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The precision of drill calibration for dynamic navigation

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ABSTRACT

Objectives: To quantify the reproducibility of the drill calibration process in dynamic navigation guided placement of dental implants and to identify the human factors that could affect the precision of this process in order to improve the overall implant placement accuracy.

Methods: A set of six drills and four implants were calibrated by three operators following the standard calibration process of NaviDent® (ClaroNav Inc.). The reproducibility of the position of each tip of a drill or implant was calculated in relation to the pre-planned implants' entry and apex positions. Intra- and inter-operator reliabilities were reported. The effects of the drill length and shape on the reproducibility of the calibration process were also investigated. The outcome measures for reproducibility were expressed in terms of variability range, average and maximum deviations from the mean distance.

Results: A satisfactory inter-rater reproducibility was noted. The precision of the calibration of the tip position in terms of variability range was between 0.3 and 3.7 mm. We noted a tendency towards a higher precision of the calibration process with longer drills. More calibration errors were observed when calibrating long zygomatic implants with non-locking adapters than with pointed drills. Flexible long-pointed drills had low calibration precision that was comparable to the non-flexible short-pointed drills.

Conclusion: The clinicians should be aware of the calibration error associated with the dynamic navigation placement of dental and zygomatic implants. This should be taken in consideration especially for long implants, short drills, and long drills that have some degree of flexibility.

Clinical significance: Dynamic navigation procedures are associated with an inherent drill calibration error. The manual stability during the calibration process is crucial in minimising this error. In addition, the clinician must never ignore the prescribed accuracy checking procedures after each calibration process.

1. Introduction

Dynamic surgical navigation is one of the computer-guided approaches used to guide the positioning of dental implants [1,2]. In comparison with static surgical guides, it offers the advantages of surgical flexibility and facilitates dental implant placement in situations of restricted mouth opening and/or limited horizontal space [3,4]. It is also more convenient when flapless zygomatic implant placement is required [5–7]. Recently published meta-analyses have shown that its accuracy is comparable to that of the static guided approach [8–10], and could be even higher in relation to angular deviations [1]. A randomised controlled trial by Afrashtehfar demonstrated that both of these guided approaches had similar levels of patient satisfaction and patient reported outcomes as the free-hand approach when it comes to short dental

Abbreviations: TM, Transformation matrix; d, Distance between the pre- and post- transformed point coordinates; AvDevM, Average deviation from mean; MaxDevM, Maximum deviation from mean; SD, Standard deviation from mean; CBCT, Cone beam computed tomography; CSV, Comma Separated Values; ICC, Inter class correlation coefficient; ALtA, Anterior left apex point; ALtC, Anterior left collar point; ARtA, Anterior right apex point; ARtC, Anterior right collar point; PLtA, Posterior left apex point; PLtC, Posterior left collar point; PRtA, Posterior right apex point; PRtC, Posterior right collar point.

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implants with a two-week follow-up period [11]. The literature has highlighted the steep learning curve for the routine use of dynamic navigation for placement of dental implants [4,12]. Included in this procedure is the calibration process to record and transfer the accurate spatial relationship between the optical pattern (the handpiece tracker) and the cutting tip of the drill or implant being used to the navigation software [13–15]. Technical errors or system malfunctions can occur during the calibration process which impact on the accuracy of the real-time tracking of the drills and implants [16–18]. Another source of error in dynamic navigation procedures is the registration process for mapping of the patient skull anatomy to the pre-planned position of the dental implant [13,19–21]. The accuracy of the calibration, registration, and tracking processes are essential to establish the spatial relationship between the drills and the jaw bones via the reference devices. It is then essential for the operator to monitor this spatial relationship in real-time to guide the placement of the implants in relation to the virtual plan on the CBCT during the surgical procedure [14,15,22].

The three main operator-related sources of error associated with the use of dynamic navigation include inaccuracies in the instrument calibration, inaccuracies in the jaw registration, in addition to application errors [13,23]. These cumulative errors impact on the overall accuracy of the dynamic navigation procedure [13,21]. In the current literature, the final implant placement accuracy is often used to show the effect of variation in each of these three sources of error [24,25]. Current dynamic navigation systems allow a calibration accuracy check which is dependent on the previous registration step [14,15]. Therefore, it is impossible for the clinician to check the magnitude of error resulting solely from the calibration process without quantifying the registration errors concealed within the navigation software [14,15].

