An Oblique Cutting Based Mechanical Model For Insertion Torque of Dental Implant

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Title page

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An oblique cutting based mechanical model for insertion torque of dental implant

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Abstract: The insertion torque of a dental implant is an important indicator for the primary stability of dental implants. Thus, the preoperative prediction for the insertion torque is crucial to improve the success rate of implantation surgery. In this present research, an alternative method for prediction of implant torque was proposed. First, the mechanical model for the insertion torque was established based on oblique cutting process. In the proposed mechanical model, three factors, including bone quality, implant geometry and surgical methods were considered by defined bone-quality coefficients, chip load and insertion speeds, respectively. Then, the defined bone-quality coefficients for cancellous bone with the computed tomography (CT) value of 235~245, 345~355 and 415~425 Hu were obtained by a series of insertion experiments of IS and ITI implants. Finally, the insertion experiments of DIO implants were carried out to verify the accuracy of developed model. The predicted insertion torques calculated by the mechanical model were compared with that acquired by insertion experiments, which were agreed match with the relative error less than 15%. This method reduces the time consumption on establishing the fitting equations for different implants and enhance the predicted accuracy by considering the effects of implants’ geometries and surgical methods.

Keywords: Insertion torque • Mechanical model • Oblique cutting • Dental implant

1 Introduction

Implant dentures have been one of the most popular options for teeth loss in the last decade [1]. After the implant socket is prepared by a series of processes such as drilling, reaming and tapping, an implant is inserted in alveolar bone with a certain torque, named the insertion torque. Many clinical data have shown that 30~70 N·cm is a reasonable range of insertion torque for the great primary stability of implants, and therefore it has been accepted to evaluate surgical success [2–4]. Although the reasonable range of insertion torque are determined by many factors such as shape and diameter of implants [5–6], loading condition [7], or age, gender and height of patients [8–9], it would not be discussed in the present research. As the insertion torque could not be obtained until the implant was fully inserted, if the implant was fully inserted and the insertion torque was not in the reasonable range, the implantation surgery would most likely fail and the patient have to endure a second surgery. Therefore, to improve success rate and avoid the second surgery, preoperative prediction for the insertion torque of implants have been the focus in clinical.

In current clinical researches, computed tomography (CT) value has been used to evaluate the condition of bone quality and proved positively correlated with the insertion torque [10,11]. In addition, the effects of implant geometries [12] and surgical methods [13–14] on insertion torque have been realized. For example, the larger insertion torque will be obtained by a conical [15], large-diameter implant [16] or a small-diameter implant socket [17,18]. As there are no quantitative models to describe the effects of implant geometry and surgical methods on insertion torques, many researchers focus on the empirical formulas fitted by CT value to predict the insertion torque [19–21]. Although the accuracy of these fitting formulas is mostly more than 80%, however, they would not work once the implant or the surgery method was changed. Moreover, it is a time and
money consuming project to establish fitted formulas for all implants and surgical methods.

In this present research, an alternative method was provided by establishing the mechanical model for the insertion torque of a dental implant. In the proposed mechanical model, three factors, including bone quality, implant geometry and surgical methods were considered by defined bone-quality coefficients, chip load and insertion speeds, respectively. Two kinds of bone-quality coefficients for different forming methods were obtained for bone with the CT value of 235-245, 345-355 and 415-425 Hu by a series of insertion experiments of IS and ITI implants, respectively. And the accuracy of developed model was verified by DIO implants with the relative error less than 15%.

2 A mechanical model based on oblique cutting theory

The insertion processes of dental implants involves two forming methods, i.e., the thread-cutting process [22] for implants with cutting edges and the thread-forming process for implants without cutting edges [23]. In this section, the implant typed DIO SFR5010 (DIO Innovation Health Care, Busan City, Korea) with 4 cutting edges in the apical part. Two coordinate systems were defined. The global coordinate system \(\{C:OXYZ\}\) was attached to the implant with the Z-axis along the rotation axis. The cutting element coordinate system \(\{c:oxyz\}\) was attached to each cutting element with the x-axis paralleling the helical path, where \(i\) indicates the \(i\)th thread.

