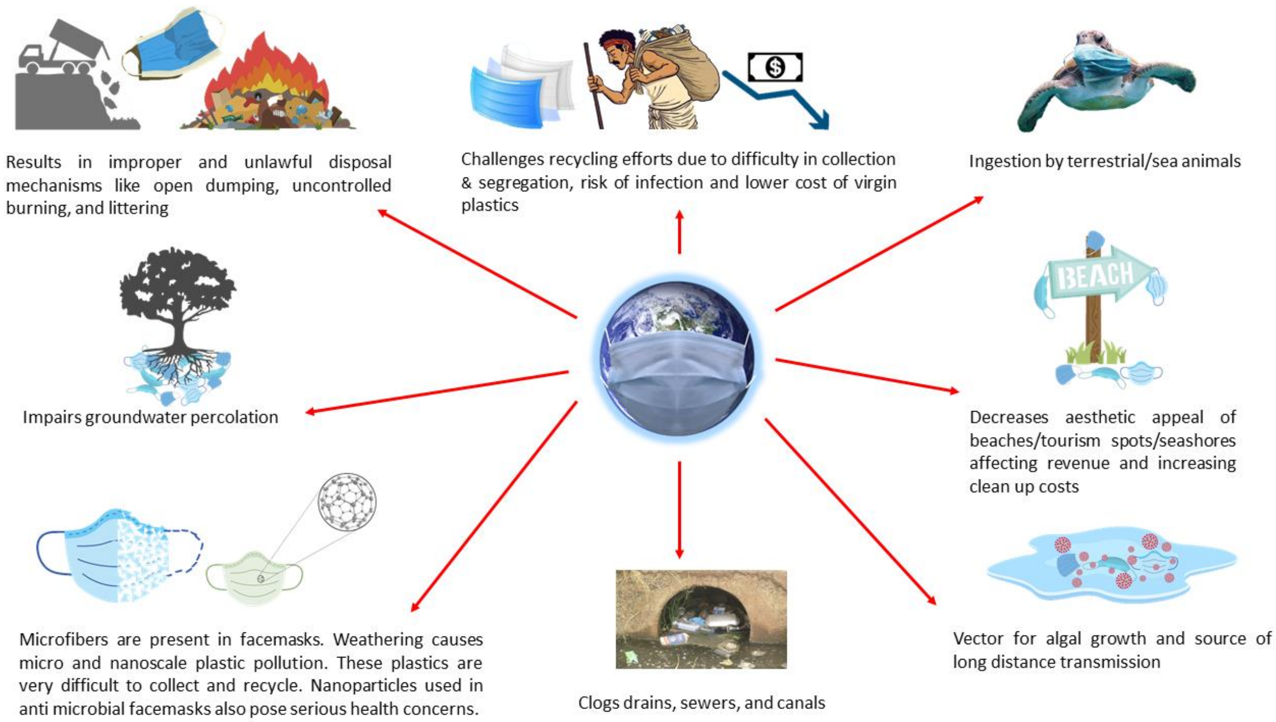


**Figure 1:** Environmental concerns due to facemask usage

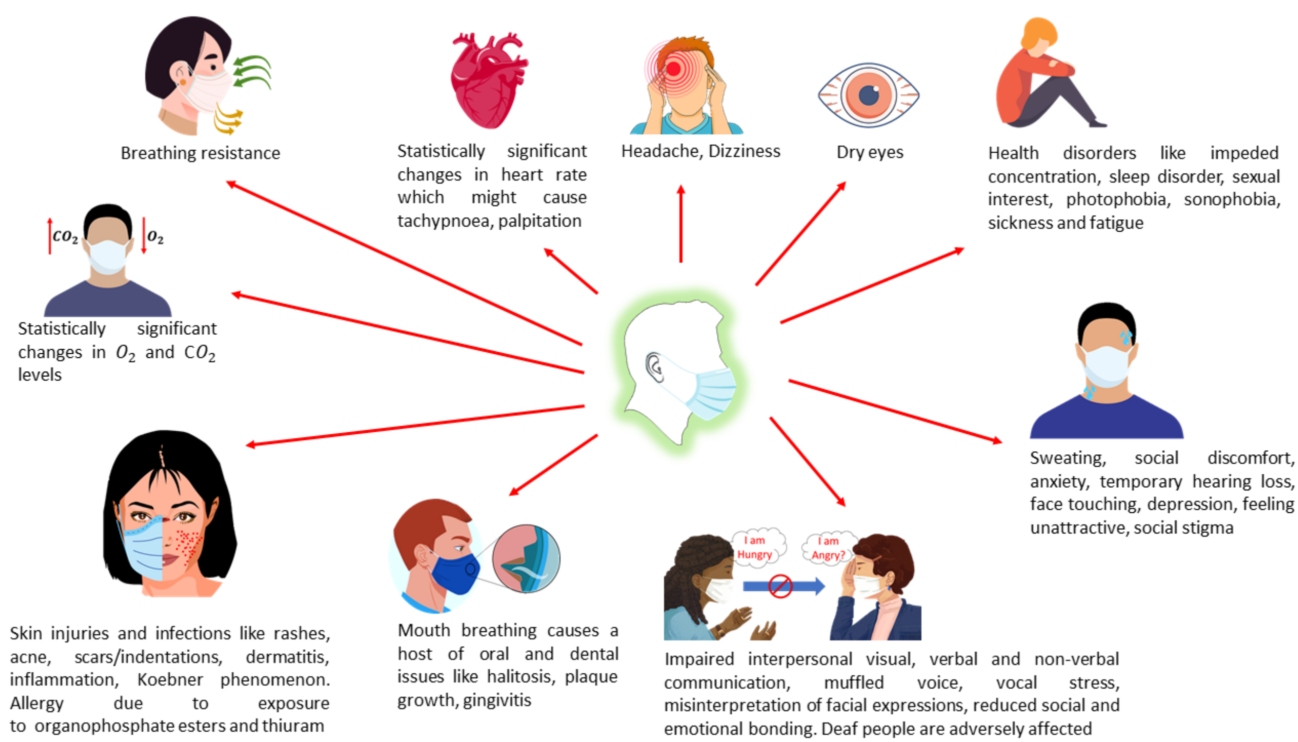


**Figure 2:** Facemask-user concerns

Facemask-user concerns relate to the direct physiological and psychological effects affecting that particular user. Physiological effects refer to the body and its functions, while psychological effects are concerned with the mind, perceptions, and attitude. However, the authors failed to find evidence of studies on the compressive forces exerted by facemasks on the auricle and the possible implications of the resultant auricular structural changes.

Pre-auricular head straps/earloop and Occipital head straps are two ways to fit and secure the facemask. The fit of the facemask influences the virions' ability to infiltrate the facemask. A close fit is required to reduce the number of virus particles passing through it. To an extent, the close fit of the facemask is achieved by tighter head straps. Occipital head straps have the elastic straps loop over the occipital region. Auricular ear loops with mask/strap extenders also fall under this category. Pre-auricular head strap/earloop is the second type in which the elastic straps loop over the outer ear. A cross-sectional survey among 383 healthcare workers in Italy observed that facemasks with pre-auricular head straps were more common (89.3%) compared to occipital head straps (10.7%) [16].

Consequently, the present study is on pre-auricular head straps/earloops. COVID-19 has added one more functionality to the auricle; to keep the facemask secure and in place. Facemasks with earloops exert compressive forces on the auricle; concha, to be precise. The present study determines the magnitude of the compressive forces and the significance of the corresponding auricular displacement and stress on user health. The study also seeks to provide an insight into the force variation among different facemasks to understand double masking.

## 2. Materials and Methods

### 2.1. *Methodology*

Figure 3 shows the methodology followed in the present study to determine the magnitude of the compressive force exerted by the facemask and subsequently the auricular stress and displacement field.

