

Energy Absorbency and Impact Resistance of D3O[®] Materials Under Dynamic Impact Loadings

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Abstract: Hand-held power tools, such as percussive riveting tools, produce vibrational forces that are transmitted through the hands, arms, and elbows. These vibrational forces may be responsible for the causation of short and long-term neuronal and/or vascular diseases. Personal protective materials are available commercially, some of which are used during the operation of percussive power tools (e.g., anti-vibration gloves). In previous studies, D3O[®] materials showed a greater absorption of impact energy in low-velocity static impact testing compared to conventional materials. In this study, D3O[®] materials were tested under dynamic impact loadings to evaluate resistance to impact characteristics to assess the adequacy of an ergonomic intervention using D3O[®] materials. An experiment was performed to evaluate material resistance to impact by evaluating the peak load values with different precompression magnitudes and loading frequencies. D3O[®] materials showed that compression magnitude was a statistically significant factor ($p = 0.00$) affecting the peak load value compared to loading frequency, which had little to no effect when tested under 14 Hz or less. As peak loads increase, the resistance to impact loading decreases and energy transmission increases. D3O[®] back protector (DBP) and D3O[®] Rifle Harness (DRH) exhibited lower peak values compared to D3O[®] Recoil Pad (DRP) material. D3O[®] materials may be considered to be utilized in a riveting and bucking intervention to reduce vibrational forces from percussive tools in a dynamic aircraft manufacturing environment.

Keywords: D3O[®] Material, Dynamic Impact Loading, Peak Load and Impact Resistance, Recovery Time

1. Introduction

Manual riveting and bucking are tasks commonly performed in aircraft manufacturing. Percussive pneumatic rivet guns are used for driving the head of the rivet, commonly called 'riveting', and metallic bucking bars are used for manually pushing against the back of the rivet, commonly called 'bucking.' The riveting and bucking tasks are typically performed at the same time, often by two sheet metal operators (a riveter and buckler) and results in flattening and expanding the diameter of the rivet to securely connect two sheets of metal.

Percussive pneumatic hand-held riveting power tools and bucking bars produce vibrations that transmit through operators' hands and upper extremities [1-3]. Over years of exposure, these vibrational forces may cause or contribute to the development of various types of musculoskeletal disorders (i.e., vascular and/or neural symptoms) called Hand-Arm Vibration Syndrome. Neurological and musculoskeletal disorders, such as carpal tunnel syndrome, were common among users of percussive tools such as rivet guns and bucking bars, which produce low and high vibration frequencies associated with high vibrational impact forces, whereas vascular disorders, such as Vibration White Finger,

were seen more among users of high-frequency vibration tools with various vibration levels but low impact forces, for example, grinders and sanders [2, 4-9].

Sheet metal operators in the aircraft industry are exposed to vibration by utilizing rivet guns and bucking bars daily. They have also often been associated with complaints of pain and stiffness in their hands and arms and symptoms of vibration-induced white finger or stiffness of the wrist [7, 9]. Moreover, vibration exposure and hand-intensive work are risk factors for the development of carpal tunnel syndrome [10, 11], which has prevalences ranging from 7% to 35% and an average of 18% among vibration-exposed workers [12]. Sheet metal operators and experienced riveters are reluctant to use vibration insulators to reduce vibration exposure if it interferes with the object being worked on [1, 13] or reduces tactile feedback. At vibration frequencies below 100 Hz, a vibration insulator containing material that is incompatible with the mechanical properties of the human hand-arm system may intensify the magnitude of vibration [1, 22]. Furthermore, this vibration insulator could still be marketed and classified as ‘anti-vibration’ product due to the wide range between the lower-frequency and higher-frequency of the published 2013 revision of the ISO 10819 standard categorizing the average vibration transmissibility [14]. This led to the search for vibration insulator materials that may provide less interference to improve the tactile feedback with mechanical properties that transmit less energy during dynamic impact loadings to attenuate the vibrational forces transmitted to the workers’ hands, arms, and elbows.

Soft materials such as expanded polypropylene foams are used in many applications such as packaging, personal safety equipment, and composite structures in the aircraft, naval, and automotive industries. The main purpose of these foams is to absorb the maximum energy under severe dynamic compression loading, which involves materials’ microstructures, density levels, strain rates, and velocity of displacement [15]. In previous studies, D3O® material showed an outstanding capability of energy absorption during static impact testing of up to 0.16 damping ratio compared to silicone and other rubber-like materials with up to 0.05 damping ratio [16-24]. These test results, however, were collected from a single static impact and may not be reflective of dynamic impact environments. Riveting is a dynamic task and to determine whether these materials would be appropriate for a riveting task, it was necessary to characterize the impact resistance and recovery process of D3O® materials in a dynamic impact testing environment that is similar to riveting and bucking. Therefore, the purpose of this study was to determine how D3O® materials respond to different vibrational impact conditions in a dynamic impact environment in which to assess the level of energy absorption by comparing the peak impact load as a function of the displacement level. Additionally, stress relaxation was measured by estimating the stabilization time of the D3O® materials undergoing a series of impact loading similar to a pattern of undergoing a series of continuously driven rivets.

2. Experiment

Samples of D3O® materials were subjected to dynamic impact loading with different precompression magnitudes and frequencies using an MTS machine to evaluate their mechanical properties and potential ability to reduce vibrational impact forces during riveting and bucking tasks. The dynamic impact testing and recovery time estimation were designed to simulate the vibrational impact forces produced by hand-held power tools during sheet metal riveting and bucking operations in aircraft manufacturing.

2.1. Materials

Three elastomeric non-Newtonian D3O® materials were acquired from products available on the market. Each material was advertised to protect the human body against a sudden impact force (i.e., D3O® Rifle Harness (DRH), D3O® Recoil Pad (DRP), and D3O® back protector (DBP)) (Figure 1). The materials profile was standardized to measure the same dimensions of $7.62 \times 10.16 \times 1.1$ cm. The cyclic loading test was performed using an 810 MTS model # 661.20E-03 (Materials Test Systems, Eden Prairie, MN, USA) (Figure 2).