Supposing the starting point as \(\text{M}(b,0,0)\) in \(\{C:OXYZ\}\), the helical path of threads can be expressed as follows:

\[
g(P, \theta) = \begin{cases} 
x(P, \theta) = (P \theta/2 \pi \tan \beta + b + h_d) \cdot \cos \theta \\
y(P, \theta) = (P \theta/2 \pi \tan \beta + b + h_d) \cdot \sin \theta \\
z(P, \theta) = P \theta/2 \pi 
\end{cases}
\]  

(1)

where, \(x, y, z\) are the point coordinates of the helical path, \(\theta\) is the angle position of the helical path, \(b, h_d, P\) and \(\beta\) is initial radius, tooth height, pitch and taper angle of DIO SFR5010, respectively. Particularly, in the tail part, there is \(\beta=0\).

The radial distance \(r\) from the Z-axis to outer geometry of \(i\)th thread can be expressed as:

\[
r_i = \sqrt{(x(P, \theta))^2 + (y(P, \theta))^2} \tag{2}
\]

The radial engagement \(h_i\) of \(i\)th cutting element can be calculated as follows:

\[
h_i = \begin{cases} 
|r_k - H_k/2 - r_k(P, \theta) - H_k/2| & i = k \\
|r_k(P, \theta) - r_i(P, \theta - \theta_{c_k})| & i \neq k 
\end{cases} \tag{3}
\]

where, \(r_k\) is the first contacted cutting element, \(H_k\) is the diameter of the implant socket connecting \(k\)th cutting element.

The inclination angle of threads \(\gamma\) can be calculated as follows:

\[
\gamma = \pi/2 + \xi - \lambda = \pi/2 + \arctan(P/2 \pi r) - \lambda \tag{4}
\]

where, \(\xi\) and \(\lambda\) is the thread lead angle and the flute helix angle, respectively.
2.2 Force–chip load relationship

Before the forces during the insertion process were discussed, three assumptions were made as follows: (i) each cutting element sustained normal and friction forces, and all forces are applied on the centroid of the respective faces; (ii) the effects of elastic recovery for the prediction of insertion torque were ignored; (iii) insertion torques generated by one thread remained constant throughout the whole insertion process.

According to assumptions, the forces applied on all cutting elements can be composed of the normal force $F_n$ and the friction force $F_f$ as follows [25]:

$$F_n = K_n A$$
$$F_f = K_f A$$

(5)

(6)

where, $A$ is chip load, which equal to the unformed chip area and depend on the implant geometry, $K_n$ and $K_f$ are specific energies, which are related to the tool geometry and work conditions as follows [26]:

$$\ln K_n = a_0 + a_1 \ln h + a_2 \ln V + a_3 \ln h \ln V$$

$$\ln K_f = b_0 + b_1 \ln h + b_2 \ln V + b_3 \ln h \ln V$$

(7)

(8)

where, $V$ is the insertion speed, $h$ is the radial engagement of each cutting element, $a_0$–$a_3$ and $b_0$–$b_3$ are the specific energy coefficients, which are dependent on materials of cutting tool (i.e., implant) and the workpiece (i.e., cancellous bone). As most of implants' material are titanium or titanium-alloys, therefore, the $a_0$–$a_3$ and $b_0$–$b_3$ were only determined by bone quality and defined as bone-quality coefficients.

Considering the normal force $F_n$ and the friction force $F_f$ are different during thread-cutting and thread-forming processes, they would be discussed in sections 2.2.1 and 2.2.2, respectively.

### 2.2.1 Forces in thread-cutting process

As shown in Figure 2, the oblique cutting model [27,28] was established based on coordinate system $\{c;oxiyz\}$ to define the forces on each elements during thread-cutting process. Two planes, the normal and chip-flow plane, were introduced. The normal plane was defined by the $x_i$-axis and $z_i$-axis and the chip-flow plane was coincident with the rake surface of cut edges. In normal plane, the normal force $F_{cni}$ was defined perpendicular to the rake surface. In chip-flow plane, the friction force $F_{cfi}$ was defined collinear with chip-flow orientation [29]. Meanwhile, the chip-flow angle $i$ was defined equal to the inclination angle $\gamma$ based on the Stabler’s rule.

$$F_{cni} = K_{cn} A_i$$

(9)

$$F_{cfi} = K_{cf} A_i$$

(10)

where, $A_i$ are the chip load of the $i$th cutting element, $K_{cn}$ and $K_{cf}$, the specific energies in thread-cutting process. According to Equations (7) and (8), they can be calculated as:

$$\ln K_{cn} = a_0 + a_1 \ln h + a_2 \ln V + a_3 \ln h \ln V$$

$$\ln K_{cf} = b_0 + b_1 \ln h + b_2 \ln V + b_3 \ln h \ln V$$

(11)

(12)

where, $a_0$–$a_3$ and $b_0$–$b_3$ are the bone-quality coefficients during thread-cutting processes, which would be further determined by insertion experiments.

