Novel Ball Head Screw and Screwdriver Design for Implant-Supported Prostheses With Angled Channels: A Finite Element Analysis

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The primary objective of this study was to design the optimal geometry of a novel screwdriver, create the grooves on a ball head screw, and demonstrate its resistance to a torque of up to 40 Ncm at angulations of 0°, 15°, and 30° by using nonlinear finite element analysis. A secondary objective was to create a foolproof, easily recognizable system. The grooved ball head screw and geometry of the screwdriver, functioning from an angulation of 0° to 30°, was generated using Pro-ENGINEER Wildfire 5.0 software. Static structural analyses among bodies in contact were performed at different angles of 0°, 15°, and 30° at a torque of 20 Ncm and 40 Ncm using nonlinear finite element simulation by means of ANSYS 12.0. The maximum stress supported by the ball head screw and screwdriver was similar at 20 Ncm and 40 Ncm. Although greater deformations were found at 40 Ncm, these were small and might not affect the performance of the system. Further, the rupture torque value for the M2 connection was 55 Ncm for 0° and 30°, and 47.5 Ncm for 15°. Numerical simulation showed that the ball head system design can achieve the mechanical strength requirements expected for screws used in implant-supported restorations at an angulation of up to 30°. Finite element analysis showed this novel ball head screw and screwdriver system to be a good solution for angled screw channels in implant-supported prostheses.

Key Words: ball head screw, angled screw channel, finite element analysis, torque, preload, screw mechanics

INTRODUCTION

Dental implants have been reported to be highly successful in treating both completely[1,2] and partially edentulous patients.[3–5]

Screw-retained prostheses were initially used for partial or full-arch rehabilitations,[1,2,6] whereas single-tooth reconstructions were generally cemented on prefabricated abutments.[7] Both types of reconstructions exhibited satisfactory long-term clinical outcomes[1,8]; however, due to the need to customize prosthetic components to improve aesthetic outcomes or correct angled implants, new components such as the cast-on UCLA abutment were developed for both screw- and cement-retained single-tooth reconstructions.[9,10]

An accurate implant position is mandatory when screw-retained reconstructions are used to achieve an optimal location of the screw access hole and obtain good esthetic results. Reconstructions cemented on angulated abutments are the current solution to implants placed in an improper position or tilted implants placed to avoid sensitive structures or anatomical cavities.[11–13] However, screw-retained reconstructions seem to be preferable, as they are more easily retrievable, facilitating the treatment of technical and biological complications.[14–16]

Angulation of the screw channel corrects emergence of the prosthetic screw access hole and constitutes an alternative to cemented reconstructions on tilted implants. This allows the dentist and the dental technician to use screw-retained reconstructions despite the implant position. A special screwdriver with the capability to apply torque to the screw in an angled channel should be used.[17,18] It would be truly beneficial to develop a foolproof new screw head and screwdriver system for use in screw-retained reconstructions with angled channels. This system should be able to achieve the recommended

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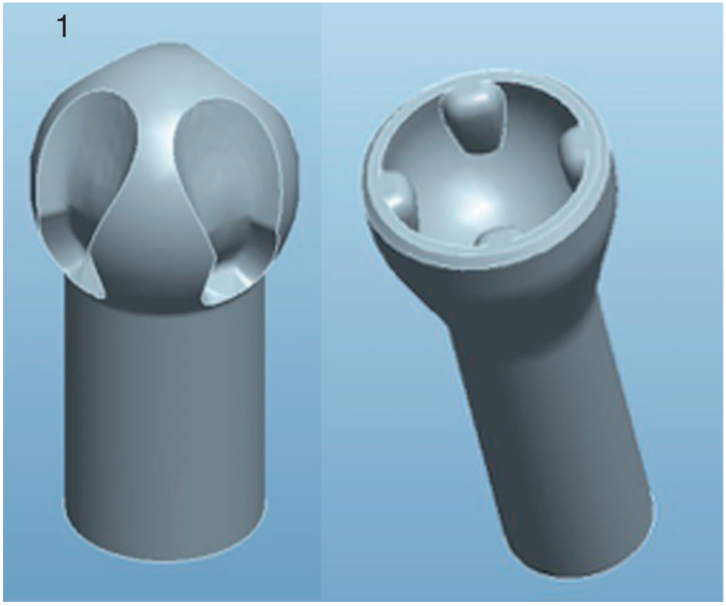