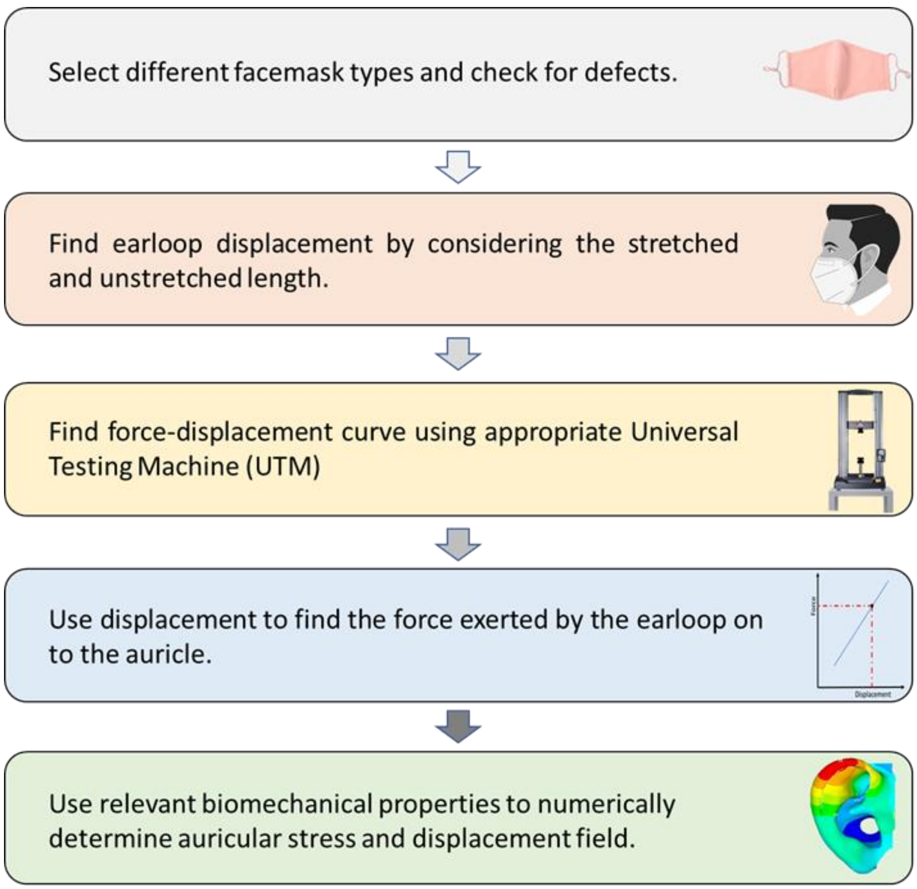


**Figure 3:** Methodology Flowchart

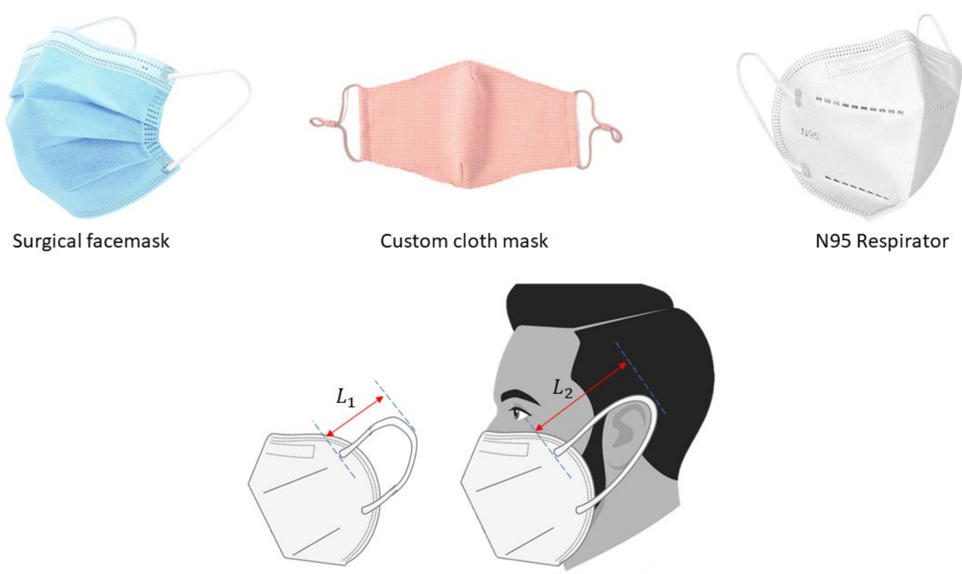


**Figure 4:** Representative image of the considered facemasks and the relevant notations

Locally sourced twenty N95 respirators, twenty surgical facemasks, and five cloth masks with pre-auricular head straps were randomly selected and checked for visible defects. For each mask, the earloop unstretched length $(L_1)$ is measured by a ruler. Facemask, when worn, experiences stretching of elastic head straps to achieve an appropriate fit. The stretched length of the earloop $(L_2)$ is also measured. The relevant dimensions are shown in Figure 4.

