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Original Article

Comparative Finite Element Analysis of Exoskeletons Materials for Durability in Rehabilitation

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Abstract

Background: *Assistive devices, such as exoskeletons, are one of the biggest breakthroughs in the medical industry, especially regarding physical therapy and rehabilitation. However, many of these devices are expensive. Due to this, one of the many concerns consumers have about these assistive devices is their durability and longevity. As such, there is a need to ensure that these devices are durable enough to handle a significant amount of use.*

Methods: *One way to ensure the durability of these devices is to use quality materials when creating them. This paper tackles this further, wherein three materials, namely aluminum, stainless steel, and titanium, are tested in two exoskeleton models, wherein nine tests per model were done. The models are inputted into the ANSYS software and tested using the "Static Structural" analysis system. These models' stress, strain, and deformation values are then obtained and analyzed.*

Results: *The results are then compared with one another and then ranked accordingly.*

Conclusion: *The study concluded that aluminum is the best primary material for exoskeletons due to its resulting mechanical properties. It should be noted, however, that both models had different results for their best material, showing that, although aluminum would be the best overall material, the best material would still depend on the model's size, shape, and purpose, which aligns with the hypothesis of the study.*

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Keywords

deformation, finite element analysis, physical therapy, rehabilitation, stress-strain

INTRODUCTION

Assistive devices are technology implemented to contribute to a person's health and well-being positively. Its use allows individuals to participate in activities they otherwise cannot do; limitations are brought about primarily due to physical constraints. Examples of these include hearing aids and glasses for auditory and visual impairments, respectively, prosthetic limbs for amputees, wheelchairs and crutches for those with mobility impairments, and text-to-speech software for blind or visually impaired individuals (World Health Organization, 2024).

One of the earliest assistive devices recorded included a wheelchair for King Philip of Spain in the 1500s. As the king was suffering from gout, the mobility issue was remedied by an upholstered chair connected to four wheels. This would be moved through the use of assistants. A similar device was found in 1655 by German Stephan Farfler after his childhood injury left him unable to move (Nias, 2019). Technology to assist the differently abled would not be limited to tools for mobility. To address communication with the blind, Louis Braille created a reading and writing system with the visually impaired and the blind in mind. The audiometer by Alexander Graham Bell addressed the hearing impaired and tested how well a person can hear. More advancements throughout the 20th and 21st centuries followed, each seeking to make life for people more bearable (Hoel, 2021).

Concerning the definition of assistive devices, an exoskeleton assists in the locomotion of a human being. This functions by relieving the effort needed to carry the load from the human body onto itself. Exoskeletons find use in assisting people requiring physical therapy, especially those who have suffered a spinal cord injury. Several designs are present. Autonomous weight-bearing exoskeletons can restore mobility in people suffering from paraplegia in select instances, while in others, they can serve as gait training aids. Joint-targeting exoskeletons are more specific, aiding select body parts to improve one's gait further. Overall, exoskeletons have been able to assist individuals in terms of mobility. Much work, however, needs to be done to consider these solutions commercially viable (Siviy et al., 2023).

This leads to the importance of good material choice and analysis in designing an exoskeleton. Appropriate materials ensure that the device functions effectively and withstands wear and tear. Materials must balance this with comfort and safety for the user. Above all, a significant factor to consider is cost. The use of exoskeletons can only be viable and widespread when cost is taken into account. Finite Element Analysis (FEA) is the most relevant analysis to the study. This involves a simulation of the design in simulation software. Meshes are then defined in order to analyze each part of the design better. This is then subject to the Finite Element Method (FEM), in which the design's structural integrity can be identified (English, 2023).

That being said, assistive devices, such as exoskeletons, have gained significant recognition in recent years due to their help in rehabilitation; most of the existing literature focuses on their functionality and design. However, concerns remain regarding their durability and material performance, especially after repetitive in rehabilitation.

Furthermore, there is a lack of studies regarding FEA and exoskeletons, specifically in comparative analysis that evaluate the mechanical properties of materials commonly used in exoskeletons. Additionally, there is a lack of studies regarding the results of these materials over an extended time of usage. As such, the lack of detailed comparative studies of various exoskeleton materials is a critical gap in current studies of rehabilitation and assistive devices.

This study aims to choose the best material for exoskeletons based on their durability. Through the use of finite element analysis, the study focuses on the exoskeleton's ability to handle and somewhat reduce, deformation, as well as its stress-strain capabilities. The study also aims to test the capabilities of open-source exoskeleton models to see if their designs can withstand ample amounts of force. Due to this, this study does not include designing an actual exoskeleton model. In addition, the study also does not include a motion analysis of these exoskeleton models, as the main focus of the study is to test the durability of these exoskeleton models based on the material and design. The use of FEA on assistive devices has been documented in previous studies.

Fakhouri et al. (2023) sought to design a device that would assist individuals, especially the elderly, to rise from the ground without external assistance. This matter is especially serious to the elderly as it has been proven that annually, about 684,000 die due to falling, made worse by the inability to call for help. The device needed to be low-cost, provide high mobility, and be easy to use. It also needed to accommodate a variety of heights and weights. The device was subject to Finite Element Analysis to identify the design's von Mises stresses and total deformation of the design. This analysis was performed in SolidWorks 2017.