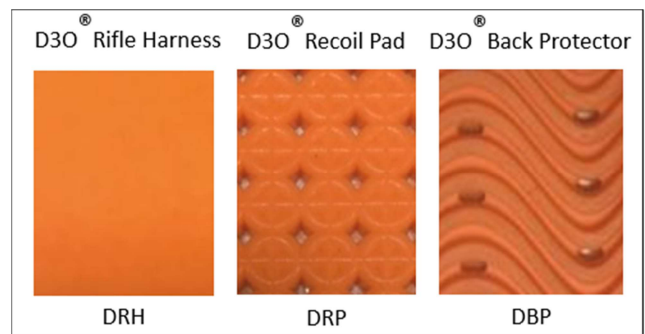


Figure 1. D3O® Materials.

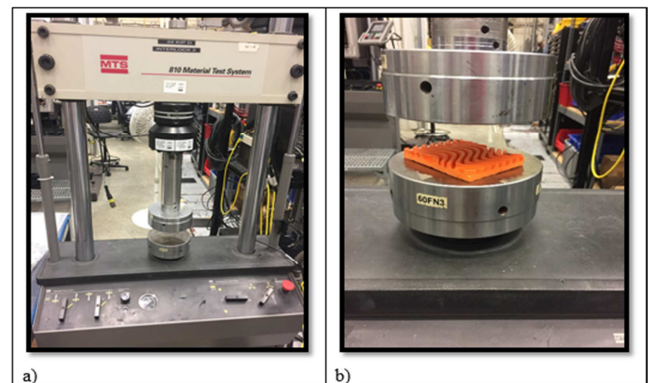


Figure 2. a) 810 Material Test Systems (MTS) model # 661.20E-03 and b) DBP material during the preparation of the dynamic cyclic loading test.

2.2. Experiment Protocol

A test run was performed using the MTS machine impacting samples of D3O® materials to evaluate the MTS machine performance at different low and high frequencies to ensure the MTS machine was free of hydraulic leaks or loose components. Dynamic impact loading testing conditions were

performed at frequencies ranging from 8 Hz and 100 Hz and data for each condition was collected from 300 cycles of continuous impact loading. These dynamic load testing conditions were performed to evaluate D3O[®] materials at frequencies to simulate rivet gun vibration frequencies [3]. Because the MTS machine was inconsistent in maintaining the selected displacement values, which showed frequent fluctuations over time at frequencies higher than 14 Hz, the dynamic impact loading tests were limited to 8 Hz and 14 Hz. Each testing condition was replicated three times to validate the consistency of the data produced by the MTS machine. After performing each condition, data were stored in the MTS's computer data file and then exported for analysis.

Each material was tested separately and the order of conditions was performed randomly. A two to five minute break time was taken between each test condition, which was used to reset the MTS machine parameters to the next selected testing condition and provide sufficient time for each material to recover from the previous impact loading. The same MTS machine was used for all testing conditions across all five days, and all testing conditions were performed indoors at a room temperature of $\approx 20^{\circ}\text{C}$.

2.3. Recovery Time Estimation

It was necessary to study the reversible deformation phenomenon (creep recovery) to understand the irreversible deformation limits of D3O[®] material and evaluate its capability relative to the riveting task. Creep recovery time was estimated from two separate dynamic impact loading tests. The first impact loading test was performed to simulate the duration of the riveting/bucking operation and elapsed time between sequential impact loading. This test served to estimate the stabilization time of the material. The second impact loading test was performed to estimate the recovery time of the material. This test was performed by assigning different elapsed times (details provided in the following paragraph) between a series of identical impact loading cycles. Precompression of 10%, displacement of 20%, and loading frequency of 25 Hz was the condition selected for both stabilization (stress relaxation modulus) and recovery time estimation (time for the material to return to its original state) tests. The peak load data were collected at a sampling rate of 100 Hz. Each testing condition was replicated three times to validate the consistency of results produced by the MTS machine. The evaluation of the displacement/time plot for the recovery testing data indicated repeatable results when tested under frequencies higher than 14 Hz (i.e., 25 Hz), which may be due to the small number of cycles at a time (25 cycles), elapsed times utilized, and frequent resetting of the MTS machine.

Material Stabilization Time Estimation. The elapsed time between each impact was one second at a frequency of 25 Hz for each material during the stabilization test. The test included 20 sequential one-second duration impacts performed to simulate 20 driven rivets. The elapsed time and frequency were considered to mimic the elapsed time between driven rivets in a repetitive riveting/bucking task. Materials were not precompressed at the initial impact loading nor remaining sequential impact loading due

to the short elapsed time selected between impacts (i.e., one second). The displacement selected was 30% of the 1.1 cm original thickness to compensate for the precompression magnitude.

Material Recovery Time Estimation. To avoid overestimated results that may occur as a consequence of operating the MTS machine at its maximum frequency range, which may cause the cylinder to overshoot beyond the selected displacement level during the first initial impact, the precompression setup was reprogrammed to reduce displacement fluctuations only at the initial impact. This reprogramming was performed because the recovery time is highly dependent on the loading dimension of displacement [25]. Specifically, the first initial impact had 0.0046 cm of compression ($\approx 0.4\%$ of the 1.1 cm original thickness). A 10% precompression magnitude was programmed for each sequential impact loading cycle.

The MTS machine was programmed to execute the following testing protocol: the initial impact compression was applied to the material, the material was then precompressed by 10% and then cyclically impact loaded at 25 Hz for one second to compress the precompressed material by 20%, the impact loading stopped, the 10% precompression was removed, the MTS machine remained idle for the designated elapsed time (i.e., waiting time), and the process beginning with the 10% precompression step was repeated for 20 cycles. The different elapsed times between impact loading cycles after the initial impact loading at time 0 were as follows: 2, 3, 6, 10, 20, 30, 60, 120, and 240 seconds (Figure 3).

2.4. Study Design

The dynamic impact loading parameters were comprised of precompression magnitude, loading frequency, and displacement magnitude. The independent variables were: 1) precompression magnitude at two levels (10% and 20% of the material thickness), which was utilized to simulate different handgrip strengths of hand-held power tools, 2) loading frequency at two levels (8 Hz and 14 Hz), utilized to expose the materials to similar frequencies of a rivet gun, and 3) displacement magnitude at 20% of the material thickness calculated after the precompression for each testing condition. The displacement magnitude was a constant variable with the assumption that the material may be compressed after the precompression (i.e., handgrip) and be farther displaced due to the rivet gun impact loading during a riveting task (Table 1). The dependent variable was the peak load (kg) produced during the impact loading from the MTS as a function of the different precompression and loading frequencies. These load values represented the average impact force from the change in kinetic energy and displacement level during this impact load testing. The peak load data were collected at a sampling rate of 1000 Hz.