The chip load $A_i$ can be calculated as follows:
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where, \(w\) is the tooth top width of \(i\)th cutting element, the radial engagement \(h_i\) can be calculated according to Equation (3) as:

\[
h_i = \begin{cases} r_k - H_k / 2 = r(P, \theta_k) - H_k / 2 & \text{if } k \\ r_i - r_i(P, \theta_i - 2\pi / N_i) & \text{if } k \end{cases}
\]  

(14)

Where, \(N_i\) is the number of cutting edges. There is \(N_i = 4\) in DIO SFR5010.

By decomposing \(F_{cni}\) and \(F_{cfi}\) into the three axes of \{c;ox;y;z\}, three axial forces \(F_x\), \(F_y\), and \(F_z\) can be obtained as follows:

\[
\begin{align*}
F_x &= \begin{pmatrix} \cos \varphi \\ 0 \\ -\sin \varphi \end{pmatrix} F_{cni} + \begin{pmatrix} -\sin \varphi \\ \sin \gamma \\ \cos \gamma \cos \varphi \end{pmatrix} F_{cfi} \\
F_y &= \begin{pmatrix} \cos \varphi \\ 0 \\ -\sin \varphi \end{pmatrix} F_{cni} + \begin{pmatrix} -\sin \varphi \\ \sin \gamma \\ \cos \gamma \cos \varphi \end{pmatrix} F_{cfi} \\
F_z &= \begin{pmatrix} \cos \varphi \\ 0 \\ -\sin \varphi \end{pmatrix} F_{cni} + \begin{pmatrix} -\sin \varphi \\ \sin \gamma \\ \cos \gamma \cos \varphi \end{pmatrix} F_{cfi}
\end{align*}
\]  

(15)

Then, the thrust force \(F_{thi}\) and tangential force \(F_{tan}\) can be calculated as Equations (16–18), respectively.

\[
\begin{align*}
F_{tan} &= F_x \cos \xi + F_y \sin \xi \\
F_{tan} &= F_x \cos \xi + F_y \sin \xi \\
M &= \sum_{i=1}^{n} F_{tan} \cdot r_i
\end{align*}
\]  

(16) \hspace{1em} \hspace{1em} (17) \hspace{1em} \hspace{1em} (18)

2.2.2 Forces in thread-forming process

In order to define the forces during thread-forming process, six faces named \(S_1\)–\(S_6\) were introduced as shown in Figure 3. The ridge would be formed as the plastic deformation and flow of bone material during the insertion process.

Figure 3 A typical form tap tooth: (a) the schematic diagram of form tap tooth; (b) three views of \(i\)th tooth.

As same as the thread-cutting process, the normal forces \(F_{ni}\) were defined proportional to the contact areas, and the friction forces \(F_{fi}\) were defined collinear with chip-flow orientation [30]. \(F_{fni}\) and \(F_{ffi}\) can be expressed as follows:

\[
\begin{align*}
F_{fni} &= K_{fni} A_{n} \\
F_{ffi} &= K_{ffi} A_{fi}
\end{align*}
\]  

(19) \hspace{1em} \hspace{1em} (20)

where, \(K_{fni}\) and \(K_{ffi}\) were the specific energies during the thread-cutting process. According to the Equations (7) and (8), they could be calculated as:

\[
\begin{align*}
\ln K_{fni} &= c_0 + c_1 \ln h_i + c_2 \ln V_i + c_3 \ln h_i \ln V_i \\
\ln K_{ffi} &= d_0 + d_1 \ln h_i + d_2 \ln V_i + d_3 \ln h_i \ln V_i
\end{align*}
\]  

(21) \hspace{1em} \hspace{1em} (22)

where, \(c_0\)–\(c_3\) and \(d_0\)–\(d_3\) are the bone-quality coefficients in the thread-forming process and they would be further determined by insertion experiments.