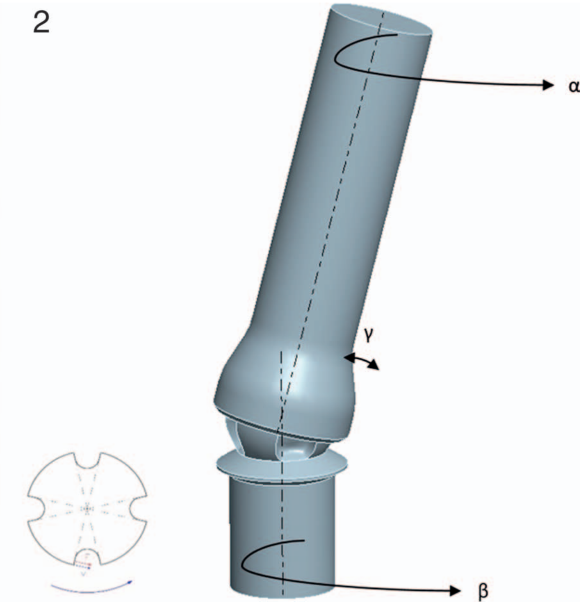

FIGURES 1 AND 2. FIGURE 1. Screw and screwdriver design. Left: ball screw head; Right: screwdriver. **FIGURE 2.** Optimal geometry of the screw and screwdriver. Left: diagram of force and linear speed. Due to the radial contact surfaces, the transmission angle is 0°. Right: angles influencing angular misalignment.

torque of 30 Ncm, even in the hardest situation of an angulation of 30°.

Nonlinear finite element analysis (FEA) has become an increasingly powerful tool for predicting stress and strain within structures in a real situation.[19] It has been successfully applied to assess the mechanical characteristics of different implant- and tooth-abutment connections.[20,21]

The primary objective of this study was to design the optimal geometry of a novel screwdriver, create the grooves on a ball head screw, and demonstrate its resistance to a torque of up to 40 Ncm at an angulation of 0°, 15°, and 30° by using nonlinear FEA. A secondary objective was to create a foolproof and easily recognizable system.

MATERIALS AND METHODS

Design concept

The concept behind the patented screw and screwdriver design—called Ball Head System (BHS)—is a spherical dented structure (Figure 1). The screw head constitutes the male component of the connection. The screwdriver, representing the female component, was designed to perfectly match the screw head from an angulation of 0° to 30°.

Final design

To design the optimal geometry of the screwdriver, the transmission angle formed between the force direction and absolute speed at the contact point between the two bodies became key design parameters. Minimizing the transmission angle improves load transmission and reduces the chance of stripping. If the transmission angle is 0°, the transmission function is satisfactory.[22] The contact surface between the screw head and the screwdriver must be radial to guarantee a 0° transmission angle. Radial lines represent contact surfaces between two bodies, where the contact force is normal to the surfaces involved. Linear speed in a circular movement is perpendicular to the radius. Hence, the angle between the force and speed direction is 0°, and the relationship between angles when the screwdriver is activated as follows: $\beta = atan(\tan\alpha/\cos\gamma)$ (Figure 2).