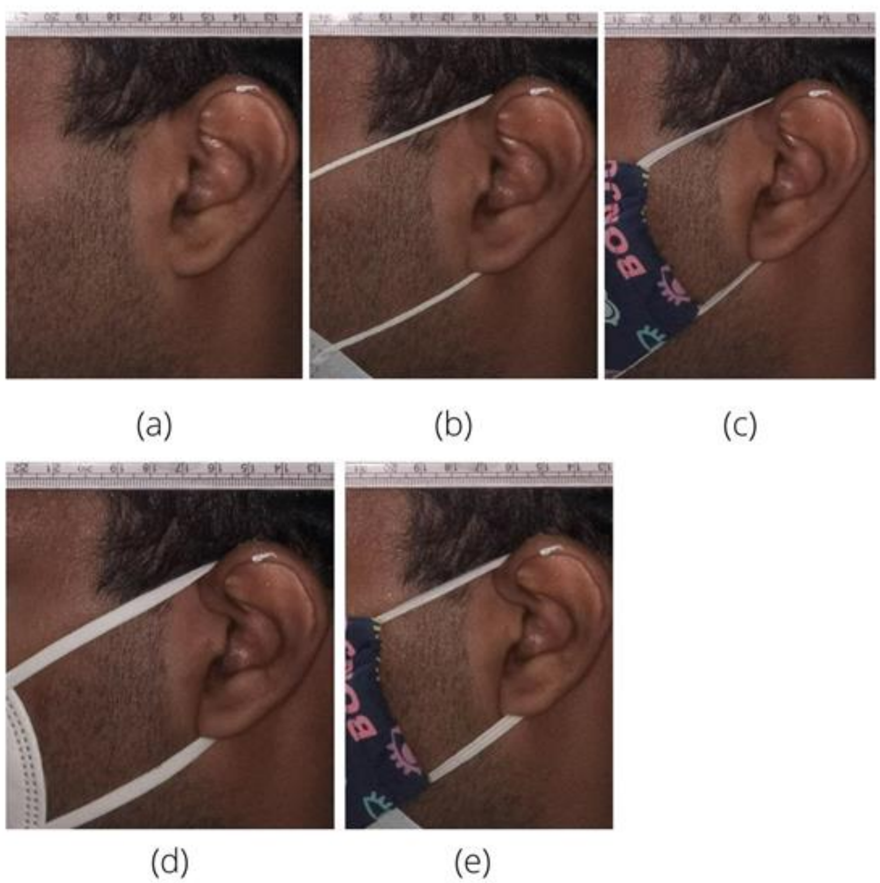


**Figure 5:** When the user wears a) no mask b) surgical mask c) cloth mask d) N95 respirator e) double mask (surgical mask + cloth mask)

We can observe the auricular shape and orientation change on wearing different facemasks. Frontline healthcare workers who work in covid contaminated environments or with infected patients require close-fitting N95 respirators, whereas surgical and cloth masks are generally used in safer surroundings and by the general population. Lack of detailed and enforced guidelines on cloth masks results in significant variations. It makes force evaluation difficult as the earloops are not standardized elastic materials. The earloop of the N95 respirator is the thickest, followed by cloth mask and surgical mask, respectively. The earloop displacement is determined from the stretched and unstretched length. The effect of anthropometric variation of the auricle is assumed to be negligible and not considered in the present study. Three new, sealed N95 respirator and surgical mask samples are tested, and the load-displacement diagram is plotted to determine the force exerted by the facemask on the auricle. Custom cloth mask was not tested due to extreme variability in dimensions, material, and shape of the facemask. The earloop pull strength or the uniaxial tension test was done in a 50 kN Dual-column Tabletop INSTRON 5969 UTM. The load-displacement diagram of three N95 respirators samples and three surgical facemasks are shown in Figure 6. The curves show the exact elastomeric nature for both surgical and N95 samples. However, the slope of the N95 samples is higher, indicating that its straps are stiffer than surgical samples.