The chip load \(A_{fi}\) can be calculated as follows:

\[
A_{fi} = \left[ S_i = S_3 = \frac{|PQ \times PM|}{2} = h_i \cdot z_i \cdot y(\eta) / 2 \right] \frac{S_2 = w \cdot h_i / \cos \eta_l \cdot y(\eta)}{23}
\]

where, \(y(\eta)\) is expressed as:

\[
y(\eta) = \sqrt{\left(\tan \alpha \right)^2 + \left(\tan \eta_1 \tan \alpha \right)^2 + \left(\tan \eta_2 + \tan \eta_3\right)^2}
\]  

(24)

where, \(h_i\) is the radial engagement of \(i\)th thread and it was given as Equation (3), \(\alpha\) is the thread angle, \(\eta_1\) and \(\eta_2\) is the incident angle and lobe-relief angle of threads, respectively, \(z_i\) is the \(z\) coordinate of point \(Q\) and it is given as follows:

\[
z_i = \sum_{i=1}^{n} h_i = r_i(P, \theta_i) - r_i(P_k, \theta_k)
\]  

(25)

where, \(r_j\) is the first-contacting thread.

By decomposing \(F_{fni}\) and \(F_{ffi}\) of the \(i\)th thread into three axes of \{c;ox;y;z\}, three axial forces can be obtained as follows:

\[
\begin{pmatrix} F_{x_i} \\ F_{y_i} \\ F_{z_i} \end{pmatrix} = \begin{pmatrix} -\cos \eta_l \\ 0 \\ \sin \eta_l \end{pmatrix} F_{fni} + \begin{pmatrix} 0 \\ \sin \eta_l \\ \cos \eta_l \end{pmatrix} F_{ffi}
\]  

(26)

Then, the thrust force \(F_{thi}\) and tangential force \(F_{tan}\) of each cutting element and the total insertion torque \(M\) can be calculated as follows:

\[
\begin{align*}
F_{tan} &= F_x \cos \xi + F_y \sin \xi \\
F_{thi} &= F_x \cos \xi - F_y \sin \xi \\
M &= \sum_{i=1}^{n} F_{tan} \cdot r_i
\end{align*}
\]  

(27) \hspace{1em} \hspace{1em} (28) \hspace{1em} \hspace{1em} (29)

According to Equations (15–18) and (26–29), it could be observed that the insertion torque was related to the normal and friction force and further determined by \(a\) bone-quality coefficients, \(b\) insertion speed \(V\), \(c\) radial
engagement $h_i$ and $d$) chip load $A$. These give a good explanation for the effects of bone quality, surgical methods and the implant geometry, respectively. When the implant and the surgical method were selected, $h_i$, $A$ and $V$ were determined. The only consideration is the bone-quality coefficients, which were given in the section 3.

3 Determination of bone-quality coefficient and validation of mechanical model

To define the bone-quality coefficients, more than 80 bone blocks with the size of $25 \times 25 \times 40$ mm$^3$ were cut from the epiphysis areas of four bovine femurs with different age, weight and gender as shown in Figure 4. The mean CT value of bone material within 1 mm around the predicted implant socket for each bone block were recorded by Planmeca ProMax 3D Mid CT (Planmeca UK Limited, London, UK). Scanning time: 13.929 s, tube voltage: 90 kV tube current: 10mA). According to recorded CT value, 36 bone blocks were selected and further classified into 3 groups with CT value of 235–245, 345–355, and 415–425 HU, respectively.