The calibration process of the drills or implants records the relationship of their tips and long axes in relation to the mathematical centre “centroid” of the handpiece tracker and generates a 4 × 4 rigid transformation matrix (TM). The rigid transformation matrix or what is also known as “the Homogenous Transform” is a common way of representing the spatial relationship between two objects in three dimensions [26]. It includes the rotation angles along the x, y, and z axes of the calibrated object in addition to the translation vector, scale vector, and global scale. When the TM is termed "rigid", this implies that there is no

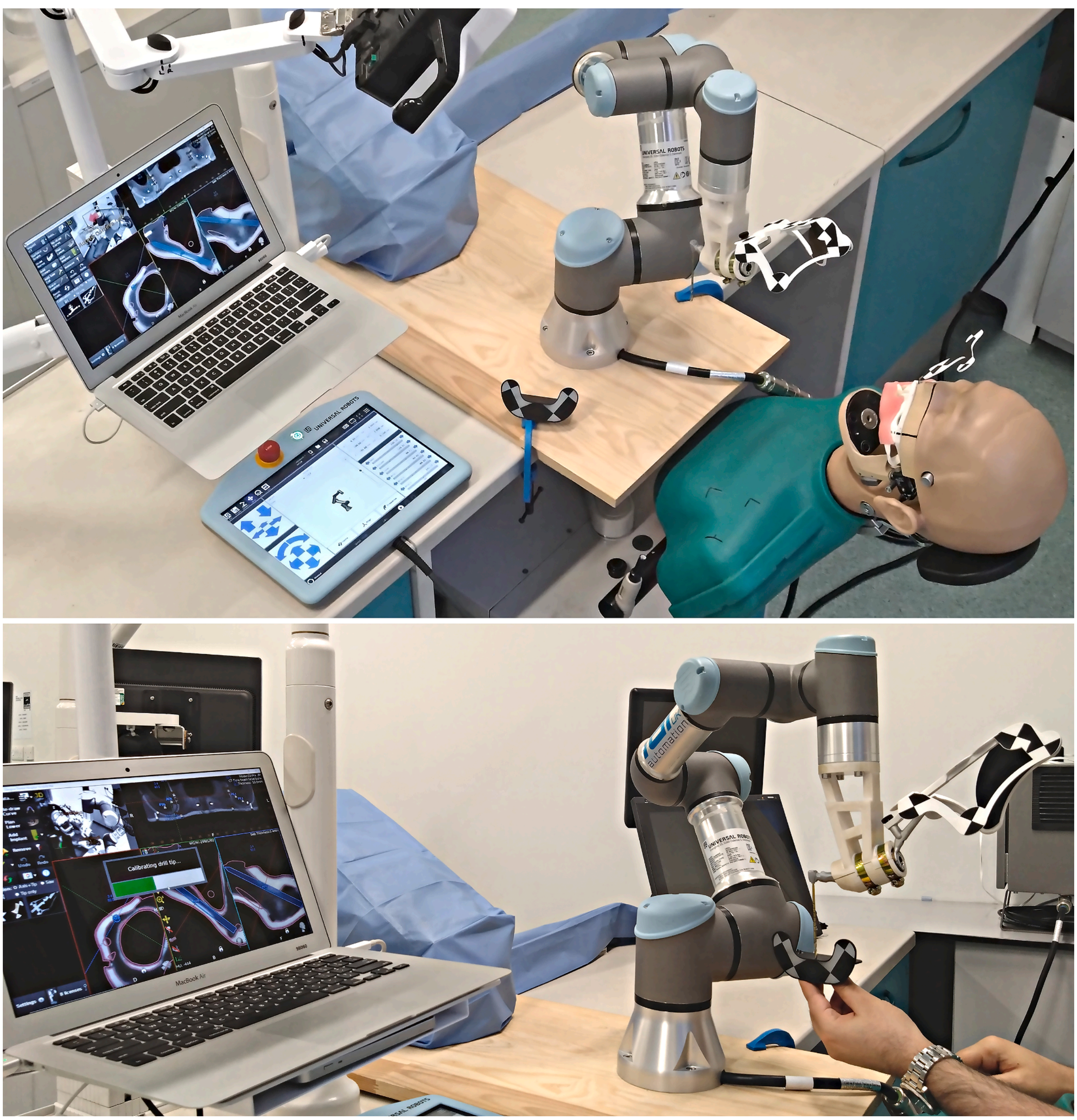

Fig. 1. Photographs showing the experimental set-up for the assessment of drill calibration reproducibility. The robotic arm here only serves to fix the spatial relationship of the handpiece tracker and the jaw tracker in relation to the tracking camera through the entire experiment.

scaling to be applied to the unit of measurement in that space [27,28].

It is therefore possible to record this TM after each calibration process for the same drill to quantify the reproducibility of this procedure and the precision of the drill tip position in 3-dimensional space independent of any other confounding factors [26].

The main aim of the study was the independent assessment of the reproducibility of the calibration process for various zygomatic implants and implant drills. The word "independent" denotes that the resulting outcome measures from this assessment must be isolated from all other sources of error implicated in dynamic navigation procedures. The null hypotheses were: (1): No difference in the calibration precision between the bone-cutting drills and implants. (2): The addition of drill extensions does not impact on the calibration precision.

2. Materials and methods

2.1. Study materials

This in vitro investigation was carried out using a dynamic navigation system (NaviDent®; ClaroNav Inc., Toronto, Canada). The trackers were the standard single use ones (handpiece tracker 0C482 and jaw tracker type S) in conjunction with the standard drill calibrator tool (Fig. 1).

