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Assessment of performance of Nitinol-based arch wedge supports in bearing forces and stresses due to human movement using FEA

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ABSTRACT

A computational investigation was performed in this study to evaluate the force bearing and deflection performance of a nitinol-based arch wedge support (AWS) design. Effects of force, boundary condition, and thickness on the mechanical behavior of the AWS design are discussed based on the obtained numerical results. Various force conditions corresponding to five typical human movements are calculated and considered for the finite element analysis (FEA) simulations. Two extreme boundary conditions are evaluated, a fully constrained case in which the AWS model cannot move, and a less constrained case to simulate the scenario that an AWS moves along the inner surface in the rear of shoe while its bottom stays in contact with the bottom inside surface of the shoe. The two selected boundary conditions represent scenarios where most and least degrees of freedom of the AWS model are constrained, respectively. Any real boundary conditions that an AWS may be subject within the shoe can be modeled as a combination of the two motions. Three thicknesses, 1 mm, 2.5 mm, and 5 mm, are evaluated in this study to determine the thickness effects. The results confirm that the proposed thin-walled nitinol AWS design is capable of resisting various forces and motions without any permanent deformation. Since this is the first time that a thin-walled nitinol AWS design is proposed and there is no previous experimental data, mesh refinement and numerical sensitivity analysis are also conducted to make sure that the FEA results would correctly reflect the real world results. Based on the results obtained from this study, a prototype of the AWS will be developed using additive manufacturing technologies for further human factors and material testing.

1. Introduction

Arch wedge supports (AWS) are an appliance within the shoes that helps with the rectification of the arch in physical activities such as standing, walking, and running \cite{1}. Currently used AWS are made of non-metallic materials such as plastics, leathers, fiberglass, graphite, and may have gel fillings for better cushioning effect. Those materials offer good shock absorption capacity and cushioning properties, however, during usage this shock absorption capacity and cushioning properties deteriorate quickly, indicating a functional fatigue in the material \cite{2}. In addition, some of the cushioning materials such as polymers are highly susceptible to environmental conditions (temperature, humidity, etc.). For instance, their functional properties may vanish in a wet environment. Therefore, a new AWS design with longer life span and less susceptibility to fatiguing and corrosion conditions is always desired.

In the last two decades, nitinol shape memory alloy, a nearly equiatomic combination of nickel and titanium, has attracted considerable interest for biomedical applications due to its superelasticity and shape memory response as well as high strength, resistance to corrosion, and biocompatibility. Superelasticity is the ability for the material retrieve its original shape after undergoing strain under mechanical loading and occurs at operational temperatures higher than a specific, critical temperature (Fig. 1). The ability of the material to recover a large plastic strain by heating up above austenite finish temperature is called shape memory behavior. As a result of its excellent mechanical properties, nitinol has been widely used for a variety of applications in aerospace, military, medical, and robotics \cite{4,5}. In biomedical engineering, the popularity of...
Nitinol is increasing because of its unique stress/strain response, similar to biomaterials such as bone [6]. Therefore, nitinol has been used extensively in various biomedical applications such as endovascular stents, vena cava filters, and endodontic files [6,7]. For example, there are many patents registered focused on artificial limbs that incorporate superelastic supports made of nitinol [8–10].

Compared with the plastics, nitinol offers high superelasticity, strength, resistance to corrosion, biocompatibility, and is more capable of being deflected to foot/AWS reaction forces. Its superelastic supporting nature can further be utilized for reinforcing and stabilizing other body parts. Compared to other metallic materials, nitinol offers great fatigue resistance even at large strains [11]. This property makes it an ideal material for the AWS. Based on the current progress of using nitinol for biomedical applications, it is hypothesized that the nitinol alloy can be an ideal material for design and fabrication of new AWS which are longer lasting and highly endurable.

The objective of this study is to apply finite element method to decide if thin-walled nitinol AWS can withstand the forces and stresses applied from medial longitudinal arch (MLA) due to human movement and assess its potential for product development and commercialization. Loading conditions caused by five different human actions which included standing, self-selected walking pace, brisk walking pace, running, and standing vertical jump were taken into account. Effects of wall thickness of the AWS on its force bearing performance are also investigated.