A similar study by Zeńczak-Praga et al. (2015) aimed to analyze assistive devices used by patients with cerebral palsy. Thirty patients suffering from the disease were given questionnaires. It sought to learn more about the patient, particularly their diagnosis, symptoms, and assistive devices used during childhood and adulthood. Through this, it was discovered that wheelchairs and standing frames were most common during childhood. While the two remained common in adulthood as well, the wheelchair was found to be utilized more. In addition, adult patients with cerebral palsy made use of rehabilitation lifts as well. Caregivers agreed that the use of assistive devices was necessary for the improvement of their patient's movement. FEA is also found useful, more specifically on exoskeletons.

Umesh and Vidhyapriya (2021) aimed to design a lower limb exoskeleton for military personnel, specifically enhancing their physical abilities or their rehabilitation after an injury. Their design would focus on the hip, knee, and ankle joints. The design was simulated on Solidworks, which is subject to FEA. The Mises stress analysis was done on the aforementioned parts to simulate the effect sitting-then-standing would have on the exoskeleton. Ding et al. (2012) carried out a similar study focusing on the lower extremities and also seeking to rehabilitate gait. The design was designed, and the FEA performed on it was done on ANSYS Workbench. Static intensity and rigidity of the exoskeleton were also scrutinized. After testing, a proposed optimization was suggested and detailed.

The study's hypothesis states no significant difference between the materials. Although there would be differences, the significance would not be big enough. As such, there is a need to consider the model used, as different models will yield different results.

METHODS

The study will use two lower limb exoskeleton models that undergo material analysis using the Ansys software. The analysis will use forces that are acting upon specific surfaces, specifically the parts of the exoskeletons that will receive more use (the joints, the feet, etc.). The methodology of the study is further explained in the following paragraphs. The lower limb exoskeleton models are obtained from an open-source library of 3D Designs called GrabCad (GrabCad, n.d.). These exoskeleton models are then inputted into a software program called Ansys, specifically the Ansys 2023 R1 version (Wahab, 2014).

A workflow diagram of the study can be seen in Figure 1 and the two chosen models (Figures 2 & 3) below.

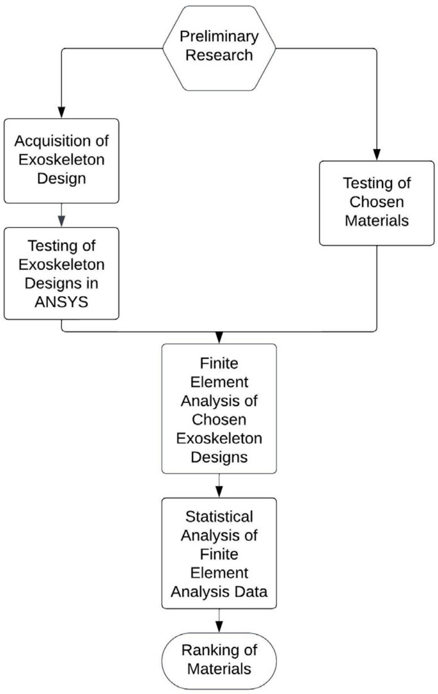

Figure 1. *Workflow Diagram of Study*

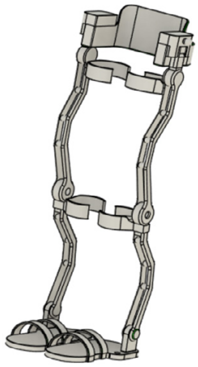

Figure 2. *Model of exo-skeleton 1*

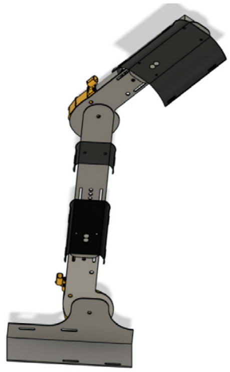

Figure 3. *Model of exo-skeleton 2*

As mentioned in the introduction portion of the study, three materials were considered in the research: aluminum, stainless steel, and titanium. These are because of the properties of the materials. Specifically, these three materials met the criteria for weight, price, durability, resistance, conductivity, and history in medical usage.

Furthermore, aluminum, already a well-known and widely used material in the medical field, has excellent thermal conductivity. Aluminum is also resistant to corrosion and lightweight due to its low density (Aalco, 2020). On the other hand, stainless steel is also resistant to corrosion. However, it also has less thermal conductivity and has higher density than Aluminum (Stainless Steel - Mechanical Properties, 2014).

Lastly, titanium, similar to aluminum and stainless steel, is also corrosion-resistant. Like aluminum, it is also less dense than stainless steel and iron. However, it also has poor thermal conductivity, similar to stainless steel (Titanium (Ti) - the Different Properties and Applications, 2013).

These materials are then inputted into the data of each exoskeleton model in the Ansys software. As the study aims to find the best material out of the three, the researchers used the analysis system "Static Structural." This is because the study will not take into account actual movement but solely rely on the strength of the materials used for the models, which would deteriorate first when it comes to use. The exoskeletons were also subjected to 1000N of force on where bearings should be and 2000N of force everywhere else. This ensures that the exoskeletons can withstand great amounts of loading conditions, which is critical to meeting its safety factors and functionality constraints.

It should be noted that the materials used were not pure but, instead, alloys. This ensures that the materials would coincide with the materials used in the medical industry. Furthermore, each exoskeleton would use each material thrice as its primary material and thrice as well as its secondary material. As such, nine runs would be done per exoskeleton model.

The Ansys software would require forces to be set up correctly in order for it to obtain results. The forces are inputted into the exoskeleton model's feet below and above. Additionally, forces are also inputted on the important joints of the exoskeleton model, namely the hip, knee, and ankle joints. This ensures that the model would have constant force and pressure on those joints, considering these joints are the ones that receive the most force.