Two factors were taken into consideration for determining the final number of grooves in the screw head: (1) The number of grooves had to ensure that the forces were well balanced even if the screw and screwdriver were not well aligned, thereby reducing the chance of stripping. The number of grooves had to be sufficient to guarantee a proper gear between screw and screwdriver. (2) The material left between grooves had to be sufficient to withstand the forces applied without easy stripping. The optimal number of grooves was finally defined as four because with only two grooves, a proper gear between screw and screwdriver was not possible at certain inclination angles, while with 6 grooves, the width between grooves was too small.

To build up the final geometry, a standard M2 abutment screw size was used as a sample. Figure 3 shows the whole process for creating the final system. First, the screwdriver was designed. To guarantee a perfect gear between the screw head and the screwdriver, a generation method was applied. An assembly containing all possible positions of the screw head was created. The following step involved cutting the negative part of the groove to obtain the positive part of the groove on the sphere. Lastly, the head was attached to the body of the screw. The final geometry can be seen in Figure 4. These geometries were generated using Pro-ENGINEER Wildfire 5.0 (PTC Corporation, Needham, Mass).

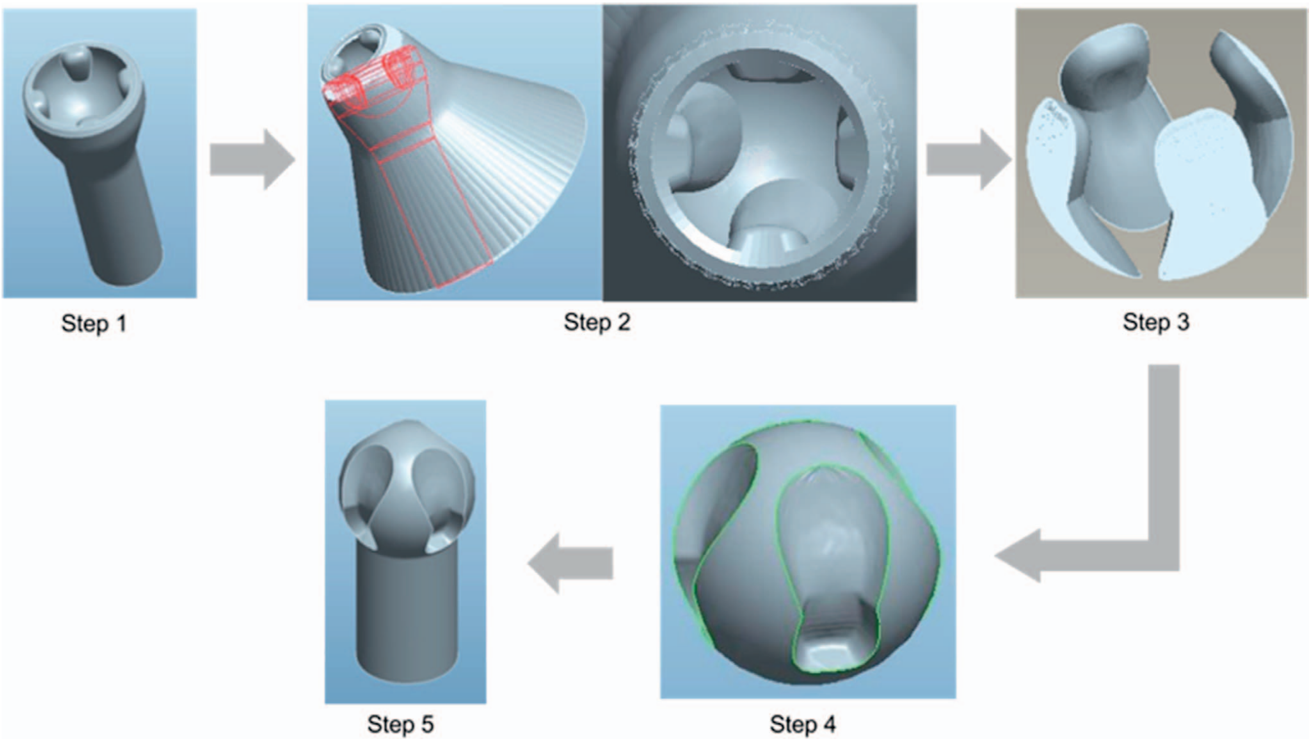

FIGURE 3. Generation of the final geometry. Step 1: The screwdriver geometry was generated. Step 2: The generation method was used to create a geometry that includes all the possible positions of the screwdriver around a spherical screw head from 0° to 30°. Step 3: The negative part of the generated groove was cut, obtaining the positive part of the generated groove. Step 4: The geometry obtained in Step 3 was used to make a cut to the sphere to obtain the final screw head geometry. Step 5: The screw head was attached to the body of the screw.

Analysis scenario

Nonlinear FEA was performed to verify that this screwdriver and screw system were viable.

