

Dependency of dental implants' primary stability on rotational speed of insertion: In-vitro investigations in synthetic and natural bone

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Abstract

Primary stability, which is a prerequisite for osseointegration, depends on bone quality, implant macro-geometry, and surgical technique. If and how insertion rotational (IR) speed affects primary stability remains unclear. Thus, the aim of this study was to examine if and how IR speed affects primary stability of dental implants inserted in a synthetic (PU-foam) and natural bone (bovine rib). Sixty identical implants were inserted in an identical manner, using computer numerical control (CNC) to eliminate human-related variability, into PU-foam and bovine rib bone at insertion rotational speeds of 5, 25, or 50 rpm (10 implants per speed per substrate). Primary stability was assessed via maximum insertion torque (MIT), insertion energy (IE), implant stability quotient (ISQ), and push-in test parameters (stiffness, ultimate load, push-in energy). No significant effect of IR speed on push-in stiffness was detected in either substrate (PU-foam, $p = 0.078$; natural bone, $p = 0.121$). ISQ increased significantly from 5 to 25 and 5 to 50 rpm in PU-foam but only from 5 to 25 rpm in natural bone. Push-in energy (PIE) increased significantly from 5 to 25 and 5 to 50 rpm in both substrates, with no significant change from 25 to 50 rpm. Push-in ultimate load showed significant increases from 5 to 25 and 5 to 50 rpm in PU-foam, and from 5 to 50 rpm in natural bone. In PU-foam, MIT showed a dependence on IR speed, but no pairwise comparison was significant. IE increased significantly from 5 to 25 and from 5 to 50 rpm ($p = 0.019$ and $p = 0.023$, respectively), but did not change significantly from 25 to 50 rpm ($p = 0.457$). In natural bone, MIT and IE did not exhibit a significant dependence on IR speed ($p = 0.246$ and $p = 0.949$, respectively). Increasing IR speed from 5 to 25 rpm improved several stability indicators, particularly ISQ and push-in energy in both substrates. However, a further increase of IR speed did not significantly improve stability indicators. No significant effect of IR speed on the elastic stiffness of the implant-substrate construct was detected in the push-in test. MIT and IE showed a significant overall dependence on IR speed in PU-foam but not in natural bone, a difference between substrates that was not formally tested.

Introduction

Nowadays, dental implants are a routine method for the treatment of missing teeth [1], and their long-term success is dependent on their ability to maintain stability under functional loading conditions. Long-term stability is achieved through a structural integration of the fixture with the surrounding bone, a process called osseointegration [2]. Osseointegration is a biological process which takes time to be established; however, before osseointegration could occur, a dental implant must be securely anchored in the surrounding bone in a purely mechanical manner, known as primary stability. Adequate primary stability limits the amount of micromotion during this critical period and promotes osseointegration [2, 3].

Primary stability is a multifactorial outcome, as it depends on bone quality and quantity [4], implant macrogeometry (shape, diameter, length, thread profile, among others) [5], and surgical technique [6]. No single measurement captures all of these contributions: maximum insertion torque (MIT) reflects the resistance encountered during insertion, the implant stability quotient (ISQ) reflects the resonance behavior of the implant–bone construct, and destructive tests such as the push-in and pull-out tests reflect the mechanical strength of the interface [7, 8]. The aforementioned assessment methods for primary stability are complementary, and their combined use is required for a comprehensive evaluation of primary stability [9].

To study the effects of individual factors on implant primary stability, it is necessary to control other parameters on which primary stability depends. Natural bone exhibits variability in both quality and quantity, which makes isolating the effect of surgical technique or implant macro-geometry on primary stability require prohibitively large sample sizes. Additionally, ethical issues and the difficulty of obtaining and handling human bone samples have led researchers to use other substitutes, like rigid polyurethane foam (PU-foam) and animal bone [10, 11]. Mechanical tests and imaging techniques, typically computed tomography (CT), are utilized to ensure that mechanical properties and bone quality are in the range of human bone [9, 12].