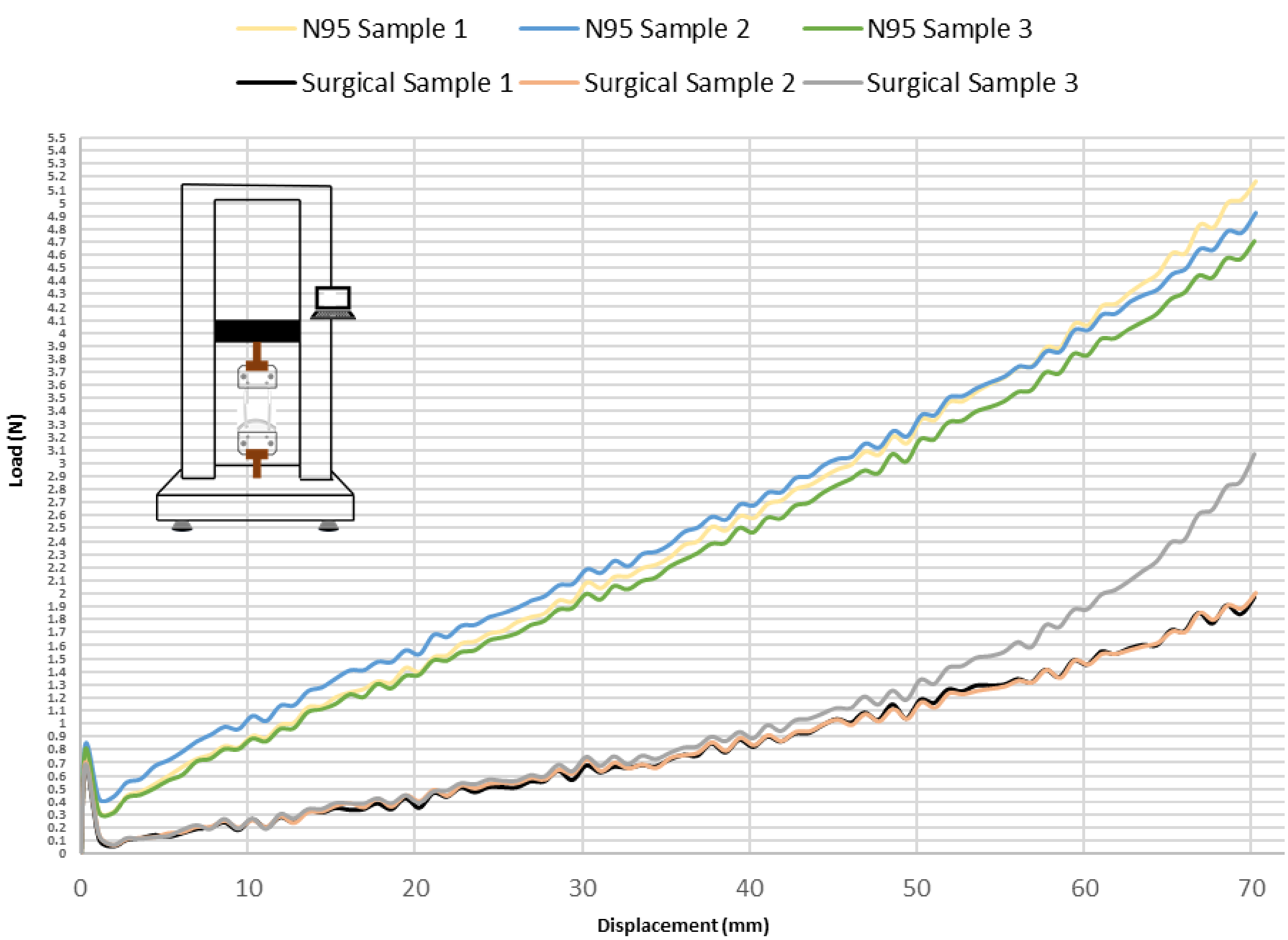


**Figure 6:** Load-displacement plot for N95 and surgical masks

## 2.2. *Analysis*

The auricle (or pinna or outer ear) is the auditory system's visible part that receives, filters, magnifies, and transmits sound waves to the ear canal. It is an elastic composite material whose principal function is to maintain its characteristic shape and not support loads [17]. The corresponding author's anthropometric data is the basis for developing an appropriate CAD model of the auricle. Solid elements are used for the discretization of the developed model. Mesh convergence is essential to strike the right balance between computational accuracy and time and ensure mesh-independent results. Mesh convergence for the present study is done by considering the auricle as a cantilever, i.e., fixing all the nodes at one end, applying appropriate point load at the other end, and observing the displacement. Multiple trials show that an element size of 0.8 shows mesh-independent results with less than 10% variation. The auricle exhibits non-linear hyperelastic material behavior. The Mooney-Rivlin model is chosen for numerical analysis to determine the auricular stress and displacement field. Limited studies on the human auricle constrained us to select a 2-parameter model. The required values given in Table 1 are taken from preceding experimental studies on human auricles [18][19].

**Table 1:** Relevant auricular biomechanical properties

| Property | Notation | Unit | Value |
|---|---|---|---|
| Average Youngs Modulus | E | MPa | 1.66 |
| Poisson Ratio | ν | - | 0.5 |
| Mooney Rivlin Constants | $C_{10}$ | MPa | 0.30 |
| | $C_{01}$ | MPa | -0.03 |
| | D | $MPa^{-1}$ | 0 |

### 3. Results

As stated earlier, the force-displacement curve was plotted for the N95 respirator and surgical facemask earloop. N95 respirator exerts a greater force on the auricle, and consequently, it was considered the extreme case for determining auricular displacement and stress. Resource constraints compelled us to approximate a linear pressure distribution on the auricle. The effective pressure was determined to be 15250 Pa or approx. 114.5 mm of Hg. However, it was verified with visual observations and error was less than 10%. We use the elastic loop displacement value in the force-displacement plot in Figure 6 to get the corresponding force exerted by the facemask. Based on this methodology, the force exerted by the surgical mask and the N95 respirator was determined to be 0.9 N and 2.7 N, respectively. The same is shown in Table 2.