2. Finite Element Model

2.1. Material Properties of Nitinol

Nitinol is selected as the material for the AWS because of its superelasticity, which is very similar to bone, and its shape memory property that helps the material deform while being used but return to its original shape after unloading. In addition, nitinol has a damping property that can help to reduce the force and stress felt by the users. Material properties of nitinol are listed in Table 1, which will be used for the FEA model. Those properties were retrieved from a web page [12]. Average values for Young’s modulus, yield stress, and ultimate tensile stress are taken to model the material for FEA.

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**Table 1. Material properties of nitinol [12].**

<table>
<thead>
<tr>
<th>Material property</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>$6.45 \times 10^3$ kg/m$^3$</td>
</tr>
<tr>
<td>Modulus of elasticity</td>
<td>66–75 GPa</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.33</td>
</tr>
<tr>
<td>Yield stress</td>
<td>200–266 MPa</td>
</tr>
<tr>
<td>Ultimate tensile stress</td>
<td>390–448 MPa</td>
</tr>
</tbody>
</table>

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**Figure 1.** Stress–strain curves of nitinol in different phases, $T$ represents the operating temperature [3].

**Figure 2.** Example of an OTC AWS [13].

**Figure 3.** Force is applied on top surface of the AWS model as a constant pressure.
2.2. CAD Model of AWS

A set of AWS CAD models are created first. The simplified AWS model is a half ellipse that is 25.4 mm high and 50.8 mm wide. Those dimensions are applied to the models displayed in Figs. 2–6. The shape and sizes of that model are determined based on a typical over-the-counter (OTC) AWS (Fig. 2). The displayed OTC AWS is a 3D solid model made of polymers. Because of its high strength, it is possible to develop a thin-walled AWS using nitinol and gain an ideal cushioning effect from the thin-walled design and mechanical properties of nitinol. Since this is the first time to present and assess a thin-walled AWS design, the effect of wall thickness on the performance of the AWS has not been examined in previous studies and remains unknown. To reveal the influence of wall thickness on load-bearing capacity and deflection mode of the AWS, three thicknesses, 1 mm, 2.5 mm, and 5 mm are chosen for this design. Compared with its overall height and width of the AWS, an AWS with a thickness varying between 1 mm and 5 mm can be considered as a “thin-walled” AWS. The generated CAD models are then exported to ABAQUS for FEA modeling and simulations.

2.3. Loading Conditions

The forces applied by the MLA on the AWS depend on different human activities a person is performing and also vary from person to person depending on their physical features (weight, height, etc.). In order to decide the effects of different human activities on the performance of AWS, five representative actions that a person usually engages in are selected for defining the loading conditions. They are standing, self-selected walking pace, brisk walking pace, running, and standing vertical jump. Among those actions, the force generated due to standing, which is a person’s body weight, represents the minimum force and is chosen as a standard force. The amount of forces generated during the five actions have been measured from 24 healthy male adults age 26 ± 8 years old using a synced 10-infra-red camera 3D motion analysis system, dual force plates, an 8-channel electromyography (EMG) system, and 2D video capture system in the Human Performance Laboratory at Mississippi State University (MSU). After the participants arrived at the Human Performance Laboratory, their weight was measured in a static standing position. Participants then performed multiple walking gait trials at several speeds starting from a self-selected pace to increasing speeds until a brisk and face paced walk is achieved. With the completion of this testing, participants were then performed 3 to 5 trials of a vertical jump and a 300-yard run. The collected forces corresponding to different activities were normalized to the participants’ body weight and are listed in Table 2. Those ratios are used to approximate the forces applied on the AWS models due to the five selected human actions.

The proposed thin-walled nitinol AWS are typically targeted at military personnel and veterans. Table 3 lists the maximum allowed weight and height for military personnel from the five military branches. From that table, it can be observed that the Navy has the highest allowable weight and considering the extreme scenario to make sure that the AWS would survive all potential conditions, the weight of 271 lbs (1201 N) was selected as the standing force and the forces due to other human activities were calculated using the ratios listed in Table 3. The calculated forces are used to determine the loading conditions for the FEA calculations. We admit that except for standing, the force...
values caused by other four activities vary during the cycle of the action and the generated forces are distributed along the foot-AWS contact surface unevenly. Unfortunately the cyclic variation of the forces and their distributions have never been studied before and cannot be measured with our current facilities. Thus, in this FEA study, those forces are applied on the contact surface of the AWS models as constant pressures (Fig. 3). Since the forces were calculated based on the ratios and the maximum allowable weight of 1201 N, the loading conditions represent the greatest amount of loading that the AWS will be subjected to.