These forces are then shown in six main results; directional deformation, total deformation, equivalent (also known as von Mises) stress, equivalent strain, principal stress, and principal strain. The directional deformation is obtained to represent the deformation's direction or the exoskeleton's displacement.

On the other hand, the total deformation represents the overall deformation of the model. The equivalent stress is obtained to show how the model would yield under tensile tests. On the other hand, the principal stress is the maximum and minimum normal stress that can develop in the model. The equivalent strain represents the limit the model would reform to its original shape. Lastly, the principal strain, similar of the principal stress, represents the maximum and minimum values of strain experienced by the model when it is subjected to loading.

RESULTS

Results of Exoskeleton 1

In the first exoskeleton model, the results show that the model has minuscule changes to the equivalent and principal stress regardless of material. This is shown in all three values of the results, namely the maximum, average, and minimum results, which means that the model can yield more or less the same amount regardless of material. Additionally, it is also able to handle the same stress levels. Due to this, for the best overall material to be chosen, the material must have the best deformation-to-strain ratio. As such, the best material is aluminum mixed with stainless steel.

Although other materials, such as pure aluminum alloy, titanium mixed with aluminum, and titanium mixed with stainless steel, were considered due to their smaller deformation values, they had less than ideal results regarding the equivalent and principal strain. Due to this, aluminum mixed stainless steel was chosen due to its performance and overall best deformation-to-strain ratio among the nine material runs. The results can be seen in Tables 1 to 3. Additionally, graphs are added, in Figures 4 to 15 for the maximum and minimum results of the model.

Table 1. *Maximum Results of Exoskeleton 1*

Material	Directional Deformation* (in m)	Total Deformation* (in m)	Equivalent Stress (in Pa)	Equivalent Strain (in m/m)	Principal Stress (in Pa)	Principal Strain (in m/m)
Titanium	5.15E-08	1.70E-04	1.32E+06	7.59E-06	8.74E+06	6.90E-05
Aluminum	6.93E-08	2.33E-04	1.28E+06	1.05E-05	8.40E+06	9.72E-05
Stainless Steel	2.54E-08	8.62E-05	1.25E+06	3.90E-06	8.22E+06	3.65E-05
Titanium + Aluminum	6.27E-08	1.73E-04	1.28E+06	9.99E-06	8.83E+06	7.01E-05
Titanium + Stainless Steel	3.19E-08	1.65E-04	1.25E+06	4.43E-06	8.51E+06	6.75E-05
Aluminum + Titanium	5.65E-08	2.30E-04	1.32E+06	8.06E-06	8.32E+06	9.63E-05
Aluminum + Stainless Steel	3.54E-08	2.25E-04	1.25E+06	4.80E-06	8.14E+06	9.45E-05
Stainless Steel + Titanium	4.12E-08	9.05E-05	1.31E+06	7.01E-06	8.42E+06	3.74E-05
Stainless Steel + Aluminum	5.07E-08	9.35E-05	1.27E+06	9.21E-06	8.50E+06	3.77E-05