As the displacement is the same for both surgical mask and N95 respirator, the instantaneous stiffness of the N95 respirator is significantly higher than that of the surgical mask. N95 respirators are close-fitting compared to surgical facemasks. The calculated values are in line with the authors observation that the stiffness of the head straps exerts a considerable influence on the closeness of the facemask fit. The cloth mask ear loop was not tested as the material and thickness show significant variation across manufacturers. However, understanding the importance of cloth masks in double masking, the possible range of force exerted was determined by plotting on N95 and surgical mask curves. The interpolation shows that if the custom cloth mask earloop was made of the same material as that of N95 respirator, the force exerted will be 3.1 N, whereas if it is made from surgical earloop material, the force exerted will be 1.5 N. Table 2 provides the value of the stretched and unstretched length of the elastic band for the three classes of facemasks that are considered for the present study.

**Table 2:** Force exerted by different facemasks

| Mask type | Lateral dimension | Unstretched length | | Stretched length | Elastic loop displacemen t | Force exerted | Displacement in x- direction |
|---|---|---|---|---|---|---|---|
| | | Range | Median | | | | |
| | mm | mm | mm | mm | mm | N | mm |
| No mask | - | - | - | - | - | - | 0 |
| Surgical | 75-80 | 50-65 | 60 | 100 | 40 | 0.9 | 3 |
| Custom cloth mask | 70-75 | 40-55 | 50 | 80 | 30 | 0.6-2.2 | 4 |
| N95 | 45-60 | 65-90 | 70 | 110 | 40 | 2.7 | 8 |
| Surgical mask+ Cloth mask | - | - | - | - | - | 1.5-3.1 | 10 |

Since N95 respirators exert the maximum compressive force for an individual mask, it was considered to understand the maximum possible stress and displacement developed on the auricle. Ansys was used for numerical analysis. The earloop was simulated by a linear pressure distribution along the eminentia conchae. As shown in Figure 7, the maximum displacement occurs at the helix region with a magnitude of 7.89 mm. The resultant x-axis displacement at a specific point (marked in white in Figure 5) was used to validate the numerical model by comparison with the visual model and was observed to show a variation of less than 10%. The helix region also shows the maximum z-axis displacement (protrusion) of 1.8 mm. Von-mises stress distribution shows that the concha region is the most stressed (1085 Pa) compared to the helix region (172.5 Pa). The concha region shows the maximum resistance to displacement, whereas as we move away from the concha region, the resistance to displacement or stress decreases.