PU-foam can be manufactured with controllable and reproducible material properties and is considerably more homogeneous than natural bone. These qualities eliminate the inherent variation introduced by natural bone samples, which are nonhomogeneous and anisotropic, and substantially reduce the sample sizes required to draw definitive conclusions. Additionally, there are well-established standards, such as ASTM D1621 (test of compressive properties) and ASTM D1623 (test of tensile properties), for testing mechanical properties of PU-foam [13, 14]. While these characteristics help simplify the research and experimentation process, they mean that PU-foam cannot completely replicate mechanical properties of natural bone. On top of that, PU-foam lacks the trabecular structure of natural bone [15]. These limitations underscore the necessity of validation with natural bone when using PU-foam as a bone substitute. Bovine rib is one of the most used animal bone substitutes for the human jaw in dental implant research, due to its bone quality as well as cortical and trabecular distribution similar to that of human jaw bone [11, 16, 17].

The dental implantation process involves drilling and insertion steps. Most studies on the surgical technique have examined the heat-induced biological damage to the surrounding bone and stability alterations caused by the drilling parameters [18, 19], while the insertion process itself is mostly left to the experience of the surgeon [20]. Implantation could be performed manually by a ratchet, with a motorized device, or a combination of manual and motorized insertion [21]. Studies suggest better accuracy and improved primary stability for using motorized insertion in conjunction with manual insertion [21, 22]. Additionally, lower heat production is reported for motorized insertion [23]. In motorized insertion, the implant is rotated at a constant rotational speed until it is fully fixed. Whether the insertion rotational (IR) speed itself affects primary stability is not yet thoroughly investigated.

An in-silico study of the insertion process reported that varying the IR speed between 30, 60, and 120 rpm had no significant effect on maximum insertion torque [24]. An experimental study, in contrast, inserted implants into PU-foam of two densities at 4, 10, 20, and 30 rpm and found that increasing the IR speed reduced maximum insertion torque and altered ISQ, the effect being more pronounced in the lower-density foam [25]. These two reports cannot be compared directly, as they differ in substrate, speed range, and methodology, and the experimental evidence remains confined to PU-foam and to non-destructive measures of stability. The effect of IR speed on the mechanical strength of the implant–bone interface has, to our knowledge, not been examined.

The aim of the present study was therefore to determine whether the IR speed affects the primary stability of dental implants, using a computer numerical control (CNC) machine to control the IR speed without operator-dependent variability, two substrates of differing nature (polyurethane foam and bovine bone), and six complementary stability measures spanning the insertion phase, the resonance response, and the mechanical strength of the interface.

Materials and methods

Dental Implants and Insertion Substrates

Sixty identical dental implants (DRI, Iran, Fig. 1d) with a diameter of 4 mm, a length of 10 mm, and a pitch of 0.8 mm were inserted at insertion rotational (IR) speeds of 5, 25, and 50 rpm in PU-foam and bovine rib (10 implants for each IR speed in each substrate). The insertion process for 5, 25, and 50 rpm took 150, 30, and 15 seconds, respectively.

IR speeds of 5, 25, and 50 rpm were selected to span the clinically relevant range. ASTM F543 [26] specifies that dental implants be inserted at 4 rpm or above, so 5 rpm represents the lower bound of standardized testing; 20–25 rpm is the range most commonly used clinically [25]; and manufacturers of surgical motors specify an implant-positioning range extending to 50 rpm, which therefore represents the upper bound of clinical practice. The range examined here is consequently wider than that of the only comparable experimental study, which extended to 30 rpm [25].