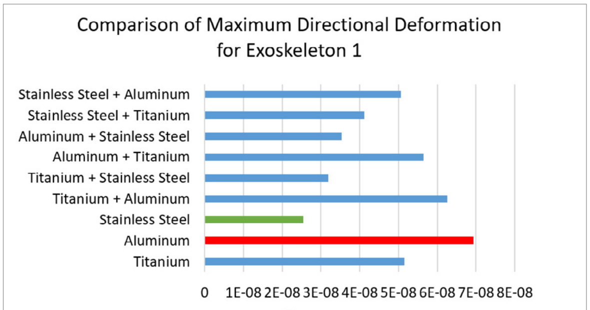

Figure 4. *Comparative Graph of Maximum Direction Deformation for Exoskeleton 1*

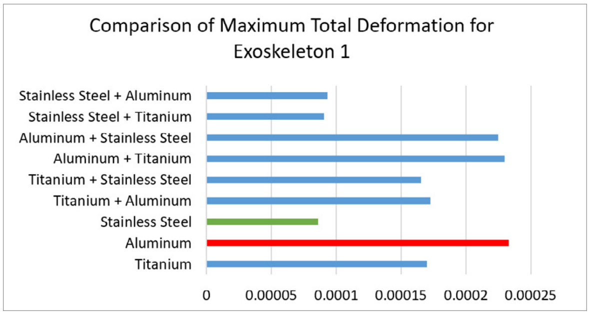

Figure 5. *Comparative Graph of Maximum Total Deformation for Exoskeleton 1*

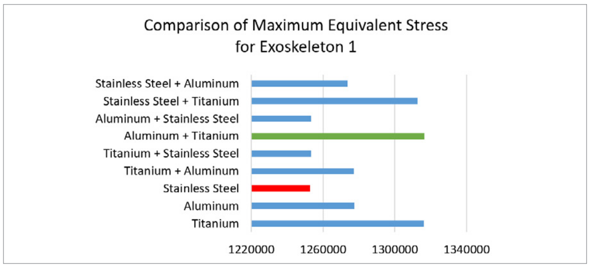

Figure 6. *Comparative Graph of Maximum Equivalent Stress for Exoskeleton 1*

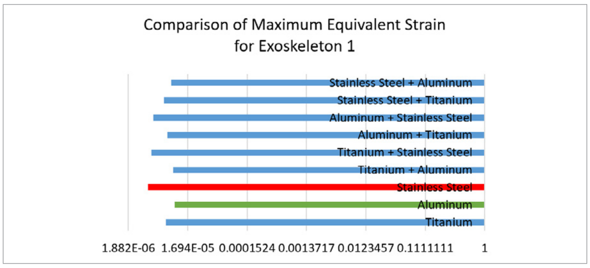

Figure 7. *Comparative Graph of Maximum Equivalent Strain for Exoskeleton 1*

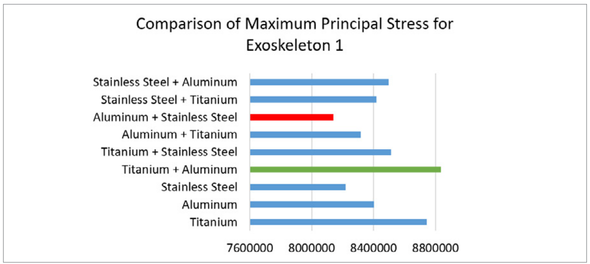

Figure 8. *Comparative Graph of Maximum Principal Stress for Exoskeleton 1*

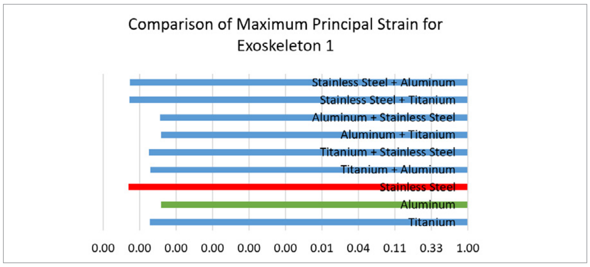

Figure 9. *Comparative Graph of Maximum Principal Stress for Exoskeleton 1*

Table 2. *Average Results of Exoskeleton 1*

Material	Directional Deformation* (in m)	Total Deformation* (in m)	Equivalent Stress (in Pa)	Equivalent Strain (in m/m)	Principal Stress (in Pa)	Principal Strain (in m/m)
Titanium	-4.31E-05	8.76E-05	1.80E+05	1.71E-06	533.95	-8.66E-09
Aluminum	-5.90E-05	1.20E-04	1.81E+05	2.34E-06	533.56	-1.04E-08
Stainless Steel	-2.18E-05	4.45E-05	1.81E+05	8.65E-07	533.02	-3.47E-09
Titanium + Aluminum	-4.33E-05	8.89E-05	1.80E+05	2.22E-06	529.96	-1.24E-08
Titanium + Stainless Steel	-4.26E-05	8.54E-05	1.82E+05	9.51E-07	518.88	2.49E-09
Aluminum + Titanium	-5.87E-05	1.19E-04	1.81E+05	1.81E-06	570.86	-6.43E-09
Aluminum + Stainless Steel	-5.82E-05	1.16E-04	1.83E+05	1.00E-06	554.18	4.71E-09
Stainless Steel + Titanium	-2.36E-05	4.54E-05	1.79E+05	1.57E-06	531.75	-1.48E-08
Stainless Steel + Aluminum	-2.37E-05	4.66E-05	4.66E-05	4.66E-05	4.66E-05	4.66E-05

Table 3. *Minimum Results of Exoskeleton 1*

Material	Directional Deformation* (in m)	Total Deformation* (in m)	Equivalent Stress (in Pa)	Equivalent Strain (in m/m)	Principal Stress (in Pa)	Principal Strain (in m/m)
Titanium	-1.47E-04	4.40E-08	1.48E+04	3.31E-07	-9.40E+06	-7.40E-05
Aluminum	-2.02E-04	5.90E-08	1.49E+04	4.52E-07	-8.97E+06	-1.03E-04
Stainless Steel	-7.46E-05	2.15E-08	1.49E+04	1.68E-07	-8.74E+06	-3.85E-05
Titanium + Aluminum	-1.49E-04	5.44E-08	1.49E+04	4.75E-07	-9.41E+06	-7.43E-05
Titanium + Stainless Steel	-1.44E-04	2.66E-08	1.49E+04	1.32E-07	-9.36E+06	-7.34E-05
Aluminum + Titanium	-2.00E-04	4.81E-08	1.48E+04	2.71E-07	-8.95E+06	-1.03E-04
Aluminum + Stainless Steel	-1.96E-04	2.94E-08	1.49E+04	1.37E-07	-8.93E+06	-1.02E-04
Stainless Steel + Titanium	-7.73E-05	3.69E-08	1.48E+04	3.62E-07	-8.79E+06	-3.89E-05
Stainless Steel + Aluminum	-7.89E-05	4.56E-08	1.49E+04	5.12E-07	-8.82E+06	-3.92E-05

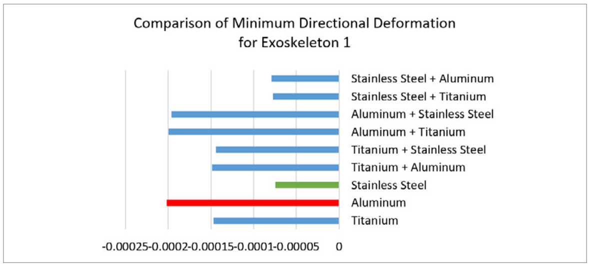

Figure 10. *Comparative Graph of Minimum Direction Deformation for Exoskeleton 1*