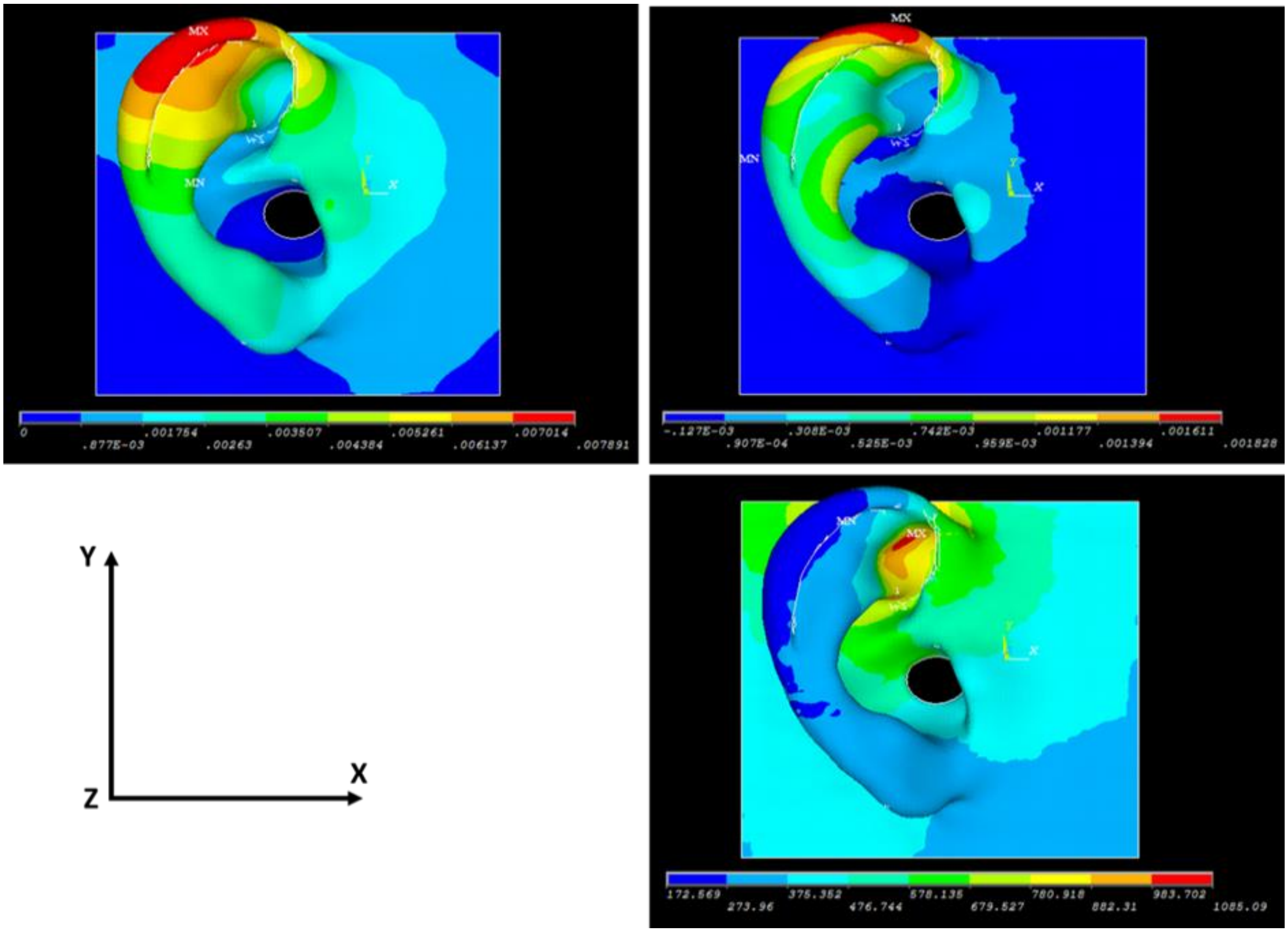


**Figure 7:** Auricular stress and displacement. Clockwise from top left a) X-axis displacement b) Z-axis displacement c) Von-mises stress

## 4. Discussion

The results quantify essential auricular stress and displacement parameters under compressive forces. We will now consider specific auricle-related phenomena and hypothesize similar outcomes due to facemask-induced auricular compressive stress and displacement. Though further studies are required to substantiate our theory, it opens research possibilities into some neglected aspects of auricle-related user health.

Splinting is a non-surgical method to treat congenital auricular shape deformations with no missing skin and cartilage. It uses splints to coerce the ear to a standard shape and maintain it until permanent correction occurs. Though studies show splinting on neonates has the highest probability of success, 9 to16-year-old children have also shown good to fair results. We observe the possibility of the opposite situation, i.e., Compressive forces distorting a normal auricle out of shape. Mandatory use of facemasks in public settings and workspaces indicates compressive forces acting on the auricle for as long as 12-14 hours a day. WHO recommends masking in children of age above 5 years. However, recommendations of national health agencies might be even lower, with CDC recommending masking in children above 2 years of age. Splinting shows a deterioration in success rate with age, as observed from 91 % in neonates to 33 % in 9-year-olds [20]. It is because ear stiffness increases with age. Facemask use in children must be studied in greater detail as the current minimum age for masking might be inappropriate. Unlike splinting, the facemask-induced compressive forces are discontinuous. It means that we do not wear face masks 24 hours a day, and consequently, the auricle is stressed only when face masks are worn. Intermittent usage of splits leads to poor results [21]. Duration of splinting vary from 2 weeks to 10 months [22]. However, the aggregate duration of facemask usage in an individual is far more than reported splinting durations. It has been more than two years since people have been wearing facemasks. The authors observe whether the discontinuous but extensive period of wearing a facemask, to some extent, reproduces the effect of the continuous but shorter period of splinting.

The pinna is so angled to collect and transmit sounds significantly from its front than from the back in humans. The sound quality in humans varies with the sound source's orientation [23]. The pinna plays a substantial role in sound localization. Pinna distortion (change in shape, orientation, or projection) temporarily affects the ability to pinpoint the origin of the sound source (i.e., sound localization) [23][24]. The numerical and experimental analysis results in the present study observe significant auricular deformation on wearing facemasks. It can be the reason for hearing difficulties experienced by people wearing masks. The ear becomes more curved, and the auricle is able to catch sounds from an even smaller area from the front. Also, it is conjectured that sound transmission may not be optimal, leading to hearing losses.

On wearing facemasks, greater occipital nerve, lesser occipital nerve, auriculotemporal nerve, posterior auricular nerve, and anterior ethmoidal nerves are the underlying facial nerves at contact areas. External compression of these nerves (depending on the facemask head strap) can cause external compression headaches as per the International Classification of Headache Disorders (ICHD-3) guidelines. It can include both external compression and external traction subcategories under it. Compression headaches due to mechanical irritation of the nerves on wearing military headwear and goggles are already well documented [25]. Recent studies have also shown the observance of headaches and neuralgia in healthcare workers due to wearing facemasks and aggravating symptoms in health workers who have a history of headaches [16][26].