We tested two drills (the long spade and the zygomatic twist) of the zygomatic drilling set (Southern Implants®, Irene, RSA) and the short spade drill of the NobelReplace® kit (Nobel Biocare®, Zurich, Switzerland). We also assessed the calibration precision of a 6 mm diameter trephine drill of a commercial trephine kit. The tested implants were ZYGAN implants (Southern Implants®, Irene, RSA) (Fig. 2).

To minimise machine-related variations arising from the location of the tracking camera, a robotic arm (UR3e; Universal Robots®, Odense, Denmark) with a custom-printed connection was used to maintain a fixed spatial relationship between the implant handpiece (contra-angle WS-75; W&H®, Bürmoos, Austria) and the tracking camera through the entire experiment. The connecting part was printed using a Rigid 10 K resin and a FormLabs 3D printer (Form 3B; FormLabs®, Somerville, USA) (Fig. 2).

Fig. 2. A photograph of the four drills, four implants and their connections used in the study. SpShort = short spade drill; SpLong = long spade drill; Implant35 = Zygomatic implant 35 mm long; Implant40 = Zygomatic implant 40 mm long; Implant45 = Zygomatic implant 45 mm long; Implant50 = zygomatic implant 50 mm long; Trephine = trephine drill; TwLong = zygomatic twist drill (2.9Φ); +Ext = with added drill extension.

2.2. Variables and outcome measures

To simplify the assessment of drill calibration precision, it was necessary to identify an outcome measure that is unaffected by any other source of errors. Therefore, frequently utilised parameters like implant final deviations were avoided [13,25].

Fig. 3 illustrates the concept of transforming a certain point between two frames of reference [26]. The distance between the pre- and post-transformed point coordinates (marked as "d" in Fig. 3) is calculated after every drill calibration process. The magnitude of this distance is of no relevance, but the reproducibility of obtaining the same magnitude with repeated calibrations is an indication of the level of calibration precision associated with each drill or implant. It is directly related to the overall reproducibility of the transformation matrix of each drill calibration process. This is a simplification of dealing with 16 numbers of every 4 × 4 transformation matrix resulting from each calibration process.

Therefore, the outcome measures in this study were:

(1) Variability range (Var. range): This represents the difference between the maximum and minimum values of "d" associated with the calibration of each drill or implant. The range is affected by both machine- and human- related factors.
(2) Average deviation from mean (AvDevM): The mean value of "d" was determined first, followed by the calculation of the average of absolute deviations from that mean. It reflects the average contribution of human variations to the overall calibration precision.
(3) Maximum deviation from mean (MaxDevM): The mean value "d" was measured first, then the maximum value of absolute deviation from that mean was calculated. It reflects the maximum contribution of human variations to the overall precision of the calibration process.

2.3. Sample size calculation

Based on a previous pilot study performed by one operator with 2 drills (the long spade drill and the zygomatic twist drill), an effect size of 0.48 was calculated from the variability ranges of 0.516 ± 0.14 mm and 0.447 ± 0.145 mm (variability range ± SD) using G*Power software v. 3.1.9.7. Incorporating this effect size to calculate the required sample size for 10 groups (assuming normal distribution, alpha was set at <0.05 and sample power set at 0.8), a total sample size of 80 was obtained (8 per group). We decided to set the sample size at 9 calibrations per drill per operator to account for further variations due to operator factors. Three operators carried out the calibration processes. Each operator received basic training to ensure standardisation of the calibration protocol prior to commencing the experiment.

2.4. Virtual planning stage

Four zygomatic implants were virtually planned on the model CBCT scan of an edentulous maxilla (ZYG NM01; SelModels®, Barcelona, Spain) using NaviDent® software (v.3.0.3); two anterior implants 50 mm long (one on each side) and two posterior implants (one 40 mm long on the right side and the other 35 mm long on the left side). The planning was performed according to the anatomical radiographic features of the zygomatic and maxillary bones derived from the CBCT scan [29–31].