The material of choice for the screwdriver was steel 17-4PH, with a tensile yield strength of 1090 MPa and an ultimate tensile strength of 1210 MPa. Steel 17-4PH is an alloy containing 0.04% carbon, 0.25% silicon, 0.40% manganese, 15.30% chromium, 4.50% nickel, 3.25% copper, and 0.3% niobium, and then subjected to thermal treatment (reheating for dissolution). The screw itself was analyzed using a Ti6Al4V grade 5 alloy containing 6% aluminum and 4% vanadium, with a tensile yield strength of 970 MPa and an ultimate tensile strength of 1100 MPa.[23]

The screwdriver and screw connection were analyzed as a static structure at angulations of 0°, 15°, and 30°. Additionally, two torque values were analyzed for each angulation (20 Ncm, and the worst-case scenario of 40 Ncm), and the rupture torque was calculated using an iterative process.

For the loading conditions, the screw was fixed at its base while torque was applied to the top of the screwdriver. The analysis was performed within the elastic range. If the stress was higher than the yield strength, the analysis was performed within the plastic range. In this case, the screw and the screwdriver were analyzed separately (first the screw and then the screwdriver); otherwise, the result would not converge.

A different mesh for the screw and screwdriver was generated for each inclination angle, refined around the contact points to increase accuracy (Figure 5). Table 1 shows the number of nodes and elements used for the screw and screwdriver mesh. The element size ranged from 0.4–0.05 mm, depending on the inclination and the torque applied.

The finite element analysis was performed by means of ANSYS v12 software (ANSYS Inc, Canonsburg, Penn).

TABLE 1

Number of nodes and elements used for the screw and screwdriver mesh

	Screw		Screwdriver	
Angulation	Nodes	Elements	Nodes	Elements
20 Ncm				
0°	13 001	7822	13 001	7822
15°	21 374	13 082	14 790	8967
30°	38 933	25 653	38 975	25 638
40 Ncm				
0°	13 001	7822	13 001	7822
15°	18 406	11 356	14 790	8967
30°	39 241	25 823	39 241	25 823

RESULTS

The nonlinear FEA yielded the following results.