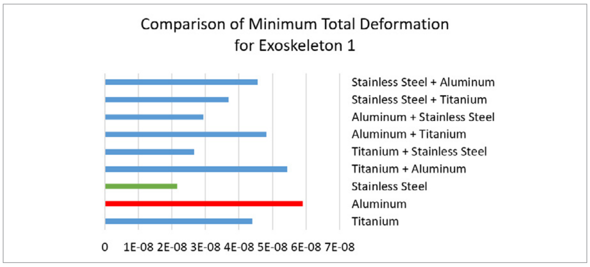

Figure 11. *Comparative Graph of Minimum Total Deformation for Exoskeleton 1*

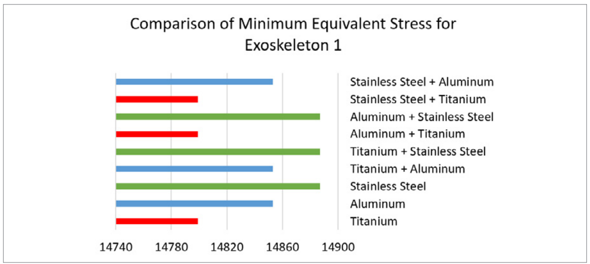

Figure 12. *Comparative Graph of Minimum Equivalent Stress for Exoskeleton 1*

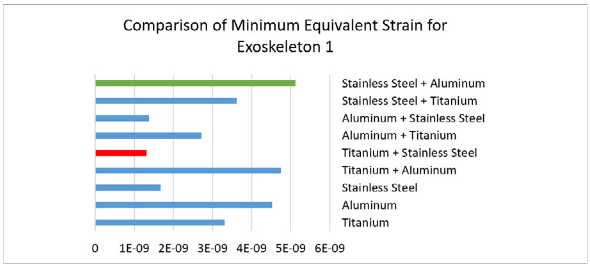

Figure 13. *Comparative Graph of Minimum Equivalent Strain for Exoskeleton 1*

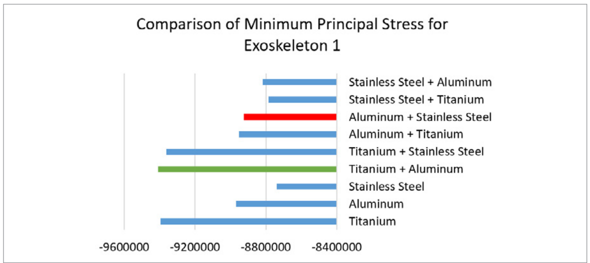

Figure 14. *Comparative Graph of Minimum Principal Stress for Exoskeleton 1*

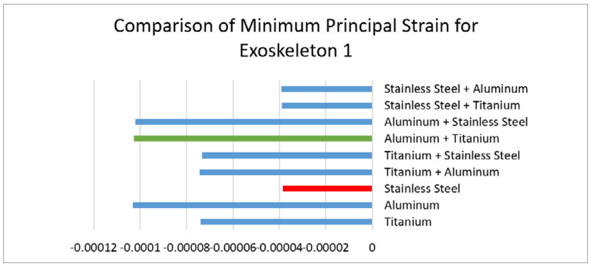

Figure 15. *Comparative Graph of Minimum Principal Strain for Exoskeleton 1*

Results of Exoskeleton 2

Similar to that first exoskeleton, the second exoskeleton's equivalent and principal stress values have minuscule differences regardless of material except for two outliers, namely titanium mixed with stainless steel and aluminum mixed with stainless steel. It should be noted, however, that these two material mixes have the broadest range of values in the aforementioned stress categories. They also have the best minimum range in the deformation values. However, these two lack strain resistance capabilities, meaning these materials are not the best at sustaining their form. As such, it is important to analyze the other materials further.

After analyzing the results, two materials stood out due to their high stress-strain values. These two materials are titanium mixed with aluminum and aluminum mixed with titanium. Although both have great values throughout, if aluminum is chosen as the primary material and titanium as the secondary material, the exoskeleton would be able to handle greater stress levels before the material breaks. Although using titanium as the main material and aluminum as the secondary material will yield better results in deformation and strain values, it cannot withstand greater levels of pressure and stress. As such, the best material for exoskeleton 2 is aluminum mixed with titanium. The results can be seen in Tables 4 to 6 below. Likewise, graphs are shown in Figures 16 to 27 for better visualization.

Table 4. *Maximum Results of Exoskeleton 2*

Material	Directional Deformation* (in m)	Total Deformation* (in m)	Equivalent Stress (in Pa)	Equivalent Strain (in m/m)	Principal Stress (in Pa)	Principal Strain (in m/m)
Titanium	2.30E-05	4.34E-05	5.26E+07	5.77E-04	7.17E+07	5.89E-04
Aluminum	3.10E-05	5.88E-05	5.36E+07	7.96E-04	7.10E+07	8.23E-04
Stainless Steel	1.14E-05	2.17E-05	5.42E+07	2.97E-04	7.06E+07	3.09E-04
Titanium + Aluminum	2.65E-05	4.74E-05	4.85E+07	7.21E-04	6.38E+07	7.42E-04
Titanium + Stainless Steel	1.65E-05	3.54E-05	6.70E+07	3.65E-04	8.63E+07	3.80E-04
Aluminum + Titanium	2.70E-05	5.36E-05	5.74E+07	6.27E-04	7.79E+07	6.43E-04
Aluminum + Stainless Steel	1.95E-05	4.39E-05	7.39E+07	4.15E-04	9.46E+07	4.19E-04
Stainless Steel + Titanium	1.59E-05	2.68E-05	4.49E+07	4.95E-04	5.79E+07	4.93E-04
Stainless Steel + Aluminum	1.82E-05	3.00E-05	4.36E+07	6.56E-04	5.46E+07	6.55E-04