Table 1. Dynamic Impact Loading Experimental Design.

Material Type	Precompression %	Frequency Hz
DRH	10, 20	8, 14
DRP	10, 20	8, 14
DBP	10, 20	8, 14

Note: displacement during each condition testing was set to 20% of the remaining material thickness after precompression.

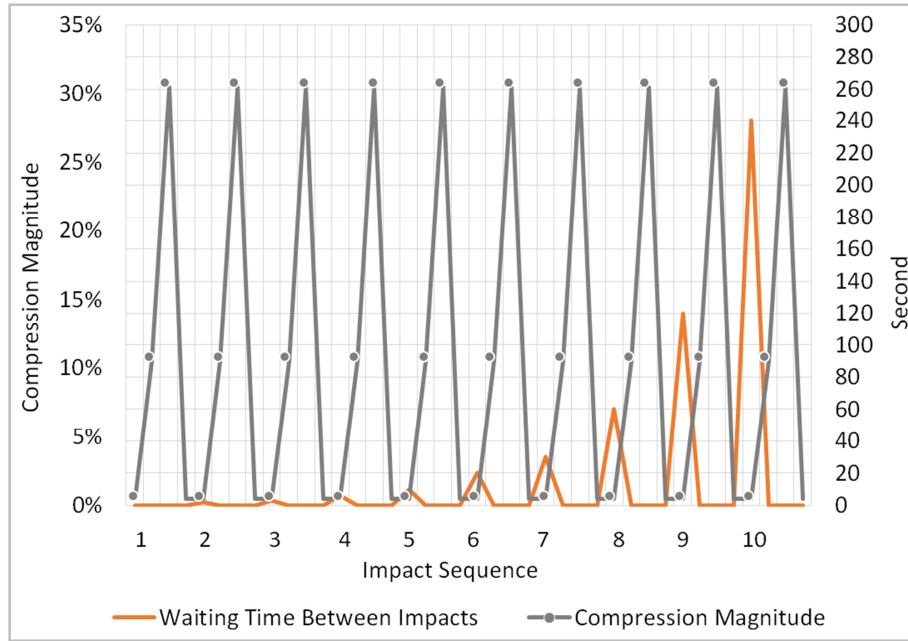


Figure 3. Material recovery time study design.

2.5. Data Analysis

The frequencies 8 Hz and 14 Hz were the common range utilized to compare the performance of the three D3O® materials. A time/displacement plot was used to evaluate the reliability and performance of the results during each testing condition. Moreover, the displacement fluctuation was analyzed by comparing the displacement's deviation from the preselected value at different loading frequencies. Data collected from 8 Hz and 14 Hz were statistically compared.

2.6. Statistical Analysis

A two-way Analysis of Variance (ANOVA) was performed to statistically compare the peak load as a function of precompression magnitude and D3O® material types. An additional two-way ANOVA was performed to statistically compare the peak load as a function of loading frequency and D3O® material types. Significant main effects were investigated by Tukey HSD post hoc tests to evaluate where the differences occurred between groups.

Significant interaction effects of the peak load by material type and precompression, and material type and frequency were analyzed utilizing Bonferroni adjustments to the level of significance to reduce the probability of a Type I error from multiple comparisons ($\alpha = 0.05/n$ where $n = 3$ for the number of material type comparisons, leading to $\alpha = 0.0167$) and ($\alpha =$

$0.05/n$ where $n = 2$ for the number of precompression and frequency comparisons, leading to $\alpha = 0.025$). All statistical analyses were performed using 2021 IBM® SPSS® software package version 28 for Windows (Chicago, IL).

3. Results

The peak load value during impact loading varied between material types. Material DRH and DBP showed similarities in their peak loading response. DBP had little to no effect when increasing the precompression and loading frequency. DRP and DRH peak load values increased as the precompression and loading frequency increased (Figure 4).

3.1. Precompression and Material Type Effect on Peak Load

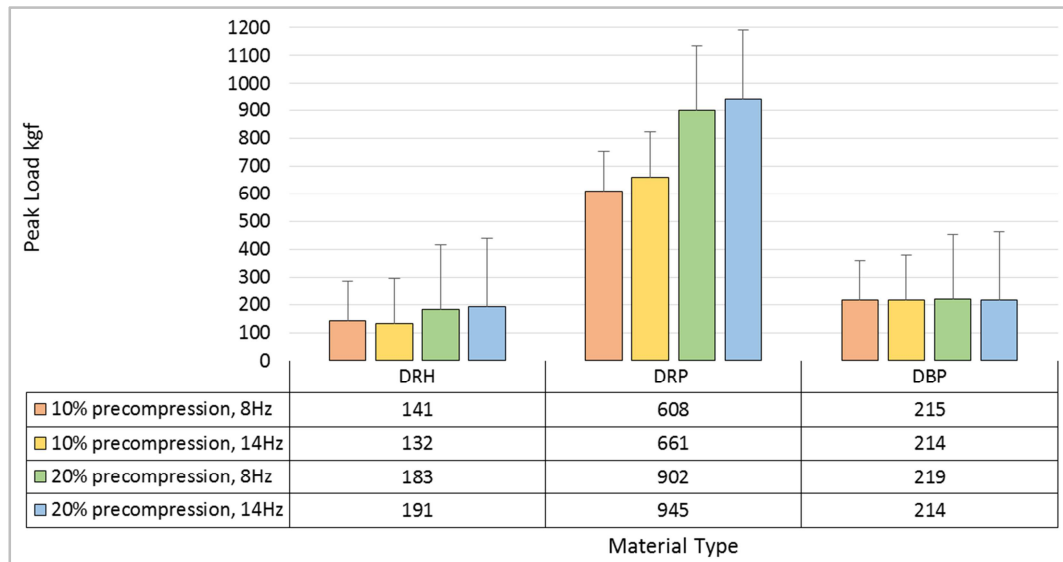
The two-way ANOVA indicated that the interaction effect between the material type and precompression magnitude was statistically significant on the peak load ($F(2, 42) = 455.28, p = 0.00$) (Table 2). The percentage of variance in the peak value (effect size, η_p^2) for each material type attributable to different precompression magnitudes showed that material DRP had the highest percentage of variance in the peak load ($\eta_p^2 = 0.97$) followed by DRH ($\eta_p^2 = 0.54$), and there was no effect for DBP ($\eta_p^2 = 0.00$) (Table 3).