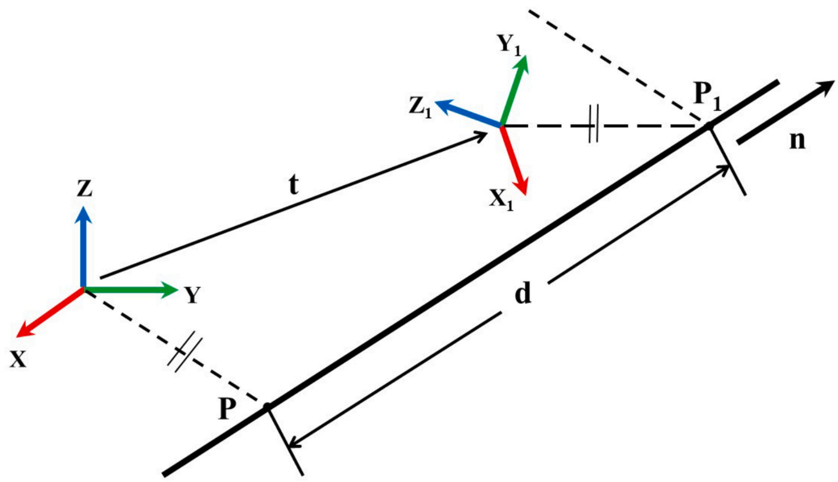

Fig. 3. An illustration of the transformation of a point coordinate frame. t = the transformation movement between the two reference frames; XYZ represent the original frame; $X_1Y_1Z_1$ represents the new frame; P = the original point pre-transformation; P_1 = the transformed point. d = the distance between the pre- and post-transformed points. n = the direction vector of point P transformation (this figure was adapted from Walker et al. [26]).

2.5. Registration and calibration stages

Six fiducial screws distributed in the anterior maxilla and both tuberosity areas were used for the registration process [13], which was performed one time only. This was followed by the calibration of the handpiece drill axis (also one time) and then the drill length was calibrated multiple times according to the manufacturer instructions, which the clinicians would follow in clinical scenarios involving "stepwise drilling process" [14]. Based on a sample size calculation relying on results derived from an earlier pilot experiment, the length calibration step was repeated 27 times (9 repetitions for each of the three operators) to assess the reproducibility and identify the margin of error associated with this process.

2.6. Data collection

NaviDent® modified the software version 3.0.3 for us to provide the required transformation matrices resulting from the calibration in the form of Comma Separated Values (CSV) files. These files also included the x, y, z coordinates of the collar (entry) and apex points for each planned implant (i.e., 8 points of the 4 planned implants) in relation the external frame of reference of the jaw tracker [32].

After a basic calibration training session, six drill variations and four implant variations (see Fig. 2) were calibrated 9 times by each of the three operators using the same 3D positional relationship between the trackers and camera. All operators had a previous experience in oral surgery (ranging from 2 to 5 years). Their ages ranged from 30 to 36 years.

Utilising the video screen capture feature in the NaviDent® software, the generated time-stamped CSV files were synchronised (i.e., matched) to the specific calibration instance executed and repeated by each operator.

The position of the dynamic navigation camera was maintained throughout the procedure, the handpiece position was firmly connected to the stationary robotic arm, and the jaw position was fixed in the dental simulator. The CSV files produced during the process were used for the analysis. This resulted in 9 CSV files per drill per operator providing 9 different TMs of every drill tip.

The reproducibility of the calibration TM was measured via the calculation of the distance between pre- and post-transformed points according to the following equation:

$$\text{Distance}_1 = \sqrt{(X_1 - X)^2 + (Y_1 - Y)^2 + (Z_1 - Z)^2}$$

where:

X,Y,Z represents point coordinates on the plan pre-transformation.

X_1,Y_1,Z_1 represents the point coordinates on the plan after transformation.

Distance_1 is the calculated distance for the 1st calibration process out of 27 per drill.

The results of these calculations were 9 distances per drill per operator for each of the entry and apex points of the 4 implants (8 points in the virtual plan).

The main outcome parameters were the range of variability in the calculated 3D distance (maximum distance minus minimum distance) and the absolute deviations from the mean value of that distance (assuming that this mean value represents the true drill tip or implant tip position).

2.7. Statistical analysis

SPSS statistics (IBM SPSS, v.26) was used for statistical analysis. For each subset of data, distribution normality testing was carried out using the Shapiro-Wilk normality test. Intra- and inter-operator reliability in each calibration group was reported in terms of intra-class correlation coefficient [33]. Intra-operator reliability statistics were based on the 9 values per point (72 deviation values from 8 different means) per operator per drill. Inter-operator reliability statistics were based on the median values of both the deviations from the means as well as the variability ranges. Correlation analysis was also performed with SPSS statistics software. GraphPad (Prism, v.9) was used to create the graphical representations.

3. Results

3.1. Descriptive statistics and normality testing

Shapiro-Wilk normality testing revealed normal distribution of the variability range and deviations from mean data from the 8 points on the plan per operator for each drill ($n = 8$). However, upon grouping all the values from drill calibrations of all the 3 operators, the variability of the data did not follow the normal distribution.

The outcome data derived from all of the three operators is shown in Table 1.

Table 1
Summary outcome data derived from drill calibration processes performed by all operators. med. = median; Op. = operator; Var. = variability; AvDevM = average deviation from mean; MaxDevM = maximum deviation from mean; Tr.+Ext = trephine drill with drill extension; SpSh. = short spade drill; SpSh.+Ext = short spade drill with drill extension; SpL. = long spade drill; SpL.+Ext = long spade drill with drill extension; TwL. = long twist drill; Im50 = 50 mm long implant; Im35+Ext = 35 mm long implant with drill extension; Im40+Ext = 40 mm long implant with drill extension; Im45+Ext = 45 mm long implant with drill extension.