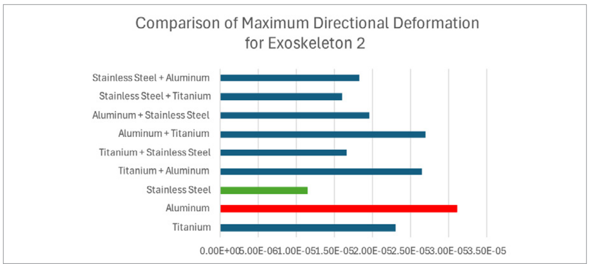

Figure 16. *Comparative Graph of Maximum Directional Deformation for Exoskeleton 2*

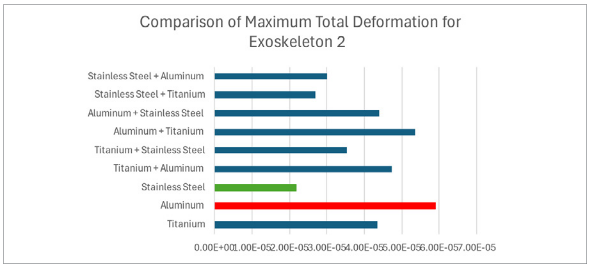

Figure 17. *Comparative Graph of Maximum Total Deformation for Exoskeleton 2*

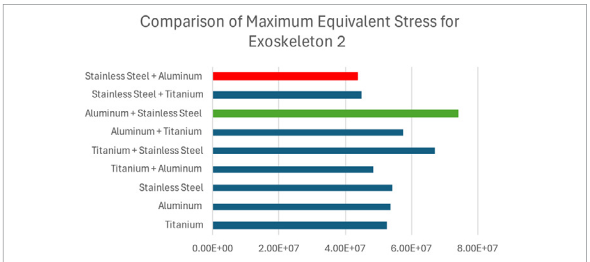

Figure 18. *Comparative Graph of Maximum Equivalent Stress for Exoskeleton 2*

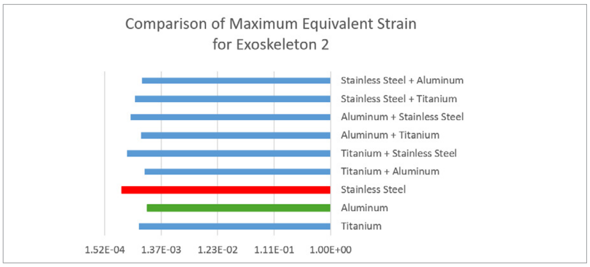

Figure 19. *Comparative Graph of Maximum Equivalent Strain for Exoskeleton 2*

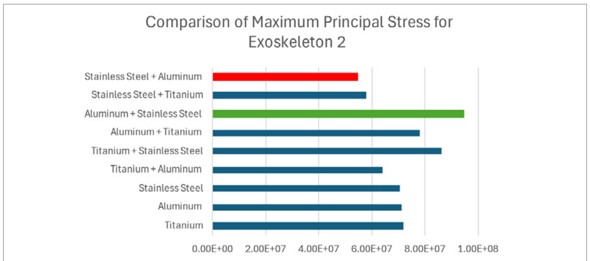

Figure 20. *Comparative Graph of Maximum Principal Stress for Exoskeleton 2*

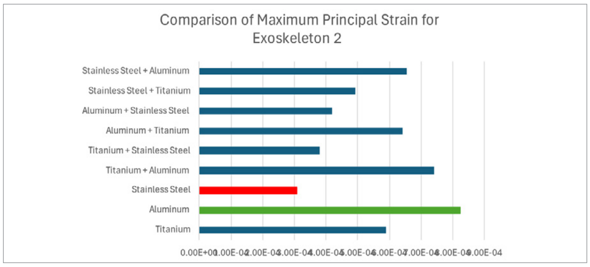

Figure 21. *Comparative Graph of Maximum Principal Strain for Exoskeleton 2*

Table 5. *Average Results of Exoskeleton 2*

Material	Directional Deformation* (in m)	Total Deformation* (in m)	Equivalent Stress (in Pa)	Equivalent Strain (in m/m)	Principal Stress (in Pa)	Principal Strain (in m/m)
Titanium	4.46E-08	4.59E-06	3.46E+05	3.76E-06	4108.00	7.42E-08
Aluminum	5.81E-08	6.22E-06	3.48E+05	5.11E-06	3914.80	9.61E-08
Stainless Steel	2.09E-08	2.29E-06	3.48E+05	1.88E-06	3787.50	3.42E-08
Titanium + Aluminum	4.65E-08	4.99E-06	3.48E+05	4.32E-06	3961.40	7.19E-08
Titanium + Stainless Steel	4.04E-08	3.80E-06	3.48E+05	2.82E-06	4072.80	8.52E-08
Aluminum + Titanium	5.43E-08	5.71E-06	3.46E+05	4.47E-06	4077.80	9.79E-08
Aluminum + Stainless Steel	5.20E-08	4.74E-06	3.49E+05	3.40E-06	3956.50	1.05E-07
Stainless Steel + Titanium	2.38E-08	2.80E-06	3.52E+05	2.61E-06	3962.30	2.02E-08
Stainless Steel + Aluminum	2.64E-08	3.08E-06	3.56E+05	3.05E-06	3843.80	1.87E-08