![Figure 4](image)

Figure 4 Preparation of bone blocks: (a) bovine femur, (b) A-A cross-section, (c) the bone blocks used in experiments and the CT scan area.

| Group 1 | Group 2 | Group 3 |
|----------|----------|----------|
| $A_{01}$ | 237.60   | $B_{01}$ | 354.86 |
| $A_{02}$ | 241.54   | $B_{02}$ | 345.35 |
| $A_{03}$ | 236.42   | $B_{03}$ | 352.68 |
| $A_{04}$ | 237.08   | $B_{04}$ | 346.42 |
| $A_{05}$ | 242.13   | $B_{05}$ | 348.57 |
| $A_{06}$ | 239.56   | $B_{06}$ | 353.63 |
| $A_{07}$ | 241.69   | $B_{07}$ | 349.21 |
| $A_{08}$ | 235.69   | $B_{08}$ | 350.96 |
| $A_{09}$ | 237.72   | $B_{09}$ | 354.12 |
| $A_{10}$ | 240.34   | $B_{10}$ | 348.56 |
| $A_{11}$ | 237.32   | $B_{11}$ | 350.12 |

Table 1 CT value of 3 group bone blocks

| Group 1 | $A_{01}$ | 237.60 | $B_{01}$ | 354.86 | $C_{01}$ | 418.48 |
| Group 2 | $A_{02}$ | 241.54 | $B_{02}$ | 345.35 | $C_{02}$ | 419.58 |
| Group 3 | $A_{03}$ | 236.42 | $B_{03}$ | 352.68 | $C_{03}$ | 417.99 |
| Group 4 | $A_{04}$ | 237.08 | $B_{04}$ | 346.42 | $C_{04}$ | 422.54 |
| Group 5 | $A_{05}$ | 242.13 | $B_{05}$ | 348.57 | $C_{05}$ | 420.26 |
| Group 6 | $A_{06}$ | 239.56 | $B_{06}$ | 353.63 | $C_{06}$ | 421.41 |
| Group 7 | $A_{07}$ | 241.69 | $B_{07}$ | 349.21 | $C_{07}$ | 417.69 |
| Group 8 | $A_{08}$ | 235.69 | $B_{08}$ | 350.96 | $C_{08}$ | 423.93 |
| Group 9 | $A_{09}$ | 237.72 | $B_{09}$ | 354.12 | $C_{09}$ | 415.34 |
| Group 10 | $A_{10}$ | 240.34 | $B_{10}$ | 348.56 | $C_{10}$ | 419.47 |
| Group 11 | $A_{11}$ | 237.32 | $B_{11}$ | 350.12 | $C_{11}$ | 416.95 |

3.2 Insertion experiments

Three groups of insertion experiments were conducted, where IS implants (IS BIS4510 and IS BIS5010, Neobiotech Co., Ltd., Seoul, Korea) with cutting edges were used to determine bone-quality coefficients $a_1$–$a_3$ and $b_1$–$b_3$ during thread-cutting process, and ITI implants (ITI RN4510 and ITI RN5010, ITI International Team for Implantology, Basel, Switzerland) with continuous thread typed were used to determine bone-quality coefficients $c_1$–$c_3$ and $d_1$–$d_3$ during thread-forming processes. DIO SFR5010 were used to verify the established model. The geometry parameters of these implants were shown as Table 2.

| Implant | Appearance | Angle (deg) | Size (mm) |
|---------|------------|-------------|-----------|
| IS BIS4510 |            | $b_1=1.0$ | $L=10$ |
|          | $a_1=17$   | $D_a=\phi 4.5$ |
|          | $a_2=6$   | $P=0.8$ |
|          | $a_2=30$  | $h=0.25$ |
|          | $\lambda=90$ | $w=0.08$ |
|          | $\varphi=0$ | $H=\phi 4.4$ |
| IS BIS5010 |            | $b_1=1.7$ | $L=10$ |
|          | $a_1=17$   | $D_a=\phi 4.5$ |
|          | $a_2=6$   | $P=0.8$ |
|          | $a_2=30$  | $h=0.25$ |
|          | $\lambda=90$ | $w=0.08$ |
|          | $\varphi=0$ | $H=\phi 4.9$ |
| ITI RN4210 |            | $\beta=0$ | $L=10$ |
|          | $\alpha=30$ | $D_a=\phi 4.8$ |
|          | $\eta=85$  | $P=1.25$ |
|          | $\eta=10$  | $H=\phi 4.2$ |
|          | $\xi=4.74$ | $w=0.1$ |
| ITI RN4810 |            | $\beta=0$ | $L=10$ |
|          | $\alpha=30$ | $D_a=\phi 4.8$ |
|          | $\eta=85$  | $P=1.25$ |
|          | $\eta=10$  | $H=\phi 4.2$ |
|          | $\xi=4.74$ | $w=0.1$ |
| DIO SFR5010 |            | $\beta_1$ | $L_1=2.5$ |
|          | $\alpha_1=8.5$ | $D_1=\phi 5.0$ |
|          | $\eta_1=85$ | $P_1=0.4$ |
|          | $\eta_2=10$ | $H_1=\phi 4.9$ |
|          | $\xi_1=1.5$ | $w_1=0.05$ |
|          | $\beta_2=8.75$ | $L_2=6.5$ |
|          | $\alpha_2=7$ | $D_2=\phi 5$ |
|          | $\alpha_3=30$ | $P_2=0.8$ |
|          | $\lambda_3=90$ | $H_2=\phi 4.2$ |
|          | $\varphi_3=0$ | $w_2=0.12$ |