Outcome (mm)	Tr.+Ext	SpSh.	SpSh.+Ext	SpL.	SpL.+Ext	TwL.	Im50	Im35+Ext	Im40+Ext	Im45+Ext
All Op. Var. range (mean of 8 points)	1.620	1.758	0.875	0.695	0.830	0.915	2.776	2.740	2.246	2.223
All Op. AvDevM (mean of 8 points)	0.310	0.228	0.231	0.118	0.171	0.211	0.561	0.576	0.525	0.468
All Op. MaxDevM	1.894	2.255	0.767	0.670	0.494	0.635	2.066	2.080	1.592	1.612
Op.1 Var. range (med. of 8 points)	0.637	0.217	0.180	0.388	0.346	0.605	1.489	1.296	1.511	0.959
Op.1 AvDevM (med. of 8 points)	0.253	0.111	0.083	0.070	0.071	0.107	0.343	0.721	0.799	0.340
Op.1 MaxDevM	0.868	0.363	0.276	0.383	0.486	0.413	1.700	2.080	1.592	0.793
Op.2 Var. range (med. of 8 points)	1.440	1.744	0.567	0.612	0.444	0.422	1.966	1.705	1.073	1.949
Op.2 AvDevM (med. of 8 points)	0.465	0.321	0.364	0.117	0.094	0.138	0.675	0.433	0.745	0.697
Op.2 MaxDevM	1.894	2.255	0.767	0.670	0.494	0.553	2.066	1.628	1.519	1.612
Op.3 Var. range (med. of 8 points)	0.528	0.156	0.194	0.321	0.316	0.445	1.078	1.139	1.090	1.144
Op.3 AvDevM (med. of 8 points)	0.142	0.088	0.283	0.075	0.190	0.258	0.389	0.284	0.226	0.387
Op.3 MaxDevM	0.687	0.313	0.493	0.363	0.463	0.635	0.931	1.477	0.839	1.241

3.2. Reliability of the calibration method

The results of intra- and inter-operator reliability for the average of absolute deviations from the mean measurements are presented in Table 2. There was a good inter-operator reliability in relation to variability range (ICC 0.755; $p < 0.0005$) and moderate reliabilities in relation to maximum deviations from means (ICC 0.665; $p = 0.007$) and average deviations from mean (ICC 0.711; $p = 0.006$). The intra-operator reliability values ranged from good to excellent ($p < 0.0005$).

3.3. The precision of the calibration process in relation to the measured variability range

Fig. 4 shows the overall calibration reproducibility (attributed to machine and human sources). The apices of the planned left side zygomatic implants (points ALtA and PLtA) showed markedly higher variability. Also, with the exception of the short spade drill, all pointed drills variability ranges were < 1.0 mm, while all implants variability ranges were > 2.0 mm.

3.4. Deviations from mean representing human calibration reproducibility

The data related to the human contribution to calibration precision are shown in Fig. 5. The 50 mm long zygomatic implant as well as the 35 mm long implant with added extensions showed maximum deviations > 2.0 mm. The unexpectedly high maximum deviation of the short spade drill could be an outlier value as it does not follow the same pattern of the average deviations line.

3.5. Relationship to drill length and shape

The results of the Pearson's correlation analysis in relation to variability range, maximum deviation from mean and average deviation from mean demonstrated no significant correlation except the strong correlation between the implant length and the reproducibility in terms of average deviations from the mean ($p < 0.05$). These are presented in Table 3.

Fig. 6 shows the negative linear trends of the three tested reproducibility parameters against the implant length as well as the pointed drill length. In other words, the longer the drill, the less is the error. Therefore, the longer the drill the higher is the precision.

Table 2
Intra- and inter-rater reliability in terms of inter class correlation coefficient (ICC) of the average of absolute deviations from the mean measurements (average from the 8 points).

Deviations from mean ICC within each operator (9 readings/ operator)			ICC between all operators
Operator.1 (M.A.1)	Operator.2 (M.A.2)	Operator.3 (C.L.)	
0.931	0.796	0.758	0.711

4. Discussion

Dynamic navigation systems offer an alternative to surgical guides for implant placement with clinically acceptable outcomes [6,7,10]. As with all other guiding techniques, they have inherent sources of positional errors which may detrimentally affect the final results [13,23], particularly if the total error exceeds the 2 mm safety margin [34].

Accurate calibration to record the relationship between the drill and the centroid of the handpiece tracker is directly dependant on the degree of the operator's precision (human factor) [14]. It may also depend, to a less extent, on the factors affecting the machine capture of this mathematic spatial relationship as well as the integrity of the handpiece-drill griping mechanism. The accuracy of the machine capture depends on the surrounding light conditions, the quality of the tracking camera, and the calibration algorithm [35].

With all dental navigation systems, clinicians perform drill calibration in two steps; initial drill axis calibration and subsequent drill length calibration. The length calibration step is readopted with each drill used for bone cutting and for placement of the implants [14,15,36]. In NaviDent®, the drill length calibration step also applies a minor correction to the initially recorded axis to compensate for the play in the chuck of the handpiece [14].