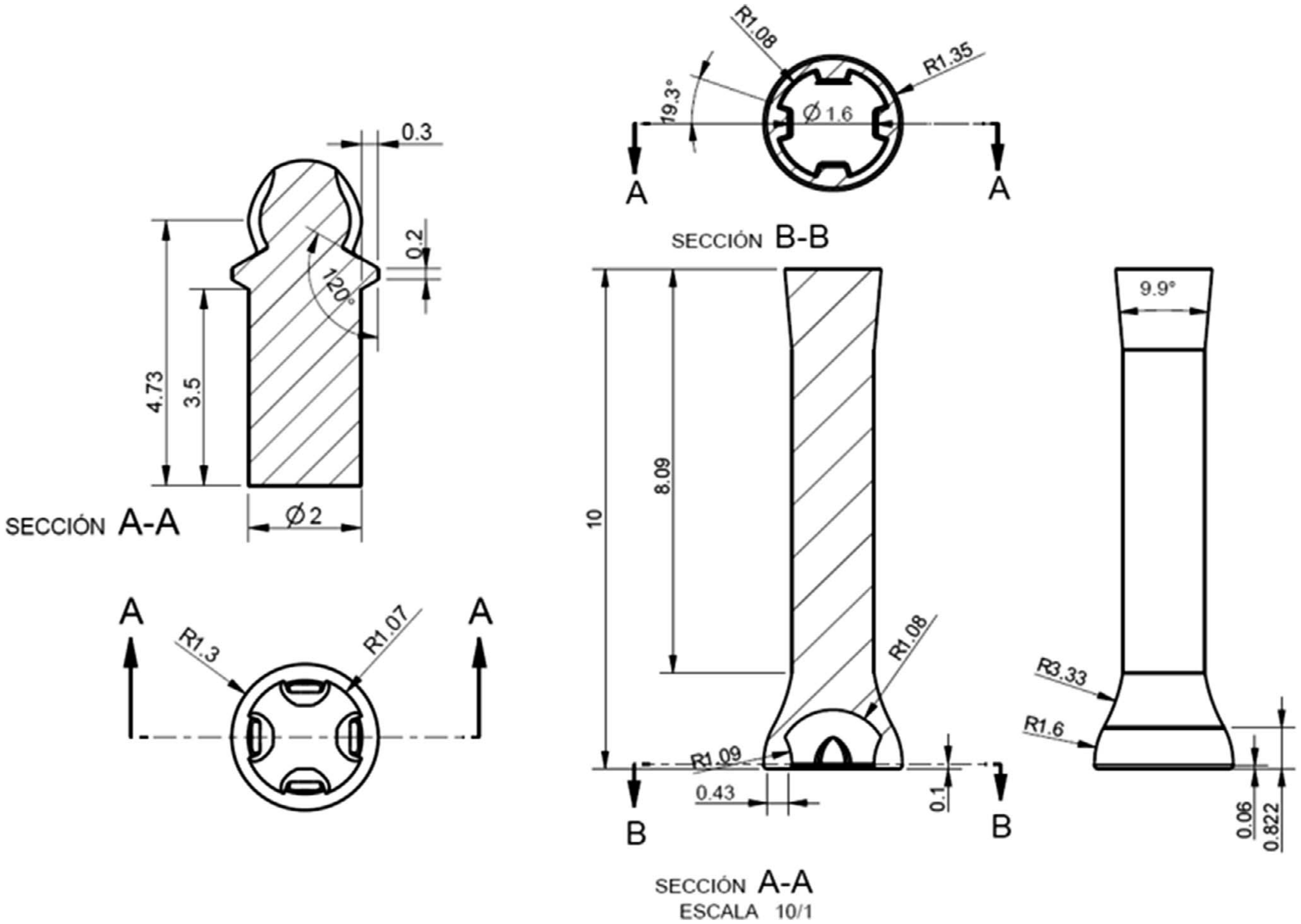

FIGURE 4. Final geometry of the screw and screwdriver. Left: final geometry of the screw head. Right: final geometry of the screwdriver.

Stress distribution

As seen in Figure 6, stress distribution was different for each inclination. However, in all cases, the maximum stress points at the screwdriver were located at the contact points on the teeth. Similarly, the maximum stress points at the screw head were also located at the contact points on the grooves and at its base.

Maximum stress analysis

Table 2 summarizes the maximum equivalent Von Misses stress obtained for each torque and angle of inclination. As shown, at 20 Ncm and 0°, the maximum stresses at the screw head and screwdriver were within the elastic range. However, in all the other cases, the maximum stresses were higher than the yield strength, creating permanent deformations.