where $\beta_1$, $\alpha_1$, $L_1$, $P_1$, $H_1$ are the parameters of apical part of implant DIO SFR5010 while $\beta_2$, $\alpha_2$, $\alpha_3$, $L_2$, $D_2$, $P_2$, $H_2$ the tail part of implant DIO SFR5010.

The insertion experiments, including the drilling process of implant sockets and the insertion process of implants, were conducted on the CNC machine (HAAS OM-2A, Haas Automation Inc., Oxnard, CA, USA) as shown in Figure 5. The parameters of drills, implants, and experiment setting were listed as Table 3. To minimize the coaxiality error between the implant and corresponding implant socket, there was no interruption between the drilling and insertion processes. The high accuracy dynamometer (Kistler9119AA2, Kistler Instruments Ltd.,
London, UK, sampling rate: 1200 Hz) was used to capture the thrust forces and insertion torques during the insertion process of implants.

![Figure 5](image)

**Figure 5**  Preparation of bone blocks: (a) bovine femur, (b) A-A cross-section, (c) the bone blocks used in experiments and the CT scan area.

### Table 3  Parameters of insertion experiments

| Drills and Implants types | Bone blocks No. | Diameter d (mm) | Insertion speed ω (rpm) | Feed rate v (mm/min) |
|---------------------------|-----------------|-----------------|------------------------|----------------------|
| IS TSD22F                 | A01~A02, B01~B02, C01~C02 | 2.2             | 1200                   | 10                   |
| IS TSD29F                 | A01~A02, B01~B02, C01~C02 | 2.9             | 1200                   | 10                   |
| IS TSD34F                 | A01~A02, B01~B02, C01~C02 | 3.4             | 1200                   | 10                   |
| IS TSD39F                 | A01~A02, B01~B02, C01~C02 | 3.9             | 1000                   | 10                   |
| IS TSD44F                 | A01~A02, B01~B02, C01~C02 | 4.4             | 800                    | 10                   |
| IS BIS4510                | A01, B01, C01      | 4.5             | 20                     | 16                   |
| IS BIS4510                | A01, B02, C02      | 4.5             | 30                     | 24                   |
| IS TSD22F                 | A03~A05, B03~B05, C03~C05 | 2.2             | 1200                   | 10                   |
| IS TSD29F                 | A03~A05, B03~B05, C03~C05 | 2.9             | 1200                   | 10                   |
| IS TSD34F                 | A03~A05, B03~B05, C03~C05 | 3.4             | 1200                   | 10                   |
| IS TSD39F                 | A03~A05, B03~B05, C03~C05 | 3.9             | 1000                   | 10                   |
| IS TSD44F                 | A03~A05, B03~B05, C03~C05 | 4.4             | 1000                   | 10                   |
| IS TSD49F                 | A03~A05, B03~B05, C03~C05 | 4.9             | 800                    | 10                   |
| IS BIS5010                | A03, B03, C03      | 5.0             | 20                     | 16                   |
| IS BIS5010                | A02, B02, C02      | 5.0             | 30                     | 24                   |
| ITI 044.210               | A06~A07, B06~B07, C06~C07 | 2.2             | 800                    | 10                   |
| ITI 044.214               | A06~A07, B06~B07, C06~C07 | 2.8             | 600                    | 10                   |
| ITI 044.250               | A06~A07, B06~B07, C06~C07 | 3.5             | 500                    | 10                   |
| ITI RN4110                | A06, B06, C06      | 4.1             | 12                     | 15                   |
| ITI RN4110                | A07, B07, C07      | 4.1             | 15                     | 18.75                |
| ITI 044.210               | A08~A10, B08~B10, C08~C10 | 2.2             | 800                    | 10                   |
| ITI 044.214               | A08~A10, B08~B10, C08~C10 | 2.8             | 600                    | 10                   |
| ITI 044.250               | A08~A10, B08~B10, C08~C10 | 3.5             | 500                    | 10                   |
| ITI 044.254               | A08~A10, B08~B10, C08~C10 | 4.2             | 400                    | 10                   |
| ITI RN4810                | A08, B08, C08      | 4.8             | 12                     | 15                   |
| ITI RN4810                | A09~A10, B09~B10, C09~C10 | 4.8             | 15                     | 18.75                |
| DIO DHI 2010SM            | A11~A12, B11~B12, C11~C12 | 2.0             | 1000                   | 10                   |
| DIO SDS 2710M             | A11~A12, B11~B12, C11~C12 | 3.5             | 1000                   | 10                   |
| DIO DTS 4110M             | A11~A12, B11~B12, C11~C12 | 4.0             | 1000                   | 10                   |
| DIO DTS 4510M             | A11~A12, B11~B12, C11~C12 | 4.4             | 1000                   | 10                   |
| DIO DTI 5010SM            | A11~A12, B11~B12, C11~C12 | 4.9             | 800                    | 10                   |
| DIO SFR5010               | A11~A12, B11~B12, C11~C12 | 5.0             | 15                     | 12                   |