Polyurethane foam (PU-foam) and bovine rib were chosen as insertion substrates. The density of the PU-foam was evaluated using four cuboid samples with a 6 cm × 5 cm cross-section and a height of 6 cm, according to ASTM D1622

[27]. Compressive and tensile properties of the foam were measured according to ASTM D1621 [13] and ASTM D1623 [14], respectively. Compressive tests were performed at a rate of 5 mm/min on the four cuboids, which were previously used for density assessment. Tensile tests were performed at a rate of 2 mm/min on three samples using a custom-made fixture according to ASTM D1623 (Fig. 1). All mechanical tests were performed by a Galdabini SUN 2500 Universal Testing Machine (Galdabini S.p.A., Italy). The averaged properties of the foam are summarized in Table 1.

Table 1

Averaged properties of PU-foam used in this study

Density	0.2 g/cm ³	
	Young's Modulus (MPa)	Ultimate Stress (MPa)
Tensile	28 ± 2.4	6.8 ± 0.6
Compressive	14 ± 4.8	1.3 ± 0.12

Cubic samples of 2 × 2 × 2 cm of synthetic bone were cut, and one implantation site in the middle of the top surface was designated (Fig. 2a). Fresh bovine ribs from a 2.5-year-old bull were collected from a local butcher shop. The ribs were marked, and a computed tomography (CT) image was performed to evaluate their bone quality (Philips Brilliance 64 CT scanner, Philips Healthcare, Amsterdam, Netherlands, Fig. 2b). The bovine ribs were then frozen at – 24°C and stored until the test day. Three-dimensional models of the ribs were then generated and used to identify the average Hounsfield Unit (HU) in implantation sites using Mimics software (Mimics 21.0, Materialise, Leuven, Belgium) [28]. All implantation sites exhibited averaged 500 HU, corresponding to type 4 bone, according to the Lekholm and Zarb classification [29]. To minimize the inherent variability in natural bone, samples with similar HU were selected (approximately 500 HU). Furthermore, the bovine ribs were obtained from the same animal, thus minimizing inter-animal variability. Implantation sites and insertion speeds were randomly distributed between the bone blocks. Thus, although multiple implants were inserted into the same bovine bone block, the implantation sites were treated as separate insertions with comparable bone-quality conditions.

Two bone blocks from the proximal section of the bovine ribs were selected as natural bone substrate for implantation and their cortical layers were removed. Before the insertion process, the frozen bone samples were left at room temperature for 4 hours and then were submerged in saline solution for 10 hours to regain lost hydration [30]. To keep bone samples level and stable during the implantation and mechanical testing, the lower half of the bone samples were submerged in quick-curing stone adhesive in a level cubical mold (Fig. 2c). The implantation sites, which were identified from CT-based bone quality analysis, were marked on the bone samples.

Drilling and insertion process

The drilling process was performed by a computer numerical control (CNC) machine according to the guideline provided by the manufacturer in two steps: an initial 2.2 mm pilot drill followed by a final 4 mm drill, both operated at 800 rpm with an axial feed rate of 1 mm/s. The insertion process was also performed by a CNC machine, enabling accurate control over IR speed, as well as eliminating any human-related variability. IR speeds of 5, 25, and 50 rpm were tested to encompass low, medium, and high IR speeds while being in the range of those used in clinical settings [24, 25, 31]. During drilling, insertion, and mechanical testing, natural bone samples were sprayed with normal saline solution to mitigate hydration loss.

Stability assessment

Primary stability for each implant was assessed by multiple methods including maximum insertion torque (MIT), implant stability quotient (ISQ), and the push-in test (Fig. 3). ISQ was averaged over measurements in three orthogonal directions using an Osstell device (Osstell AB, Stampgatan, Göteborg, Sweden). Insertion energy (IE) was also calculated as the area under the torque-time curve multiplied by the IR speed according to Eq. 1, where T is the applied torque (N.cm), t is time (s), and ω is IR speed (rad/sec). Some studies suggest that insertion energy might be a better parameter for stability assessment [31], while others doubt its reliability [32]. The push-in test was chosen as the mechanical test, as it better represents natural loading conditions of dental implants [8]. For the push-in test, the implants were subjected to axial compressive loading at a rate of 6 mm/min [8]. From the push-in test, the slope of the initial linear section of the force-displacement curve and the maximum force tolerated by the bone-implant construct until failure, respectively named push-in stiffness and push-in ultimate load, were calculated (Fig. 3c). Push-in energy (PIE) was also calculated as the area under the curve until ultimate load of the force-displacement curve of the push-in test according to Eq. 2, where F is the applied force (N), and δ is displacement (mm).