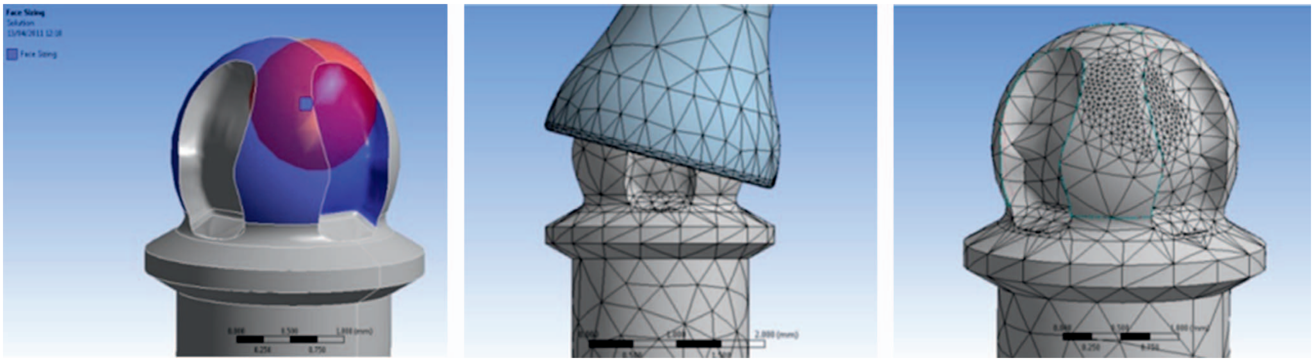

FIGURE 5. Different meshes for the screw and screwdriver generated for each inclination angle to increase accuracy. Left: sphere used to refine the mesh around the contact point at an inclination angle of 15°. Middle: screw and screwdriver mesh. Right: refinement of the screw mesh at the contact point.