### 3.3 Bone-quality coefficients

The results of thrust forces $F_{thc}$ and insertion torques of IS and ITI implants were presented as follows:
Figure 6 The insertion torques and thrust forces obtained by insertion experiments: (a)–(f) data of IS implants, (a) and (b), (c) and (d), (e) and (f) were insertion torques and thrust forces of 235–245 Hu, 345–355 Hu and 415–425 Hu, respectively; (g)–(l) data of ITI implants, (g) and (h), (i) and (j), (k) and (l) were insertion torques and thrust forces of 235–245 Hu, 345–355 Hu and 415–425 Hu, respectively.

The peak torque and thrust force were used to determine the bone-quality coefficients for thread-cutting and thread-forming processes. The obtained bone-quality coefficients were listed in Tables 4 and 5.

Table 4 Bone-quality coefficients for thread-cutting

| Group | $a_0$ | $a_1$ | $a_2$ | $a_3$ | $b_0$ | $b_1$ | $b_2$ | $b_3$ |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 1     | 14.5  | 0.16  | 0.44  | 0.03  | 12.9  | 0.01  | 0.17  | 0.00  |
|       | 610   | 62    | 29    | 32    | 085   | 76    | 46    | 33    |
| 2     | 16.6  | 0.36  | 0.77  | 0.06  | 13.2  | 0.01  | 0.17  | 0     |
|       | 887   | 97    | 43    | 62    | 065   | 91    | 68    | 0     |
| 3     | 58.1  | 4.80  | 8.18  | 0.86  | 52.8  | 4.43  | 7.29  | 0.79  |
|       | 214   | 69    | 65    | 13    | 202   | 48    | 09    | 47    |

It was observed that the bone-quality coefficients $a_0$–$a_3$, $b_0$–$b_3$, $c_0$–$c_3$ and $d_0$–$d_3$ were different in 3 group with CT value of 235–245, 345–355 and 415–425 Hu, which is the great explanation for the effects of bone quality.

3.4 Validation of mechanical model
Substituting obtained bone-quality coefficients into the established model, the predicted insertion torque and measured insertion torque were shown in Figure 7 and Table 6.