Table 2. Two-Way ANOVA for Material Type and Precompression Effect on Peak Load.

Source	SS	DF	MS	F	P value
Precompression	157437.52	1	157437.52	733.15	0.00
Material Type	3756704.17	2	1878352.08	8747.06	0.00
Precompression * Material Type	195535.17	2	97767.58	455.28	0.00
Error	9019.13	42	214.741	-	-
Total	11265101	48	-	-	-

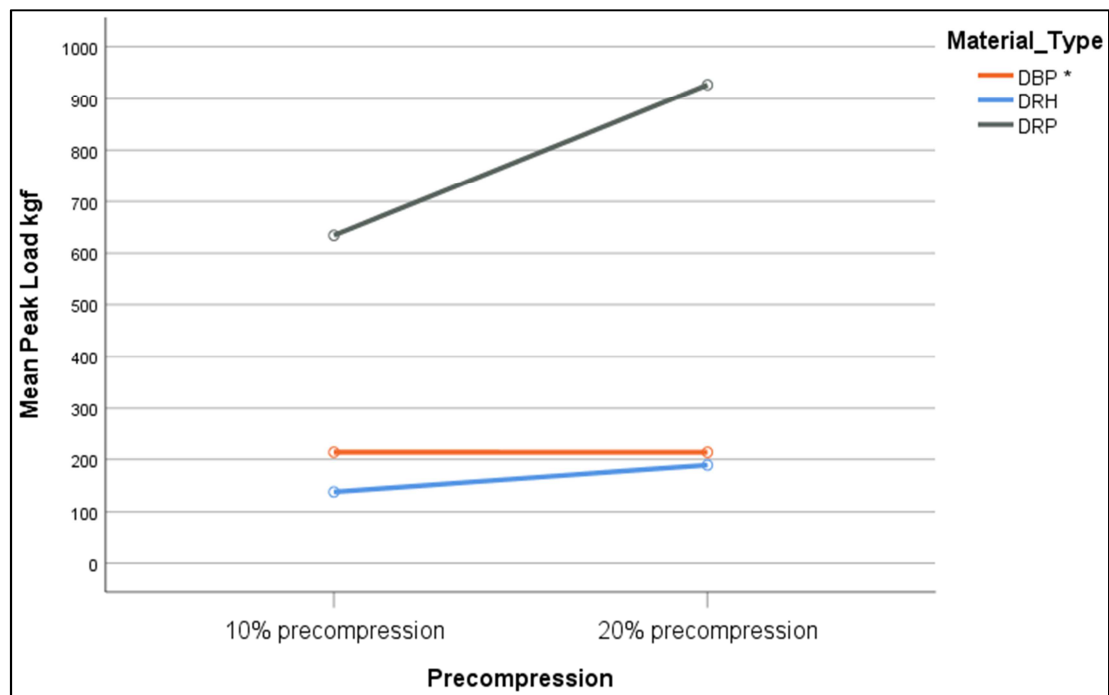
Table 3. Effect Size of Precompression on Peak Load by Material Type.

Material Type	SS	DF	F	P value	Partial Eta Squared (η_p^2)
DBP	0.063	1	0.00	0.986	0.00
DRH	10455.06	1	48.69	0.00	0.54
DRP	342517.56	1	1595.03	0.00	0.97

**Figure 4.** Mean peak load values comparison between material types during dynamic impact loading test (colors represent testing condition only). Error bars represent 1.0 standard deviation.

A post hoc pairwise comparison of the interaction effect presented that materials DRH and DRP had a statistically significantly different peak load at different precompression magnitudes, 10% and 20%, ($p < 0.01$), but not material DBP ($p > 0.84$). At the same time, there was no statistically significant difference between material DRH and material

DBP peak values when tested under different precompression impact loading magnitudes, 10% and 20%, $p = 0.22$ (Figure 5). Moreover, material DRP was statistically different from materials DBP and DRH at both precompression magnitudes, $p = 0.00$ (Figure 5).



* No statistical difference between precompression magnitudes on peak load.

Figure 5. Mean peak load variations between materials and precompression magnitude.

3.2. Frequency and Material Type Effect on Peak Load

Materials reacted similarly at both frequencies, 8 Hz and 14 Hz. The two-way ANOVA indicated that the interaction effect between material types and frequency was not statistically

significant for the peak load ($F(2, 42) = 0.01, p = 0.99$) (Table 4), and the frequency did not have a significant impact on the peak load ($F(1, 42) = 0.001, p = 0.99$) (Figure 6).

Table 4. Two-Way ANOVA for Material Type and Frequency Effect on Peak Load.

Source	SS	DF	MS	F	P value
Frequency	4.69	1	4.69	0.001	0.99
Material Type	3756704.17	2	1878352.08	218.02	0.00
Frequency * Material Type	134	2	67	0.01	0.99
Error	361853.13	42	8615.55	-	-
Total	11265101	48	-	-	-