If the AWS design can resist such loading conditions, it should also be able to survive any other loading conditions during the recording of each human actions.

2.4. Boundary Conditions

Detailed descriptions of motions of the AWS within a shoe to coordinate with the lower extremity movements are still not very clear. However, by taking the worst scenarios into account, two extreme boundary conditions are defined for this FEA model: (1) the AWS is fully constrained and cannot move; and (2) the AWS can move along the inner surface in the rear of the shoe while its bottom has to stay in contact with the bottom inside surface of the shoe. It is believed that any motion of the AWS within the shoe can be treated as a combination of the two motions. The first condition is related to a tight fitting shoe with the foot pressed against the AWS. As shown in Fig. 4, such boundary condition is achieved by fully constraining the side and bottom edges of the AWS model. The second boundary condition is depicted in Fig. 5, where the side edge can move up and down (along the inner surface in the rear of the shoe, Y-axis, motion along Z direction is constrained) and the bottom edge can also move freely but has to stay in contact with the bottom surface (X–Z plane and motion along Y direction is constrained). Under that
boundary condition, the AWS will move against the inner surface in the rear of the shoe and that motion will lead to deformation on its bottom because the bottom edge has to stay in contact with the bottom surface (X–Y plane).

2.5. FEA Model

FEA models for the thin-walled nitinol AWS are then created based on the CAD models with aforementioned material properties, force (pressure) conditions, and boundary conditions assigned. With the application of the high performance computing facilities at MSU, the generated FEA models are three dimensional and are meshed using eight-node solid hexagonal elements.

Since the thin-walled nitinol AWS is proposed for the first time in this study and the presented computational study represents the first effort in evaluating the force bearing and deflection performance of the AWS model, there is no previous experimental data that can be used to validate and verify the FEA results. Due to the lack of an experimental benchmark for the FEA simulations, the FEA models are resolved with successively finer and finer meshes until the results converge satisfactorily [19,20]. Each FEA AWS model with a certain wall thickness kept being refined for 6 times until further refinement does not result in significant changes on the results (Table 4). For example, Fig. 6 displays the AWS model with 1 mm thickness meshed with a minimum of 118 elements with an average aspect ratio of 21.71 and with a maximum of 115,012 elements with the average aspect ratio of 1.96.

3. Results and Discussion

Stress and deflection of the AWS models were calculated from the FEA simulations to reveal the effects of

<table>
<thead>
<tr>
<th>Elements</th>
<th>Fully constrained (MPa)</th>
<th>Roller supports (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>118</td>
<td>5.374</td>
<td>7.530</td>
</tr>
<tr>
<td>422</td>
<td>7.315</td>
<td>7.618</td>
</tr>
<tr>
<td>1808</td>
<td>11.132</td>
<td>7.842</td>
</tr>
<tr>
<td>6788</td>
<td>12.129</td>
<td>7.644</td>
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<tr>
<td>28,620</td>
<td>13.215</td>
<td>7.609</td>
</tr>
<tr>
<td>115,012</td>
<td>13.751</td>
<td>7.593</td>
</tr>
</tbody>
</table>
three wall thickness (1 mm, 2.5 mm, and 5 mm), two boundary conditions (fully constrained and roller supports), and five actions (standing, self-selected walking pace, brisk walking pace, running, and vertical jumping) on force bearing and deflection performance of the nitinol AWS. For example, Table 4 lists the maximum stress calculated from the 1 mm thick AMS model under a pressure due to standing. To acquire correct numerical results, the mesh was refined six times until the yielded stresses converged. From that table it can be deduced that when a person of 1201 N (271 lbs) stands on the 1 mm AMS model, a maximum stress of 13.75 MPa will be generated when the AMS is fully constrained and about 7.6 MPa will be generated when the AMS can move against the inner surface of a shoe.