Figure 7 Insertion torques obtained by the mechanical model and experiments
Table 6  Comparison of averaged insertion torques from experiments and predictions

| Thread number | Group 1           |          | Group 2           |          | Group 3           |          |
|---------------|-------------------|----------|-------------------|----------|-------------------|----------|
|               | Measured (N·cm)   | Pred (N·cm) | Measured (N·cm)   | Pred (N·cm) | Measured (N·cm)   | Pred (N·cm) |
| 1             | 1.899             | 1.669    | 2.256             | 0.693    | 1.036             | 1.167    |
| 2             | 4.872             | 4.559    | 5.270             | 2.237    | 4.693             | 6.012    |
| 3             | 9.805             | 10.272   | 8.284             | 4.693    | 7.125             | 9.779    |
| 4             | 12.050            | 12.197   | 11.298            | 8.693    | 12.362            | 12.617   |
| 5             | 15.874            | 13.893   | 14.312            | 13.369   | 14.639            | 17.314   |
| 6             | 17.274            | 15.325   | 17.326            | 15.693   | 18.693            | 21.082   |
| 7             | 18.326            | 20.186   | 20.340            | 18.639   | 22.237            | 24.849   |
| 8             | 22.264            | 20.362   | 23.354            | 24.363   | 23.140            | 28.617   |
| 9             | 23.592            | 21.369   | 24.279            | 26.964   | 27.063            | 30.256   |
| 10            | 24.362            | 22.012   | 25.206            | 27.365   | 28.634            | 31.895   |
| 11            | 24.982            | 23.937   | 26.132            | 29.369   | 29.363            | 33.534   |
| 12            | 25.193            | 24.102   | 27.058            | 30.069   | 31.693            | 35.174   |
| error         | 7.4%              | 12.3%    | 0                 | 16.9%    | 10.9%             | 0        |

As shown in Figure 7, the variations of material properties of bone blocks brought a significant fluctuation of the initial insertion torques obtained by experiments. But the trends and predicted peak insertion torques by mechanical models agreed well with that acquired by insertion experiments. The relative errors were calculated as follows.

\[
\frac{T_{\text{pred}} - T_{\text{measured}}}{T_{\text{measured}}} \times 100\% \quad (30)
\]

4 Conclusions

In this present research, a mechanical model was established for predicting insertion torque of dental implant. The effect of bone quality, the surgical method and the implant geometry were explained by the model parameters: \( a \) bone-quality coefficients, \( b \) insertion speed, and \( c \) radial engagement \( h_i \), chip load \( A \) and implant diameter \( r_i \), respectively. The more specific conclusions can be drawn as follows:

1. The bone-quality coefficients were determined by bone CT value and different in implants with or without cutting edges. The reasonable explanation for this phenomenon may be the bone quality depended on not only bone density, i.e., bone CT value, but also the microstructure of trabecular bone.
2. The error of this mechanical model may result from the effects of local anisotropy of cancellous bone, which were ignored in the present research.
3. The established mechanical model can help clinicians to make accurate assessment whether the implants and surgical methods are reasonable for individual. Comparing to the fitting formula, this method could avoid plenty of experiments caused by changing implants and surgical method.

5 Declaration

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Availability of data and materials

The datasets supporting the conclusions of this article are included within the article.

Authors’ contributions

The authors’ contributions are as follows: Song Zhang was in charge of the whole trial; Luli Li wrote the manuscript; Luli Li, Quhao Li, Cuirong Bian, Airong Zhang assisted with
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Competing interests
The authors declare no competing interests.

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Figure 1

DIO SFR5010 and its insertion process: (a) the geometry of DIO SFR5010 and two coordinate systems, (b) geometric parameters of DIO SFR5010 and the insertion process: the initial position was in red and the position of one rotation cycle was in black, (c) the relationship of angle parameters $\gamma$, $\xi$ and $\lambda$. 
Figure 2
The oblique cutting process

Figure 3
A typical form tap tooth: (a) the schematic diagram of form tap tooth; (b) three views of ith tooth.
Figure 4

Preparation of bone blocks: (a) bovine femur, (b) A-A cross-section, (c) the bone blocks used in experiments and the CT scan area.

Figure 5

Preparation of bone blocks: (a) bovine femur, (b) A-A cross-section, (c) the bone blocks used in experiments and the CT scan area.
Figure 6

The insertion torques and thrust forces obtained by insertion experiments: (a)~(f) data of IS implants, (a) and (b), (c) and (d), (e) and (f) were insertion torques and thrust forces of 235~245Hu, 345~355 Hu and 415~425 Hu, respectively; (g)~(l) data of ITI implants, (g) and (h), (i) and (j), (k) and (l) were insertion torques and thrust forces of 235~245Hu, 345~355 Hu and 415~425 Hu, respectively.
Figure 7

Insertion torques obtained by the mechanical model and experiments