Having performed a jaw registration process, the clinicians are subsequently required to check the accuracy of drill calibration depending on that registration [14,15,25,36]. Therefore, the only way for the operator to check the calibration accuracy separately (from registration accuracy) is to have access to the internally generated data by the tracking equipment. NaviDent® provided our research team with a modified software version in which this data can be exported as time-stamped CSV files. This has enabled the authors to assess the reproducibility of the drill calibration process independently. However, to be able to objectively quantify the magnitude of error arising from this source, one would require a gold standard measurement (e.g., with a laser tracker) to be used as a yardstick for comparison which was not technically possible in this study [37,38]. As an available simple alternative, we calculated the reproducibility variables of the repeated calibration process as references to assess the relative precision of this procedure [39,40].

We fixed the spatial relationship between the trackers and the camera in a rigid manner according to the recommended optimal distance (about 50 cm) to minimise the effect of machine factors on the calibration process [14]. Subsequently, the operator held the calibrator tool against the drill tip using the non-dominant hand to simulate the clinical scenario [14].

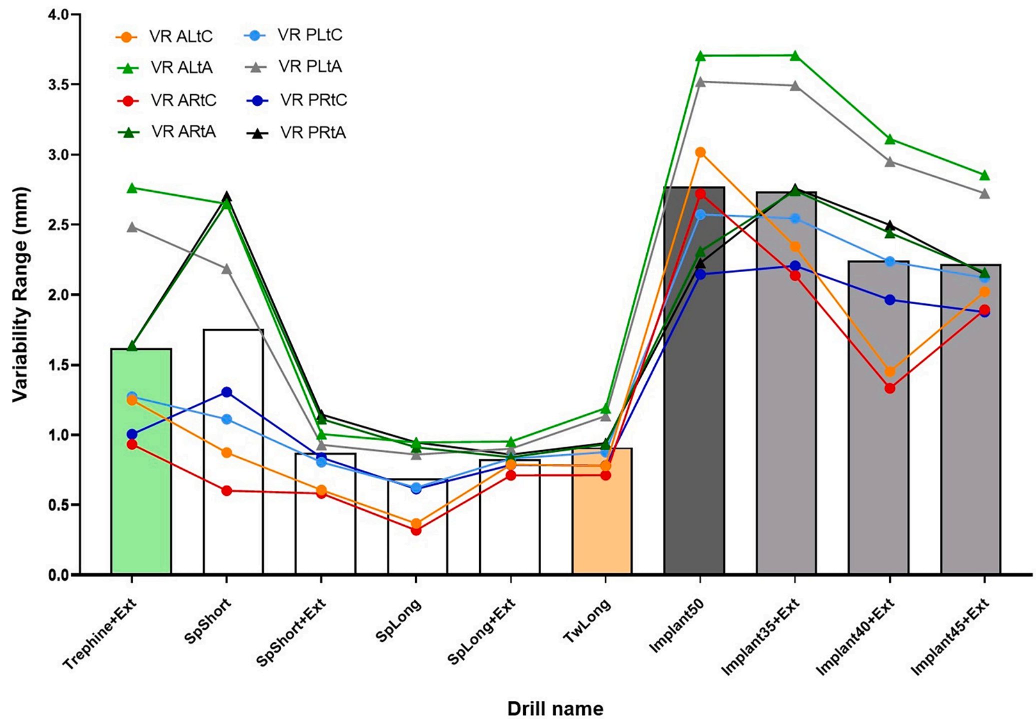

Fig. 4. A combined line and bar graph showing the variability range of the 27 readings for each drill. Each line represents different point coordinates that were used for testing the reproducibility of the transformation matrix. Each bar represents the average of variability ranges from the 8 points. Trephine = trephine drill; SpShort = short spade drill; SpLong = long spade drill; TwLong = zygomatic twist drill (2.9Φ); Implant35 = zygomatic implant 35 mm long; +Ext = with added drill extension; VR = variability range; ALtC = anterior left implant collar point; PRtA = posterior right implant apex point.