External pressure is exerted on the facial areas of contact while wearing facemasks. The contact areas are predominantly the auricular region (for facemasks with ear loops), occipital region (for facemasks with occipital head straps), and contact area at the nose bridge. The pressure results in compression and shearing effects, breaking down the skin, decreasing and even cutting off nutrients and oxygen supply to the tissues, resulting in pressure ulcers, necrosis, and skin injuries of varying grades of severity. Studies state that pressure above 32 mm Hg will develop pressure sores [27]. However, some studies contradict this observation and point out that critical pressures as high as 78.6 mm of Hg on the body are required to cause pressure sores [28]. In short, high pressure over a brief period or low pressure over a longer duration can cause pressure ulcers. The external pressure on the auricle is determined to be 114.5 mm of Hg, which is more than the prescribed limit. This is supported by the fact that skin breakdown and pressure sores are commonly reported adverse effects of wearing facemasks.

## 5. Conclusions

Facemasks are essential in preventing the spread of COVID-19 and are worn in outdoor and indoor public settings. Facemasks with pre-auricular head straps/earloops are notably common than facemasks with occipital head straps. The present study quantitatively analyzes the compressive forces generated by the earloop on wearing a facemask. It was essential in understanding the auricle's resultant stress and displacement field. N95 respirators exert the maximum force on the auricle, while surgical masks exert the minimum force. The cloth masks being non-standardized are presumed to lie between these two extreme values. The force exerted by an N95 respirator is thrice that of a surgical mask. Auricle shape distortion was also visually observed on wearing facemasks. The forward displacement of the auricle on wearing an N95 respirator was almost three times that of wearing a surgical facemask. The present study indicates that double masking causes the auricle to deform more than any other type of facemask worn individually. Subsequently, the force exerted by double masking may be more than by an N95 respirator. The numerical analysis indicates that the concha is the most stressed region of the auricle while the helix is the region experiencing maximum deflection. The authors also acknowledge the limitations in the present study to neglect the effect of anthropometric variation. Some people pull facemasks below their chin, changing the resultant force direction. This scenario is also not considered. Based on related studies on the auricle, we correlate the similarities and conjecture that the compressive forces on the auricle may result in the following adverse effects, as shown in Figure 8.

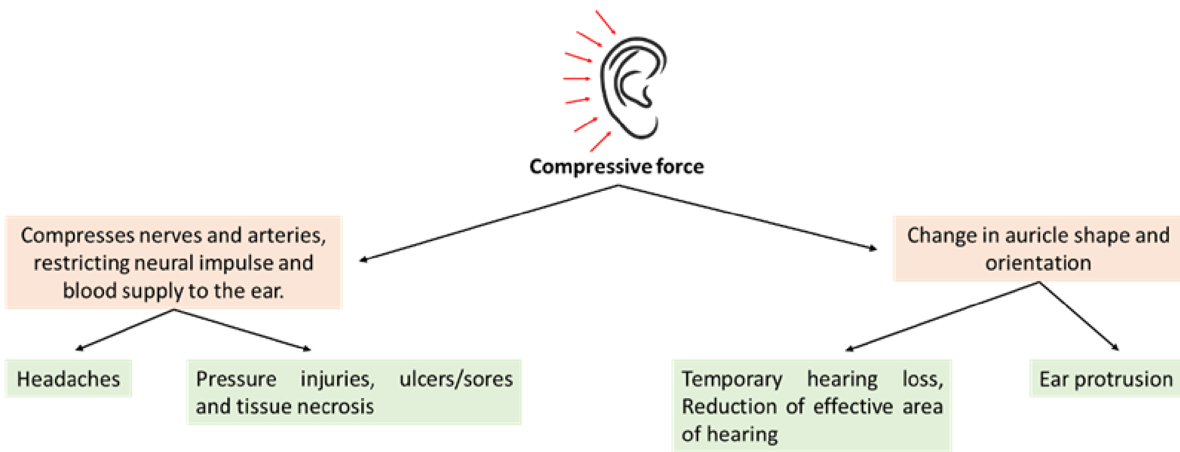


**Figure 8:** Possible adverse effects of compressive force on the auricle

Also, wearing extenders might not be a solution as we are stretching it more so that the compressive force increases. We are merely changing the contact area to the occipital region. Detailed studies in this aspect are also required.

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