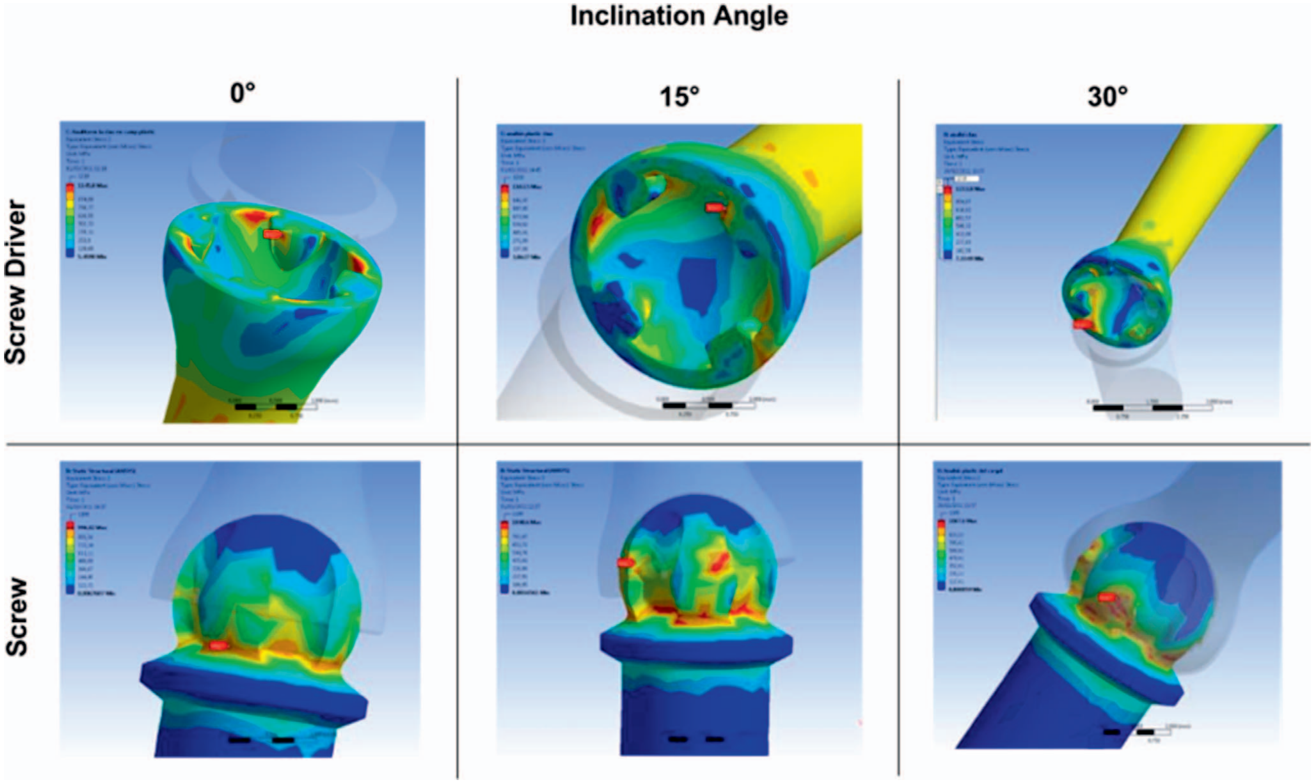

Figure 6. Stress distribution for each inclination. Von Miss equivalent stresses at 0°, 15°, and 30° and at 40 Ncm torque. At 20 Ncm, the stress distribution was similar; however, the absolute stress values were different.

Probably due to the gentle slope, the maximum stresses for 20 Ncm and 40 Ncm were very similar. Although the deformations beyond 40 Ncm were greater, they were still very small and might not affect the operation of the screw and screwdriver. Nonetheless, mechanical tests with a prototype would be needed to confirm this.

It is worth noting that maximum stress and deformation on the screwdriver were higher at 15° than they were at 0° and 30°.

Rupture stress analysis

Table 3 shows the minimum rupture torque of a series of iterative analyses for each angulation, with the purpose of establishing the maximum torque levels that cause rupture tensions in one of the two elements in the connection.

As shown, at 0° and 30°, the screwdriver required significantly more torque to fail. In this case, the screwdriver was close to its strength limit, while the screw had more than 50 MPa of margin. Nevertheless, at 15°, both the screw and screwdriver were very close to their failure limits.

Table 2

Maximum tensions in relation to torque

Angulation	Screw Maximum Stress (MPa)	Screwdriver Maximum Stress (MPa)	Screw Maximum Deformation (mm)	Screwdriver Maximum Deformation (mm)
At 20 Ncm				
0°	796.9	1037.3	0.0093	0.0042
15°	1040.3	1141.1	0.018	0.058
30°	1041.5	1103.9	0.011	0.046
At 40 Ncm				
0°	996.0	1145.8	0.019	0.085
15°	1048.6	1159.2	0.03	0.213
30°	1067.6	1153.8	0.039	0.11

Discussion

Finite element analysis has been the most common and powerful tool for simulating dental restorations under various loading conditions.[19] FEA has also been extensively used to predict the biomechanical performance of various dental implant designs,[24] as well as the effect of clinical factors on implant success.[25] According to Geng et al,[26] the results obtained from FEA are a good starting point and could be

Table 3

Minimum rupture torque

Angulation	Torque (Ncm)	Screw Maximum Stress (MPa)	Screwdriver Maximum Stress (MPa)
0°	55	1048.0	1184.6
15°	47.5	1092.9	1182.5
30°	55	1049	1202.5

extrapolated to clinical situations, with due consideration of the limitations of the method.

That said, most previous reports lack rigorousness in model construction.[20,27] Thus, in the present study, a different mesh was generated for each inclination angle for both the screw and the screwdriver. Moreover, refinement around the contact points was made to increase accuracy (Figure 5). Other variables—such as screw threads, abutment, implant, and surrounding bone—were ignored to ensure that the screw head and screwdriver connection behavior was the only variable in this investigation. In this regard, our results may be extrapolated to other metrics and fields where accessibility and angulation are needed.