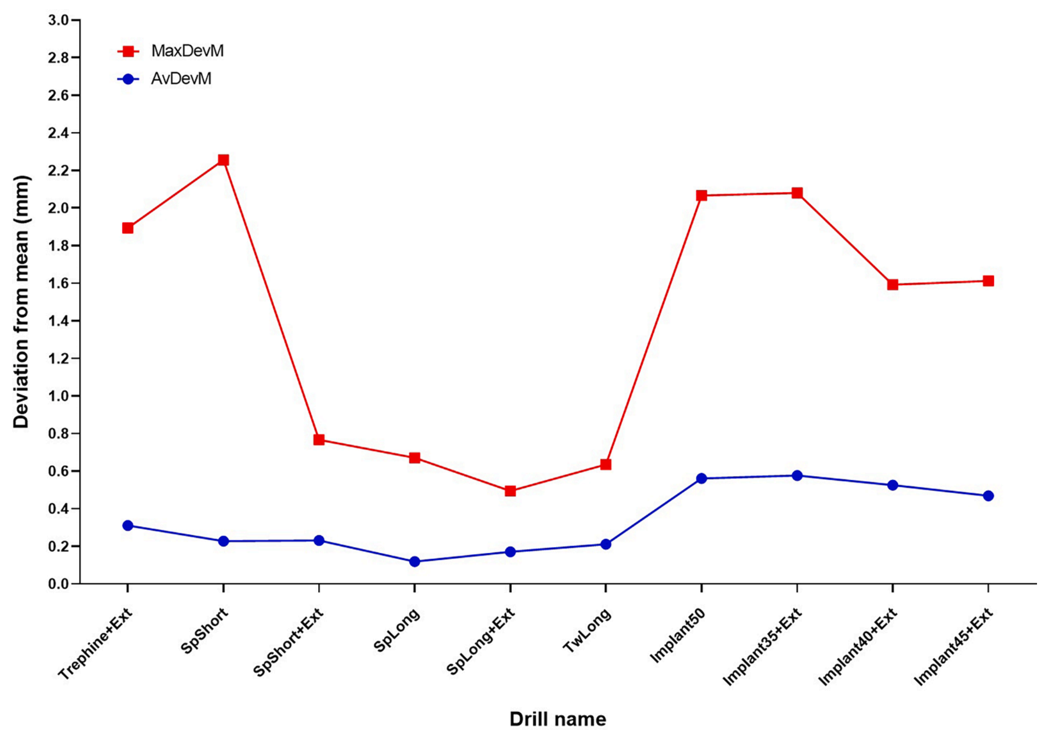

Fig. 5. A line graph showing the deviations from mean obtained from the 27 readings for each drill. MaxDevM = Maximum deviation from mean; AvDevM = Average deviation from mean (average from 27 readings per point then mean of the 8 points). Trephine = trephine drill; SpShort = short spade drill; SpLong = long spade drill; TwLong = zygomatic twist drill (2.9Φ); Implant35 = zygomatic implant 35 mm long; +Ext = with added drill extension.

The mean of the calculated distances derived from the TMs of the repeated calibrations of each specific drill has no meaningful value in itself. However, the absolute deviations from the mean distances were interpreted as the human error in the reproducibility of the calibration process.

The good intra- and inter-operator reproducibility support the

Table 3
Correlation coefficients to test the presence of linear correlation between the drill or implant length and the resulting reproducibility parameter. The tests included the five pointed drill variations and the four implant variations. MaxDevM = Maximum deviation from mean; AvDevM = Average deviation from mean.

Drill Type	Variability Range		MaxDevM		AvDevM	
	Coefficient	P value	Coefficient	P value	Coefficient	P value
Pointed drill	−0.608491	0.276143	−0.734819	0.157242	−0.214022	0.729593
Implant	−0.919357	0.080643	−0.892595	0.107405	−0.986725	**0.013275**