Table 6. *Minimum Results of Exoskeleton 2*

Material	Directional Deformation* (in m)	Total Deformation* (in m)	Equivalent Stress (in Pa)	Equivalent Strain (in m/m)	Principal Stress (in Pa)	Principal Strain (in m/m)
Titanium	-5.59E-06	0.00	0.00	0.00	-3.80E+07	-3.46E-04
Aluminum	-7.36E-06	0.00	0.00	0.00	-3.75E+07	-4.74E-04
Stainless Steel	-2.65E-06	0.00	0.00	0.00	-4.83E+06	-1.76E-04
Titanium + Aluminum	-7.56E-06	0.00	0.00	0.00	-3.32E+07	-4.13E-04
Titanium + Stainless Steel	-3.46E-06	0.00	0.00	0.00	-5.60E+07	-2.69E-04
Aluminum + Titanium	-5.68E-06	0.00	0.00	0.00	-4.53E+07	-4.18E-04
Aluminum + Stainless Steel	-3.96E-06	0.00	0.00	0.00	-6.61E+07	-3.30E-04
Stainless Steel + Titanium	-5.32E-06	0.00	0.00	0.00	-2.66E+07	-2.32E-04
Stainless Steel + Aluminum	-6.53E-06	0.00	0.00	0.00	-2.45E+07	-2.60E-04

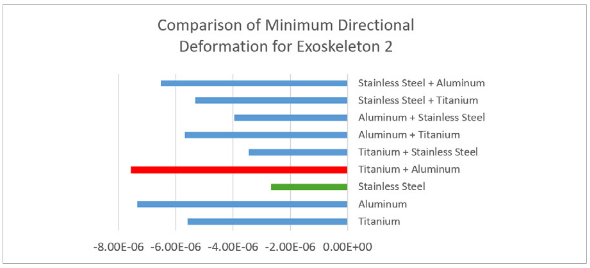

Figure 22. *Comparative Graph of Minimum Directional Deformation for Exoskeleton 2*

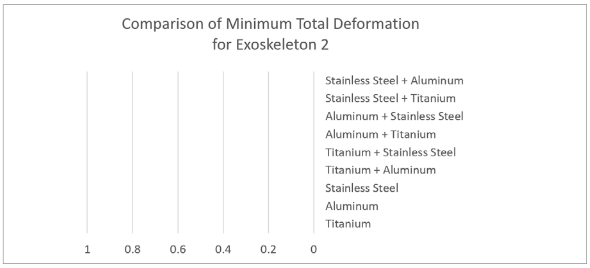

Figure 23. *Comparative Graph of Minimum Total Deformation for Exoskeleton 2*

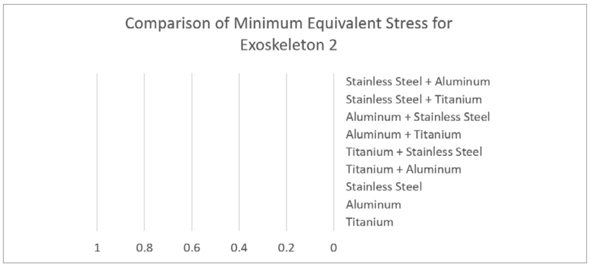

Figure 24. *Comparative Graph of Minimum Equivalent Stress for Exoskeleton 2*

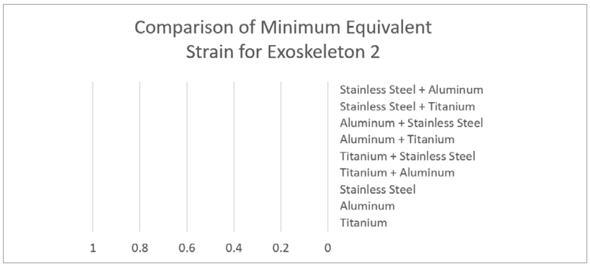

Figure 25. *Comparative Graph of Minimum Equivalent Strain for Exoskeleton 2*

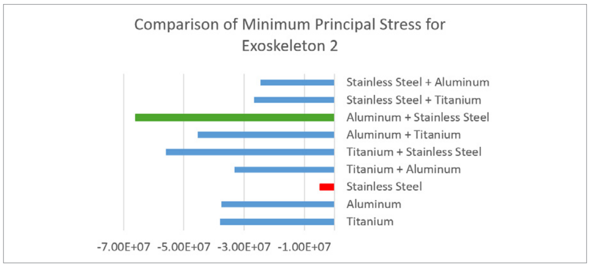

Figure 26. *Comparative Graph of Minimum Principal Stress for Exoskeleton 2*

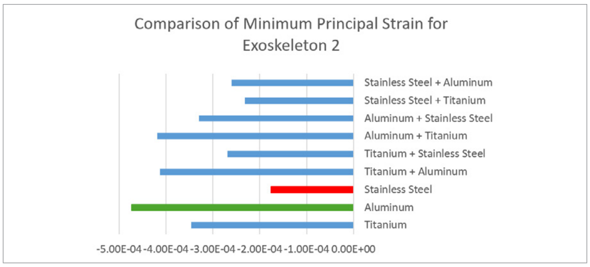

Figure 27. *Comparative Graph of Minimum Principal Strain for Exoskeleton 2*

DISCUSSION

Due to the differences in the best material per model, there is a need to find the best material as a whole, considering the results of the two models. In terms of deformation, the material that performed the best in total and direction deformation in both models is stainless steel. It had low deformation values when used as the primary material.

On the other hand, in terms of stress, the best material would be aluminum mixed with stainless steel. Although it did not perform the best in the first exoskeleton, the results of which material performs the best on the model could be exchanged due to their minuscule differences. As such, the bearing on the second model was higher due to the differences between the materials.

In terms of strain, the best material is aluminum. This can be seen in both exoskeletons. Additionally, whether aluminum is used as a primary or secondary material, it can still handle a significant amount of strain.