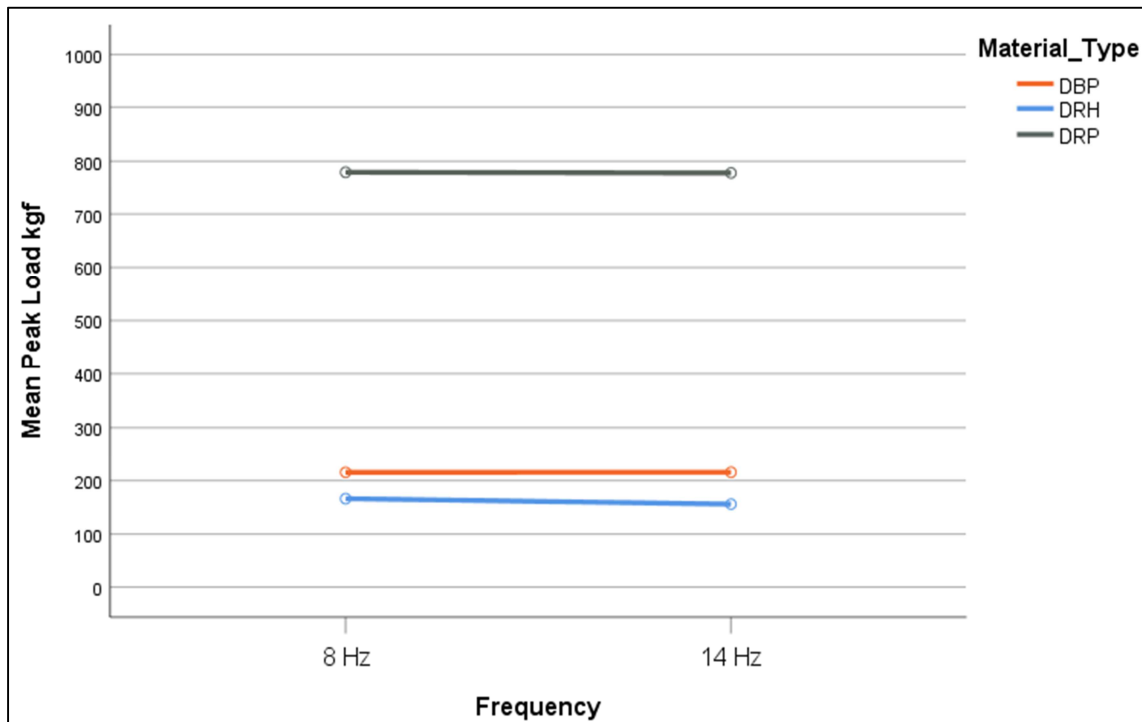


Figure 6. Mean peak load variations between materials and loading frequency.

The main effect of material type on the peak load was statistically significant, ($F(2, 42) = 218.02, p = 0.00$) (Table 4). Tukey HSD post hoc test indicated that there was no statistically significant difference between materials DBP and DRH ($p = 0.29$) however, both materials (DBP and DRH) were significantly different from material DRP ($p = 0.00$).

3.3. Recovery Time

Material Stabilization Time. DBP material had a decrease in resisting the impact loading until its peak load value stabilized after ≈ 12 consecutive impacts, which represented the material's stress relaxation modulus at the given fixed strain level (Figure 7). Materials DRH and DRP (Figure 8 and Figure 9, respectively), on the other hand, stabilized after ≈ 8 consecutive impacts (all materials had a one-second interruption between each impact). The peak load value associated with the material stabilization value represents the maximum level of load that the material can absorb over time

(see Figure 7, Figure 8, and Figure 9).

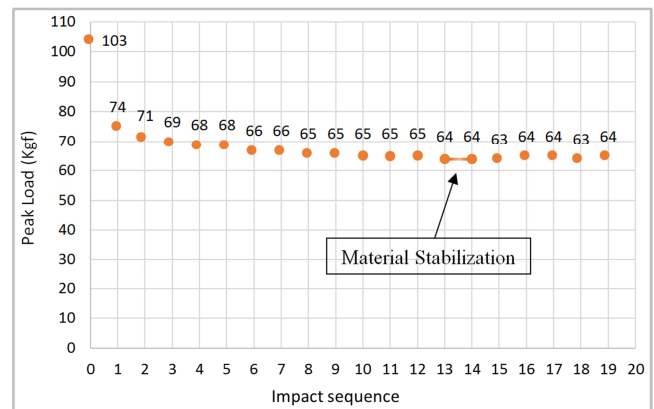


Figure 7. DBP compression relaxation characteristic during sequential impacts. Data were used to estimate DBP stabilization time.

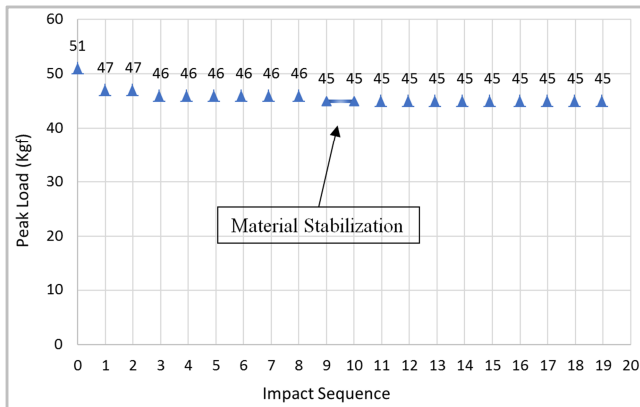


Figure 8. DRH compression relaxation characteristic during sequential impacts. Data were used to estimate DRH stabilization time.

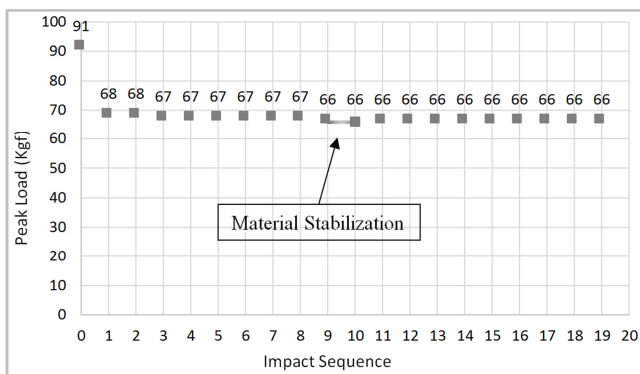


Figure 9. DRP compression relaxation characteristic during sequential impacts. Data were used to estimate DRP stabilization time.

Material Recovery Time. The peak load value was used to estimate the start of the recovery time and the full recovery time of each material. All three materials started to recover from the impact loading at the assigned elapsed time of 2 seconds, but each material had different recovery progress (93% - 99%). The full recovery time was between 120 to 240 seconds for DBP (Figure 10), 10 seconds for DRH (Figure 11), and 6 seconds for DRP (Figure 12).

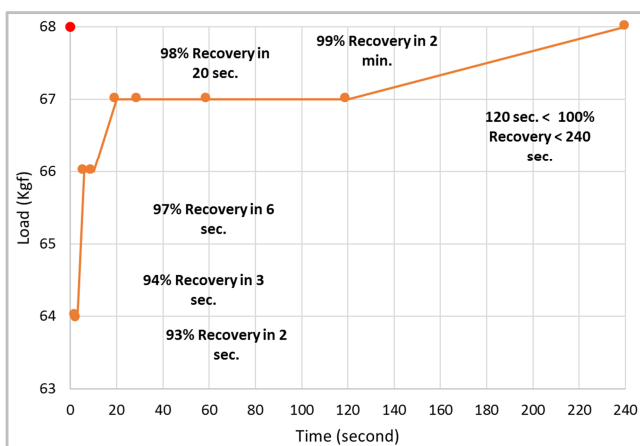


Figure 10. DBP recovery time data during the dynamic impact loading.