The calculated results were graphed to display the maximum stress and deflection incurred by different human activities on each AWS model with different thickness, boundary condition, and number of elements. Figures 7–12 show the stress results and Figs. 13–18 display the deflection results.

### 3.1. Numerical Sensitivity to Mesh Refinement

From above figures it can be seen that as the mesh is refined, the maximum stresses yielded from the fully constrained 1 mm and 2.5 mm AWS models quickly increase and approach to steady state values. However, the 5 mm fully constrained AWS model and all three AWS models with the roller supports are not very sensitive to the mesh density. This is because higher maximum stress values and significant stress concentration were found from the fully constrained models with thin wall thicknesses (1 mm and 2.5 mm). Thus, the stress changed very quickly on the surfaces of those models and has to be correctly captured by very fine elements. It is because of that reason, the fully constrained AWS models with thicknesses of 1 mm and 2.5 mm showed high stress sensitivity to mesh density. However, for the fully constrained 5 mm AWS model, the calculated maximum stress significantly decreased and the stress concentration was reduced. Therefore, the stress distributed along its surface changed much more slowly, which can be captured by the coarse models with relatively large element size. The phenomenon that the maximum stress decreases with growing thickness of the structure was also observed by Lewinski [21]. More details about the effects of thickness on the FEA results can be found from Section 3.4 and Tables 5 and 6.

The stresses calculated from the AWS models with roller supports are not significantly affected by the mesh density because the roller supports give mobility to the AWS models, which will help to redistribute the stress evenly along their surfaces and reduce the stress concentration. Therefore, those models are not as sensitive to the mesh density as the fully constrained models would be.

Figures 13–18 show that the influence of the mesh density on the displacement results is much less than
that on the stress results. The displacement results yielded from the AWS models which are fully constrained are slightly affected by the mesh refinement while the results from the models with roller supports, which are meshed with different number of elements, are almost the same. This is because that in finite element method, element displacements are first solved; afterwards, the element strains and stresses are calculated from the displacements based on the strain/displacement relationship and a material’s stress/strain (constitutive) relationship. Therefore, compared to the stresses, the displacements are more accurate and can be calculated using relatively coarse models. Effects of thicknesses and boundary conditions on the displacement sensitivity to the mesh refinement are similar to those on the stress sensitivity and can be explained in the same way.

At last, after inspecting above figures, it can be confirmed that all the calculated results converge as the meshes are refined. Therefore, the obtained stress and displacement results are reliable and will form a benchmark for future experimental validation and verification. Under the same force and boundary conditions, the displacement results converge more quickly than the stress results which has been explained in above paragraph.

### 3.2. Effects of Loading Conditions

All the result plots (Figs. 7–18) confirm that as the force (pressure) level increases, the resulting stress and displacement also increase. It is not surprising to observe that the maximum stresses and displacements on the AWS models caused by the running action are the highest while those results caused by the static standing remain the lowest. It can also be observed from those figures that the stress and displacement results yielded by standing, self-selected walking, and brisk walking are close to each other. The results corresponding to the vertical jumping action are clearly larger than the results caused by standing, self-selected walking, and brisk walking; and the results caused by the running activity are again larger than those caused by the jumping. Those phenomena can be explained in terms of the magnitudes of the forces due to the different human activities and their relationships, as listed in Table 2.

The maximum stress and displacement results calculated from the thin-walled AWS models with different thicknesses and subjected to forces due to various motions are displayed in Table 5 (fully constrained) and Table 6 (with roller supports). All the displayed results were selected from the models with the finest mesh because those results are considered more accurate. The largest stress yielded from the present FEA simulations occurred in the 1 mm thick AWS that was fully constrained, which is almost 38 MPa (Table 5). However, the largest displacement was obtained from the 1 mm thick AWS model with the roller supports, which equals 69 μm (Table 6). In both cases, the AWS
model was subjected to a pressure generated due to the running activity. This is because that a fully constrained model (boundary condition 1) intends to cause stress concentration and lead to higher maximum stress, while a less constrained model (boundary condition 2) may give rise to larger displacement because the model is allowed to move under that boundary condition. Also, since the largest stress is less than 20% of the yield stress of nitinol (Table 1), it is convinced that the proposed thin-walled nitinol AWS is strong enough to resist the various forces and motions a user places on his/her feet. The AWS models would restore to their original shapes after they were unloaded, as could be seen from the animations.