Within the limitations of the methodology used in this study, the results of the numerical simulation showed that the BHS could improve and easily achieve the required mechanical strength for screws used in screw-retained reconstructions with angled channels, even in the demanding situation of an angulation of 30°. Our study confirmed that both the required nominal torque of 20 Ncm and the required maximum torque of 40 Ncm were achieved. Based on iterations to determine the maximum torque at which the connection could support, we demonstrated that with an angulation of 0° and 30°, the screwdriver broke first at 55 Ncm, although at 15°, the screw broke at 47.5 Ncm. These rupture torques should be taken as an approximation and checked experimentally by means of torsion testing of the connection. Nevertheless, this would not constitute rupture per se but rather a permanent deformation of the groove. There would be no danger of screw head rupture because the slots required for removal would still be intact, so it could be unscrewed.

A possible underestimation of the results obtained by FEA needs to be clarified. The material limits used for FEA are obtained from tensile tests. However, the connection at the screw and screwdriver is under compression and shear stress, which offers higher limits than if it were under tensile stress conditions. The goodness of the model can be summarized as a realistic geometrical structure and elastoplastic model for the material description, affording correct definition of the contacts and existing tolerance among the different system components, and with good reproduction of the preloading stress condition.[28]

Few studies have addressed the influence of screw head design tested over a range of angles of application of the respective screwdriver, the torque value at which the screw head strips, or the torque at which screwdriver engagement fails. Spencer et al[29] tested the behavior of titanium screws with four different head designs under different angulations. These screw head designs did not reach optimal torque values with increasing angulation. At 30°, slot and cross screw head designs were those which achieved a maximum torque value of 23.4 Ncm and 19.4 Ncm, respectively. Because those designs were not specifically created for applying torque with angulation, the application of an axial force (amount of force applied to each screw along its axis) was necessary by the examiner. This force increased with increasing angulation to maintain the radial force (amount of force at the screw head). Hence, the BHS was designed with a transmission angle of 0° to achieve a minimum axial force and improve load transmission and patient comfort.

The use of tilted implants is an alternative to bone augmentation and sinus lift,[30] and no negative effects have been seen in terms of implant survival or marginal bone loss compared to straight implants.[31] The BHS allows the application of 30 Ncm torque to screw-retained reconstructions with angled channels; as such, it could become a good solution to solve esthetic demands and nonparallel situations between the axial direction of the superstructure and the implant. Further, some publications[17,18] have shown that clinicians use the angled screw channel with suboptimal screw and screwdriver designs, implying a potential risk of damaging the screw head. This is an indicator that BHS offers the required solution and is safe and easy to recognize.

Following the satisfactory results of the numerical simulation of BHS comprising a ball head screw and screwdriver, the next step should be to perform mechanical tests. These would obtain much more reliable data in terms of the static test. We also need to analyze the behavior of BHS under fatigue conditions with the aim of validating its use for implant-supported prosthesis.

CONCLUSIONS

Within the limitations of this study, the following conclusions can be drawn:

- The BHS is a state-of-the-art design comprised of a ball head screw and screwdriver designed with the most severe requirements, a system specifically indicated for implant-supported restorations with angled channels.
- Numerical simulation has shown that the BHS design can achieve the mechanical strength requirements expected for screws used in implant-supported restorations at an angulation of up to 30°.
- The ball head screw design is exclusive and easily recognizable by the operator, which ensures use of the right screwdriver, preventing potential damage to the screw head.
- Further research based on mechanical evaluation is required to validate the accuracy of this novel ball head screw and screwdriver system for implant-supported prosthesis.

ABBREVIATIONS

BHS: Ball Head System
FEA: finite element analysis

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NOTE

The authors have conflicts of interest, as patent registrations have been obtained for the external connection [BHS30

EXTERNAL: WO/2009/150350] and for the internal component [UBH INTERNAL: US8978525 / EP2420354 B1 / CN102395447 B]. This work was supported by the company Ball Head System, S.L.

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