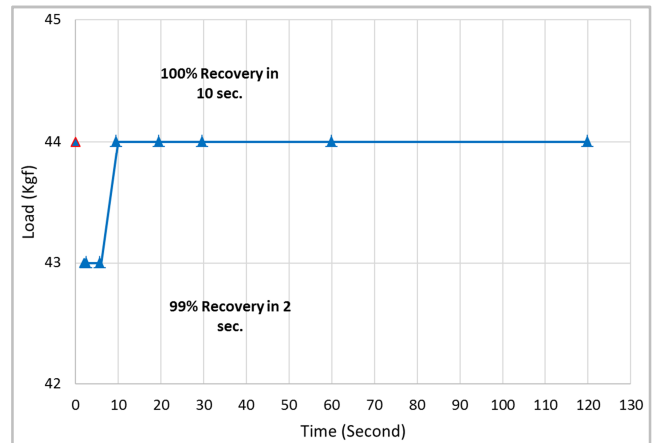


Figure 11. DRH recovery time data during the dynamic impact loading.

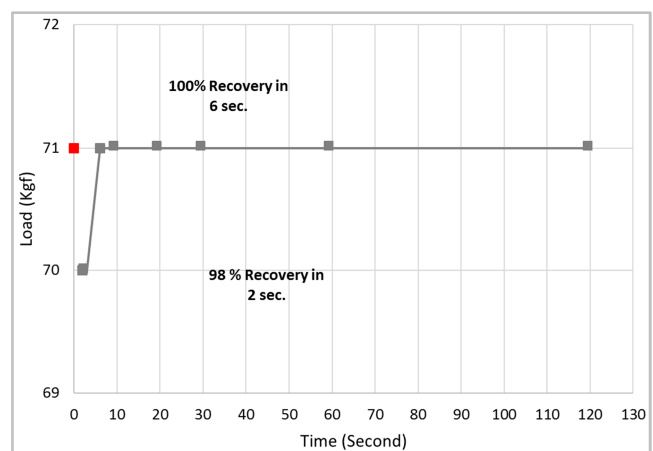


Figure 12. DRP recovery time data during the dynamic impact loading.

4. Discussion

Four dynamic impact loading tests were performed on D30[®] materials to mimic exposure to vibration waves representative of the riveting and bucking tasks. Material DRH followed by DBP showed the lowest mean peak impact load compared to DRP. The impact peak load value increased as the precompression magnitude intensified for materials DRH and DRP, but not for material DBP. Material DBP maintained a close mean peak load value and was not affected by the increase in precompression, which represented a hand gripping the material during a riveting task. Materials DRP and DRH were sensitive to the precompression magnitude and their peak load values increased as the precompression magnitude increased. This may indicate that as gripping harder on the DBP material against the rivet gun's handle the material may still have the same damping effect on the vibration.

Peak loads for material types were not affected when tested under impact loading at 8 Hz and 14 Hz loading frequencies, however, the peak loads were different when tested under impact loading at 10% and 20% precompression magnitudes. Materials DBP and DRH showed more capabilities to damp impact loading than DRP at both precompression magnitudes. Loads were generated based on the displacement of material thickness under impact loading and as a result of the mechanical

properties of each material. Material DRH may have the ability to damp more vibrational impact loading similar to DBP and significantly more than DRP material as observed by the low peak loads, as the material exhibited an inverse relationship between the impact toughness and damping ratio [26-29]. Materials DRH and DBP showed superior impact loading absorption compared to material DRP at both precompression magnitudes. Material DBP showed similar peak load values during impact loading at both 10% and 20% precompression magnitudes, which was observable during the slow compression drop throughout the stabilization impact loading test (Figure 7) compared to material DRH (Figure 8). This result indicated that material DBP may continue to absorb the energy of the impact loading as the impact loading continues compared to material DRH. It may also be due to the open slotted grooves of material DBP shape design (Figure 1).

All three materials recovered more than 90% of their original state within two seconds after the applied load was removed. Comparisons of the percentage increase in recovery time indicated that material DRP (100% in 6 seconds) and material DRH (100% in 10 seconds) recovered faster than material DBP (98% in 20 seconds). These recovery time differences may indicate a higher viscosity level in material DBP, which may be explained by the longer time consumed to stabilize under impact loading as indicative of the D3O® non-Newtonian (dilatant) property. This mechanical property allows the viscosity to increase (thickening) with the shear strain level (higher stress level, lower shear rate). This feature of D3O® material may make it act as a spring-damper when being exposed to high-impact hand-held power tools to reduce or absorb more of the vibrational transmitted forces associated with the riveting and bucking tasks. Additionally, the higher resulting viscosity may contribute to increased tactile sensations when gripping hand-held power tool handles during riveting and bucking tasks. On the other hand, material DBP showed no response after 0.75 seconds at 20% precompression, 20% displacement, and 25 Hz (Figure 13). Material DBP showed a cut-off at ≈ 0.75 seconds when exposed to a frequency of 25 Hz. These characteristics might also be explained by the thickening feature (or structural changes under high impact loadings and speed) when exposed to sudden shocking vibrational impacts, which may be caused by the material not being able to recover and return to its original size and shape (material DBP deforms slowly and steadily returns to its original shape). Furthermore, there might not have been enough contact between the material DBP and MTS cylinders at a higher frequency due to the stress relaxation phenomenon (or the response rate of those soft materials was insufficient under continuous impact loadings). Load absorption is highly dependent on the level of displacement, loading dimension, and length of operation [25].

Driving one rivet in a sheet of metal consumes approximately one second and depends on the rivet diameter, the rivet length, and the type of rivet gun used to drive the rivet [9, 30]. If material DBP has the capability of absorbing a significant amount of vibration energy for ≈ 0.75 seconds at higher frequencies during impact loading, then it may be beneficial to evaluate the reduction of vibration transmitted

through workers' hands when using this material. If material DBP absorbed a significant amount of vibration energy for ≈ 0.75 seconds, this may suggest that the material absorption time was sufficient to reduce the vibration impact forces during a one-second driven rivet (Figure 13). As is illustrated, the damping process stopped after ≈ 0.75 seconds, which may be related to the lack of chain orientation of the polymers, entanglement of the chains, excessive heat formation, or slow dissipation of heat caused by the high-frequency impact/vibration. Similar observations can also be observed in other soft polymeric foamy materials [15, 25, 28, 29].