### 3.3. Effects of Boundary Conditions

Comparing Table 5 with Table 6, it is evident that the displacements calculated from the models with roller supports are much larger than those yielded from the fully constrained models. This is because the boundary conditions imposed by the roller supports released some degrees of freedom of the models so that those models have higher mobility than the fully constrained models and, therefore, intend to produce larger displacements. Influences of the boundary conditions on the maximum stress values are complicated. For the 1 mm thick model and under the same loading condition, the maximum stresses calculated from the fully constrained model are twice as high as the stresses obtained from the model with roller supports. For the 2.5 mm thick model, the stresses from the fully constrained models are only slightly higher than the stresses predicted by the model with roller supports. However, for the 5 mm thick model, the stresses from the models with roller supports are 70% higher than those from the fully constrained models. This is an unanticipated phenomenon because usually the stress calculated on a highly constrained model is higher than that from a less constrained model. However, on inspecting and comparing Fig. 19a and b, this phenomenon can be explained in terms of the stress distribution along the thickness direction.

Figure 19a and b plot the stress distribution for a 5 mm thick AWS model subjected to standing force under boundary condition 1 and 2, respectively. The maximum stress of 1.75 MPa ("–" denotes that this stress is a compressive stress) was calculated from the fully constrained model and that stress appears in inner surface of the AWS model and in an area close to its bottom edge. While for the model with roller supports, the calculated maximum stress of 2.97 MPa (compressive stress) not only appears in the inner surface of the AWS model but also along the inner side of its side edge, which is also very close to its bottom edge. However, the stress on the outermost layer of the fully constrained model is tensile stress while the
stress on most part of the outermost layer of the model with roller supports is still compressive stress except for a belt region close to its bottom edge. Figure 19 also reveals that for the fully constrained model, the stress state on the edges varies from compressive to tensile stress along the thickness direction while for the model with roller supports, the stress state on its edges remains as compressive stress in most areas. Thus, it can be deduced that different boundary conditions do not only affect the maximum stress value but substantially change the stress distribution mode along the thickness direction. Similar phenomenon was not observed from the 1 mm thick model because when the thickness is very small, the stress distribution along the thickness direction can be ignored. In that case, the boundary conditions only influence the maximum stress values. As the wall thickness increases, the change of stress distribution mode and its influence on the calculated maximum stress are less ignored.

In summary, the second boundary condition (roller supports) leads to larger displacements the first boundary condition (fully constrained) does. When the wall thickness is small, the first boundary condition leads to higher peak stresses than the second boundary condition does. As the wall thickness increased, the maximum stress value is jointly influenced by the boundary condition and the wall thickness. More discussions about the effects of the thickness on the FEA results are included in the next section.

### 3.4. Effects of Wall Thicknesses

Results listed in Tables 5 and 6 also clearly indicate that as the thickness increased, the maximum stress...
and deflection results decreased. This is because the increase in wall thickness will strengthen the AWS structure and will facilitate the stress distribution along the model. It needs to be mentioned that even for the 1 mm thick AMS model, the maximum stress is still less than 20% of the yield stress of nitinol and the maximum deflection is only 69 μm. Those results confirm the outstanding applicability of nitinol for AWS and other biomedical applications, all the thin-walled AWS models analyzed in this study can resist the various forces and motions and return to their original shapes after unloading.

4. Potential Commercial Impact
The typical customers of the proposed nitinol foot orthoses are (1) active military service members and veterans, (2) athletes, (3) other professionals suffering from foot or ankle injuries due to work or exercise, or (4) those who belong to the footwear industry (orthopedic shoemakers, orthotists, physical therapists, etc.). Currently customers purchase over-the-counter (OTC) foot orthoses at $50, which are made of foam, plastic, fiberglass, graphite, and may have gel fillings for better cushioning effect. Some customers have their podiatrists to prescribe custom orthoses for them, which are made of the same materials but more suited for their medical situation. The custom orthoses are much more example, for about $400 to $600 each pair. However, many currently used foot orthoses fail to resolve symptoms because they are not made of material that will resist fatigue and corrosion and will withstand body weight and physical activity. Average life span of typical foot orthoses for military personnel is 9 months of normal wear and tear, and 2 to 4 months in case of high activity. For the proposed nitinol foot orthoses, its unit price is estimated as $85, but its life expectancy is twice as long as that of the current foot orthoses. The unit price can be further reduced with the application of new additive manufacturing process and the replacement of nitinol other cheaper superelastic alloys.