In terms of both stress-strain values, there were a few options. However, aluminum stands out the most, regardless of whether it's used as a primary or secondary material. This can be seen in both models, as aluminum boasts the highest range regarding to the stress-strain curve. This shows flexibility because it has the highest maximum stress-strain average values, as well as the lowest minimum values.

Due to this, the best primary material overall would have to be aluminum. Its stress-strain values are the best among the choices and, due to this, prove that it can withstand great amounts of stress and pressure. There is a reason as to why both models included aluminum when considering its best material, regardless of primary or secondary. Although aluminum is the best primary material, the secondary material is arguable. Using titanium as the secondary material to aluminum would grant the exoskeleton better strain resistance while using stainless steel would grant it better stress resistance. Using aluminum as the sole material, is also feasible as it already has the best stress-strain value average. However, combining it with another material would boost its strength.

As such, using finite element analysis, it could be concluded that aluminum is the best primary material for exoskeletons out of the three materials used in the study. Whether or not the exoskeleton would contain another material relies on the creator themselves and what they are trying to achieve with their assistive device.

Aluminum has also been widely used in many industries, including automotive and medical devices. Due to its reliability in these fields, aluminum alloy one of the most ideal materials for exoskeleton design ensures its feasibility as a material. Additionally, the material's mechanical properties ensure its durability and safety factors when created as exoskeletons.

However, through the use of ANOVA, it was seen that there is no significant difference between each material, regardless of the model. As such, although aluminum has the best overall properties, there is not a huge difference between it and other materials. The results of ANOVA can be seen in Table 7 and Table 8.

Table 7. *Statistical Analysis Model 1*

Factor	SS	df	MS	F	P-value	F crit
Directional Deformation	1.250E-08	8	1.570E-09	0.265	0.969	2.510
Total Deformation	2.270E-08	8	2.840E-09	0.381	0.916986	2.51
Equivalent Stress	1.250E+10	8	1.560E+09	0.003	1.000	2.510
Equivalent Strain	6.910E-10	8	8.640E-11	1.089	0.413682	2.510
Principal Stress	7.960E+10	8	9.950E+09	0.000130	1.000	2.510
Principal Strain	7.500E-10	8	9.380E-11	0.0170	1.000	2.510

Table 8. *Statistical Analysis Model 2*

Factor	SS	df	MS	F	P-value	F crit
Directional Deformation	6.900E-11	8	8.620E-12	0.041	0.999	2.510
Total Deformation	5.110E-10	8	6.390E-11	0.121	0.998	2.510
Equivalent Stress	2.630E+14	8	3.290E+13	0.032	0.999	2.510
Equivalent Strain	7.660E-08	8	9.580E-09	0.088	0.999	2.510
Principal Stress	3.590E+14	8	4.480E+13	0.014	0.999	2.510
Principal Strain	3.190E-08	8	3.980E-09	0.018	0.999	2.510

CONCLUSION

Assistive devices, such as exoskeletons, can help humanity in various ways. For those unable to be independent of such devices, their quality of life has only improved with these devices. On the other hand, for those who can live independently without these devices, using them may help their bodies in various ways, from enhancing their mobility to increasing their physical strength. Finding ways to improve these devices, no matter how much, may ensure their effectiveness and evolution in the future.

Material analysis is one of the most important aspects of creating technology, as it ensures whether or not a specific material would fit appropriately in the creator's vision. Due to this, it is necessary to double-check whether or not the properties of a specific material are present and compare them with existing ones. Quality-checking these materials would also help in the grand scheme of things. This makes sure that the material used is of the best quality, proving that the device or technology is also of the same quality.

The study concluded that out of three materials, namely aluminum, titanium, and stainless steel, the best primary material for exoskeletons would be aluminum or aluminum alloys. It was also noted that using aluminum by itself or with other materials would both be feasible due to aluminum already having great mechanical values by itself, and that it would depend on the device's creator on what they would rather have. Additionally, aluminum is already one of the standard materials used in exoskeleton design and manufacturing. As mentioned, this is due to its ideal mechanical properties, as well as its cost-effectiveness and longevity. This makes aluminum an ideal material for exoskeletons and a sustainable material overall. However, through the use of ANOVA, it was noted that aluminum performed relatively well as the main material, but there is no significant difference between it and the other materials. This shows that the null hypothesis is correct and that there is no significant difference between the materials.

It is recommended that more materials for future studies, as it would greatly give better insights and results. Using more exoskeleton models would also ensure that the data is not biased and skewed to a certain point. As the models were only obtained from an open-source library, the authors also recommend using exoskeletons that future researchers independently obtained. As such, testing the materials on a self-created or self-produced design could greatly help gaps in current studies. Lastly, testing the materials on actual exoskeletons would also greatly benefit the research. Although it would be more costly and time-consuming, creating actual prototypes using these materials would further prove the feasibility of the study.

Author Contributions

Roque: Conceptualization, Methodology, Experimental Design, Literature Review, Formal analysis, Writing - Original Draft; **Gabasan:** Data Curation, Visualization, Literature Review, Investigation; **Camacho:** Methodology, Experimental Design, Data Analysis, Writing - Original Draft; **Bugtai:** Supervision, Funding Acquisition, Resources, Writing - Review & Editing; **Munsayac Jr. III**; Project Administration, Data Validation, Writing - Review & Editing.

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Ethical Approval

Not Applicable.

Competing Interests

The authors declare that there are no conflicts of interests.

Data Availability

Data will be made available by the corresponding author on request.

Declaration of Artificial Intelligence Use

Not applicable.

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