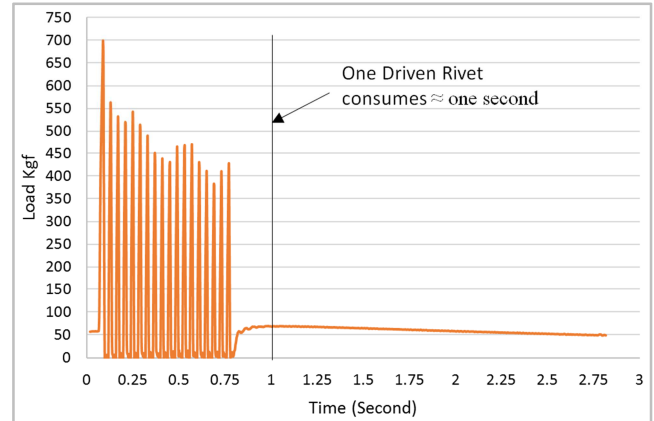


Figure 13. Load value analysis of DBP material damping vibration (20% precompression and 20% displacement at 25Hz) during a riveting task.

Finally, these results suggest that the materials may be ranked in terms of viscous to glassy as follows: 1) DBP (very viscous), 2) DRH (viscous), and 3) DRP (glassy). Holding the rivet gun handle when driving a rivet head provides a tactile feeling that indicates when to stop driving the rivet. Therefore, materials DBP and DRH (more deformable and viscous) may be beneficial by wrapping around the handle of a rivet gun or inside a glove. Holding the bucking bar when bucking a rivet butt provides tactile feedback that indicates to the user when to stop bucking the rivet. Therefore, using material DRP (glassy) as a layer within the bucking bar may be more suitable to reduce the vibration before it reaches the buckers' hands. Utilizing these materials in a riveting and bucking task may also require acclimation as to when it is sufficient to stop driving the rivet head (riveter) and stop bucking the rivet butt (bucker) given the potential for decreased vibration transmission and differences in tactile feedback. Performing riveting/bucking task experiments using D3O® materials among human participants to evaluate vibration transmission into riveters' and buckers' hands, arms, and elbows, including an assessment of the relationship between satisfaction, performance, and tactile sensation level, may be necessary for the application of vibration insulators in future studies.

The findings of this study should be viewed in light of several limitations. First, all materials testing was performed at room temperature. Higher or lower temperatures may affect the material properties, which may cause the material to react differently, influencing its characteristics and responses.

Second, the D3O[®] materials were laid down flat during testing, so it is unknown if the material will respond similarly when wrapped around a rivet gun handle and/or bucking bar. Third, the frequencies used during the dynamic impact tests were somewhat lower than what a rivet gun may generate. At the same time, the MTS machine used for the testing had two heavy steel cylinders, each of which with a diameter of at least twice the size of an average-sized adult's palm. Fourth, the vibrational forces produced during the impact loading may be different than the vibrational forces produced by a hand-held percussive power tool. Finally, the life expectancy of D3O[®] materials under the tested loading conditions is unknown. Determining the lifecycle information as well as the material biocompatibility of the material was beyond the scope of this study.

5. Conclusions

D3O[®] materials showed a similar response under dynamic impact loading with different load peak values. Vibrational frequencies less than 25 Hz had less effect on the peak load value of the materials compared to the precompression magnitudes. Materials DBP and DRH showed greater energy absorption which indicated a thickening feature when exposed to impact loading. Material DBP also showed a longer duration of damping to impact loading compared to DRH and DRP. Utilizing materials DBP and DRH wrapped around a rivet gun handle and bucking bar may be suitable because both materials showed softness and high viscosity and deformability associated with lower peak values during impact loading, which indicates that these materials may act as a spring-damper. Using DRP as a filler inside a bucking bar due to its stiffness property may increase the absorption of energy transmitted from the rivet gun. Overall, D3O[®] materials indicated potential damping to impact loading under low-frequency, high-impact loading, which suggests that this material may potentially be an appropriate intervention to reduce vibration transmission to the hands and arms of workers during repetitive aircraft manufacturing operations.

6. Recommendations and Future Work

This experiment suggests that there are potential benefits of utilizing D3O[®] material for sheet metal operators for bucking and riveting tasks for their upper extremities. The D3O[®] material's performance was tested in a laboratory and found that its resistance to cyclical impacts can be significant. Study limitations include lack of human in the loop, interaction of tools with the material, and riveting and bucking tasks. Recommendations for the future studies include comparing between different anti-vibration materials with the use of current technological tools to measure vibrational forces transmitting through hands, arms, and elbows of the operator. Finally, the composition of material, rheological testing to perform viscosity analysis, heat exchange capacity, and hysteresis tests were out of the scope of this study. Therefore,

performing these tests on the D3O[®] material may reveal results that may indicate how and why this material may be of potential.

Conflict of Interest Statement

The authors declare that they have no competing interests.