5. Future Work
In the future, the proposed thin-walled nitinol AWS will be prototyped for testing and experimental validation. Currently, the true potential of nitinol superelastic supports has not been fully realized due to the difficulty in its machining and fabrication. Although nitinol can be cold worked into simple shapes (wire, sheets, tubing, etc.), its machining into complex geometries is difficult due to severe tool wear and chip breaking. During the past decade, additive manufacturing (AM) has evolved significantly from prototype-scale production to fabrication of functional parts for service. In contrast to traditional “subtractive” fabrication methods, AM techniques allow parts to be built vertically-upward, layer-by-layer, with combined material deposition and energy delivery. As found by Thompson and Shamsaei, AM provides the opportunity to fabricate complex, customized parts for a variety of applications even in logistically weak (remote) locations from only CAD files [22,23]. More importantly, AM techniques can be used to optimize the pore size.
and distribution and build patient-specific, cellular parts such as foot orthotics.

Several nitinol parts have been successfully fabricated at the Center of Advanced Vehicular Systems (CAVS) at Mississippi State University [11,24]. Its life cycle under axial, torsion, and multi-axial loading (typical human’s movements) have been characterized. Figure 20 shows variation of the mechanical behavior of the additively manufactured nitinol specimens by changing its characteristic temperatures through post-build heat treatment. As can be seen from that figure, the nitinol specimens fabricated using AM method are completely superelastic with a high stress plateau level. Based on the previous experimental data and the FEA results obtained from this study, it is anticipated that novel foot orthotics such as the proposed thin-walled AWS can be developed by combining the superelasticity of nitinol with the capabilities of AM. The cellular structure of nitinol can aid in redistributing impact forces realized during human activities, which can be fabricated using AM methods.

Another shortcoming of this study is that the fatigue stress as a result of the repetitive loading caused by proposed human actions (except for standing) was not considered in the numerical modeling and simulation. It is anticipated that the fatigue stress will also have a significant impact on the lifetime of the suggested AWS design and that influence will be included in the next phase.

6. Conclusions

A thin-walled nitinol AWS is presented in this study, and its capacity to resist various forces and motions has been evaluated through FEA. Five human activities, two boundary conditions, and three thicknesses are considered for the simulations and their effects on the force bearing and deflection of the AWS design are revealed. Following conclusions are drawn from examining the FEA results:

1. The stress and displacement of the AWS models increase with growing force applied by the models. Therefore, the running motion yields the highest stress and displacement values and the stress and displacement results caused by standing remain the lowest.
2. The less constrained models (with roller supports) would yield larger displacements than the fully constrained model.
3. For the AWS models with thin thickness (1 mm and 2 mm), the maximum stresses calculated from the fully constrained models are clearly higher than those from the less constrained models.
4. For comparatively thick models (thickness = 5 mm), the maximum stresses from the fully constrained models are lower than those from the less constrained models because the boundary conditions not only influence the maximum stress values, but also affect the stress distribution along the thickness direction, which is usually ignored for thin-walled models.
5. As the thickness increases, the maximum stress and displacement decreases. Strength of the thin-walled AWS design increases with the growing thickness.
6. The presented thin-walled nitinol AWS design is strong enough to resist various forces and motions and can restore to its original shape after unloading.

Due to the lack of experimental data, the created FEA models were resolved with successively finer and finer meshes until the results converge satisfactorily. Sensitivity analysis shows that the maximum stresses calculated from the fully constrained models with thicknesses of 1 mm and 2.5 mm are highly sensitive to the mesh size; the stresses calculated from the fully constrained models with a thickness of 5 mm and all the models with roller supports are less sensitive to the mesh size; The displacement results are nearly not affected by the mesh density.

In the next phase, a prototype of the thin-walled nitinol AWS will be developed using additive manufacturing technologies and used for both human factors testing and material testing to fully realize the true potential of superelastic nitinol and other cheaper superelastic alloys in biomedical applications.

References