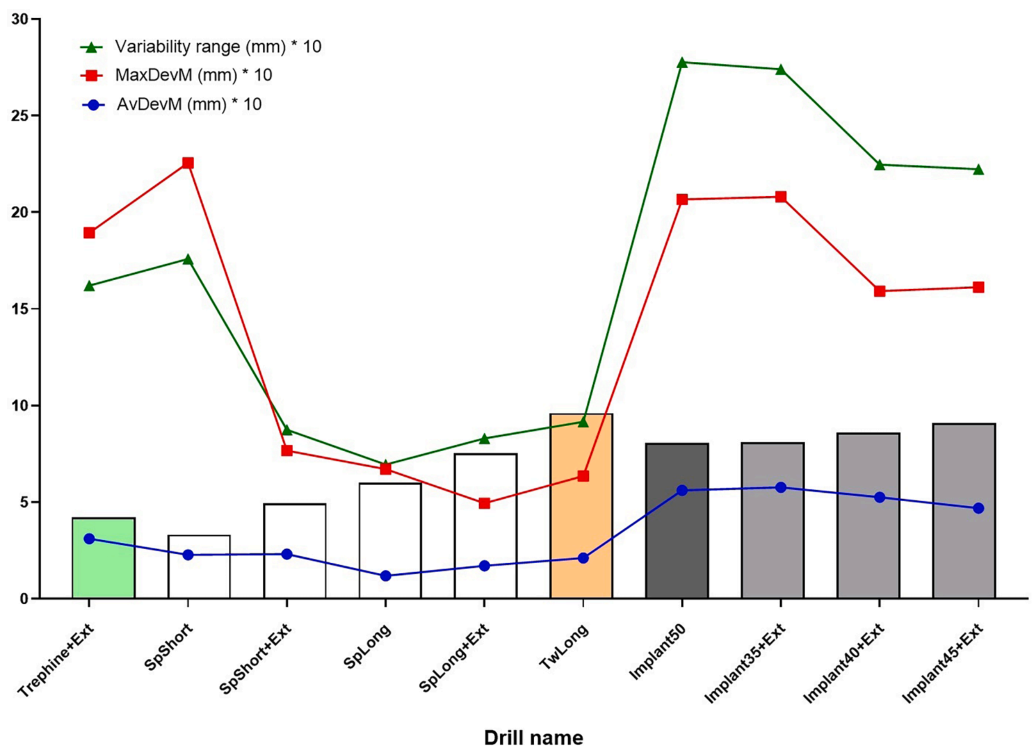

Fig. 6. A combined line and bar graph depicting the association between drill or implant length (in cm) (the height of each bar) and the 3 reproducibility parameters (the 3 parameters were scaled to match the length bars). AvDevM = Average deviation from mean; MaxDevM = Maximum deviation from mean; Trephine = trephine drill; SpShort = short spade drill; SpLong = long spade drill; TwLong = zygomatic twist drill (2.9Φ); Implant35 = zygomatic implant 35 mm long; +Ext = with added drill extension.

stability of the tracking system and the adequate training of the three operators in performing this step. However, the wide range of the reproducibility (from good to excellent) can be explained by the difference in the level of experience in performing this step specifically. The results of two operators showed good intra-operator reproducibility. The results of the 3rd operator (operator.1) showed excellent reproducibility due to his long experience in using dynamic navigation.

The variations observed with the calibration of the same drill or implant group are attributed to mathematical error during the application of the transformation matrix to the coordinates of the points. These wide ranges of variability also highlight the importance of the accuracy checking process after calibration and prior to commencing the surgical procedure [36].

In contrary to the good level of inter-operator reliability associated with the variability range, the moderate level of reliability observed in the magnitude and pattern of deviations from the mean values supports that this latter outcome measure is more related to the human contribution rather than any other confounding factors. The degree of precision and focus in placing the tip in its accurate position on the calibrator tool could well be different for another operator performing the same repetitive procedure. This is also supported by the migration from the normal distribution when the outcome measures from all 3 operators were combined, as opposed to looking at the same outcome measures for each operator separately. The same reasoning could explain the high outlier value of the short spade drill with operator no.2., as it was the first drill to be calibrated after the training session. The drill might have been loose inside the handpiece or the tip of the drill might have not been stable inside the designated calibration point on the calibrator tool.

Increasing the length of the drill or implant can improve the reproducibility of the calibration transformation matrix. This could be due to the rotation component of the matrix, as longer drills have more chance of reproducing the same rotational transformation relationship between the two frames of reference. In addition, the capture of the calibration spatial relationship is more accurate if recorded over longer distances. The flat tips of the implants and their susceptibility to “wobble” due to their loose non-locking connection within the implant adapter produced larger error ranges and deviations from the mean values.

In summary, calibration reproducibility error is small in average (< 0.6 mm). However, its maximum value could exceed the 2 mm safety margin that is usually included in the implant planning process. It could thus be implicated in causing damage to the vital structures surrounding the apex of a drill and/or implant. The secure connection of a drill extension does not seem to compromise the calibration process. However, non-locking implant adapters present serious calibration accuracy issues. Increasing the length of the drill or implant (as long as it remains relatively non-flexible) appear to enhance the reproducibility of the calibration transformation matrix.

Future studies may include wider variations of drills and implants to detect statistically significant linear correlation with the drill length and shape.

The main limitation of this study is the lack of a gold standard yardstick to locate the true drill tip position to identify the accuracy of the calibration rather than just its precision [39]. It was difficult to compare our results with previously published studies as none of them had assessed the precision or accuracy of the calibration step on its own, they all measured the deviations in implant placement which combines application error, registration error as well as the tracking errors of the dynamic navigation system [23,25].

5. Conclusions

The positional variation arising from the drill calibration step is expected to be small in general (< 0.6 mm), but it could be up to 3.7 mm. Therefore, we emphasise the importance of the following standard accuracy checks as described by the manufacturer.

The precision of calibration is affected by the shape of the drill tip (i.e., whether it is pointed or flat) and whether the drill is composed of loosely connected pieces or not. Therefore, the operator needs to carefully perform this step especially for long implants and short drills that don't have sharp tips. Hand stability during calibration capture by the optical camera has a crucial effect on minimising this source of error. Consistently unacceptable results of the standard accuracy checks could be related to insufficient operator training or disfunction of the handpiece chuck that necessitates maintenance or replacement.

CRediT authorship contribution statement

Mohammed Y. Al-Jarsha: Conceptualization, Data curation, Writing – original draft, Writing – review & editing. **Ashraf F. Ayoub:** Conceptualization, Supervision, Writing – original draft, Writing – review & editing. **Mohammed M. Almgran:** Data curation, Formal analysis, Writing – original draft. **Chieh-Han Liu:** Conceptualization, Data curation. **Douglas P. Robertson:** Conceptualization, Writing – original draft, Writing – review & editing. **Kurt B. Naudi:** Conceptualization, Supervision, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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