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References

- [1] Griffin, M. J., (1990). *Handbook of Human Vibration*. Academic Press Limited: London.
- [2] Kihlberg, S. & Hagberg, M. (1997). Hand-arm symptoms related to impact and nonimpact hand-held power tools, *International Archives of Occupational and Environmental Health*, 69, 282-288.
- [3] Dale, A. M., Rohn, A. E., Burwell, A., Shannon, W., Standeven, J., Patton, A., & Evanoff, B. (2011). Evaluation of anti-vibration interventions for the hand during sheet metal assembly work. *Work*, 39 (2), 169-176.
- [4] Pelmear, P. L. (1998). Epidemiology of hand-arm vibration syndrome. *Hand-Arm Vibration: a Comprehensive Guide for Occupational Health Professionals*, 103-126.
- [5] Pelmear, P. L., & Leong, D. (2000). Review of occupational standards and guidelines for hand-arm (segmental) vibration syndrome (HAVS). *Applied Occupational and Environmental Hygiene*, 15 (3), 291-302. DOI 10.1007/978-1-4614-1150-5_15.
- [6] Farkkila, M. (1978). Grip force in vibration disease. *Scandinavian Journal of Work, Environment and Health*, 4, 159-166.
- [7] Burdorf, A. & Monster, A. (1991). Exposure to vibration and self-reported health complaints of riveters in the aircraft industry, *Annals of Occupational Hygiene*, 35, 287- 298.
- [8] Bonvenzi, M., Fiorito, A., & Volpe, C. (1987). Bone and joint disorders in the upper extremities of chipping and grinding operators. *International Archives of Occupational and Environmental Health*, 50, 189-198.
- [9] Dandanell, R., & Engström, K. (1986). Vibration from riveting tools in the frequency range 6 Hz—10 MHz and Raynaud's phenomenon. *Scandinavian journal of work, environment & health*, 338-342.
- [10] Van Rijn, R. M., Huisstede, B. M., Koes, B. W., & Burdorf, A. (2009). Associations between work-related factors and the carpal tunnel syndrome—a systematic review. *Scandinavian journal of work, environment & health*, 19-36. <https://doi.org/10.5271/sjweh.1306>.
- [11] Palmer, K. T., Harris, E. C., & Coggon, D. (2007). Carpal tunnel syndrome and its relation to occupation: a systematic literature review. *Occupational Medicine*, 57 (1), 57-66.

- [12] Nilsson, T., Wahlström, J., & Burström, L. (2017). Hand-arm vibration and the risk of vascular and neurological diseases—a systematic review and meta-analysis. *PLoS One*, 12 (7), e0180795. <https://doi.org/10.1371/journal.pone.0180795>.
- [13] Melhorn, J. M. (1996). A prospective study for upper-extremity cumulative trauma disorders of workers in aircraft manufacturing. *Journal of Occupational and Environmental Medicine*, 38 (12), 1264-1271.
- [14] Budd, D., & House, R. (2017). Examining the usefulness of ISO 10819 anti-vibration glove certification. *Annals of work exposures and health*, 61 (2), 137-140.
- [15] Bouix, R., Viot, P., & Lataillade, J. L. (2009). Polypropylene foam behaviour under dynamic loadings: Strain rate, density and microstructure effects. *International journal of impact engineering*, 36 (2), 329-342. <https://doi.org/10.1016/j.ijimpeng.2007.11.007>.
- [16] Tyler, D. J., & Venkatraman, P. D. (2012, May). Impact resistant materials and Design Principles for Sportswear. In *Proceedings of the 88th Textile Institute World Conference: Bridging Innovation, Research and Enterprise*. The Textile Institute. ISBN 9781622763443.
- [17] Kajtaz, M., & Subic, A. (2015). Experimental investigation into suitability of smart polymers As an impact-absorbing material for an improved rugby headgear. In *Proceedings of International Conference on Mechanics, Materials, Mechanical Engineering and Chemical Engineering* pp. 62-74.
- [18] Venkatraman, P., & Tyler, D. (2015). Impact-Resistant Materials and Their Potential. *Materials and Technology for Sportswear and Performance Apparel*, 205-230.
- [19] Tang, M., Huang, G., Zhang, H., Liu, Y., Chang, H., Song, H., & Wang, Z. (2017). Dependences of Rheological and Compression Mechanical Properties on Cellular Structures for Impact-Protective Materials. *ACS omega*, 2 (5), 2214-2223.
- [20] Gondaliya, R., Kim, D. W., & Sypek, D. (2015, November). Improving Damage Tolerance with Energy Absorbing Mesh in Composite Laminates: An Experimental Study. In *American Society for Composites 30th Technical Conference* (pp. 28-30). East Lansing, MI: Kellogg Center, Michigan State University.
- [21] Gondaliya, R. B. (2016). Improving Damage Tolerance of Composite Sandwich Structures Subjected to Low Velocity Impact Loading: Experimental and Numerical Analysis.
- [22] Shargawi, A. A. (2020). Mechanical testing and evaluation of D3O® material for adequacy of an ergonomic intervention for vibration transmission reduction in aircraft manufacturing (Doctoral dissertation, Wichita State University).
- [23] Shargawi, A. A., Amick, R. Z., Jorgensen, M. J., & Asmatulu, R. (2021). Experimental Investigation of Energy Absorbency and Dampening Characteristics of D3O® Material during Low Velocity Static Impacts. *J Ergonomics*, 5, 5. Doi: 10.35248/2165-7556.21.s5.003.
- [24] Bachmann, H., & Weber, B. (1995). Tuned vibration absorbers for “lively” structures. *Structural Engineering International*, 5 (1), 31-36.
- [25] Ren, X. J., Smith, C. W., Evans, K. E., Dooling, P. J., Burgess, A., Wiechers, J., & Zahlan, N. (2006). Experimental and numerical investigations of the deformation of soft materials under tangential loading. *International journal of solids and structures*, 43 (7-8), 2364-2377. <https://doi.org/10.1016/j.ijsolstr.2005.07.013>.
- [26] Nassef, M. G., Elkhatab, A., & Hamed, M. (2015). Correlating the vibration modal analysis parameters to the material impact toughness for austempered ductile iron. *Materials Performance and Characterization*, 4 (1), 61-72. <https://doi.org/10.1520/MPC20150004>.
- [27] Ozkaya, N., Nordin, M., Goldsheyder, D., & Leger, D. (2012). *Fundamentals of biomechanics* (pp. 221-236). USA: Springer.
- [28] Klimanek, P., & Pötzsch, A. (2002). Microstructure evolution under compressive plastic deformation of magnesium at different temperatures and strain rates. *Materials Science and Engineering: A*, 324 (1-2), 145-150. [https://doi.org/10.1016/S0921-5093\(01\)01297-7](https://doi.org/10.1016/S0921-5093(01)01297-7).
- [29] Wu, J. H., Li, C. H., Chiu, H. T., & Shong, Z. J. (2008). Dynamic properties of rubber vibration isolators and antivibration performance of ethylene-propylene-diene monomer/nylon 6 blend systems. *Journal of applied polymer science*, 108 (6), 4114-4121. <https://doi.org/10.1002/app.28070>.
- [30] Cherng, J. G., Eksioğlu, M., & Kızılaslan, K. (2009). Vibration reduction of pneumatic percussive rivet tools: mechanical and ergonomic re-design approaches. *Applied ergonomics*, 40 (2), 256-266.