$$IE = \int_0^{t_{\text{end}}} T(t) \omega dt \quad 1$$

$$PIE = \int_0^{\delta_{\text{end}}} F(\delta) d\delta \quad 2$$

Three sources of data loss occurred and were handled as follows. For two specimens inserted at 5 rpm in the synthetic substrate, the torque acquisition device malfunctioned and the recorded torque-time curves were inconsistent with the remainder of the group; maximum insertion torque and insertion energy were therefore treated as missing for these two specimens, while ISQ, push-in stiffness, push-in ultimate load, and push-in energy were retained. One specimen in bovine bone (5 rpm speed) was excluded from all analyses because the bone sample shifted during insertion and the implant was not seated coaxially within the prepared osteotomy. For two further bovine specimens (one at 25 rpm and one at 50 rpm), the torque-time trace was not saved and insertion energy could not be computed; maximum insertion torque had been recorded independently during the procedure and all remaining outcomes were measured, so these specimens were retained for every outcome except insertion energy.

Statistical analysis

The statistical analysis was performed in R (version 4.3.3). The effect of insertion rotational (IR) speed on primary stability indicators was evaluated using Welch's ANOVA to account for unequal group sizes and unequal variances. This was followed by two-sided pairwise comparisons using Welch's t-test. The p-values were adjusted using Holm's method to account for multiple comparisons, with the significance level set at $p < 0.05$. Effect sizes (Hedges' g) and 95% confidence intervals (CIs) were reported for each comparison.

Results

The key results of this study, including maximum insertion torque, insertion energy, implant stability quotient (ISQ), and push-in test parameters, are summarized in Tables 2 and 3.

In synthetic bone (PU-foam), maximum insertion torque (MIT) showed a statistically significant overall effect of IR speed (Welch's ANOVA, $p = 0.0466$). However, in synthetic bone, none of the pairwise comparisons of MIT based on IR speed remained significant after Holm adjustment (see Table 2). ISQ of the implants in synthetic bone increased significantly with increasing IR speed from 5 to 25 rpm ($p = 0.001$) and from 5 to 50 rpm ($p < 0.001$), but no statistically significant difference was observed when comparing ISQ as IR speed increased from 25 to 50 rpm ($p = 0.666$). Additionally, for the implants inserted in synthetic bone, push-in stiffness did not change significantly with increasing IR speed ($p = 0.078$), while push-in ultimate load and push-in energy (PIE) increased significantly from 5 to 25 rpm (both $p < 0.001$) and from 5 to 50 rpm (both $p < 0.001$). Neither push-in ultimate load nor PIE showed a significant difference when increasing IR speed

from 25 to 50 rpm ($p = 0.706$ and $p = 0.281$, respectively). Similarly, IE for implants inserted in synthetic bone increased with increasing rotational speed from 5 to 25 rpm and from 5 to 50 rpm ($p = 0.019$ and $p = 0.023$, respectively), while increasing IR speed from 25 to 50 rpm did not have a significant impact on IE ($p = 0.457$).

In natural bone (bovine rib), IR speed did not have a significant effect on MIT ($p = 0.246$), push-in stiffness ($p = 0.121$), or IE ($p = 0.949$). On the other hand, ISQ increased significantly when IR speed increased from 5 to 25 rpm ($p = 0.012$), but comparing ISQ at IR speeds of 5 to 50 rpm and 25 to 50 rpm revealed no significant difference ($p = 0.145$ and $p = 0.268$, respectively). Additionally, push-in ultimate load exhibited a significant increase with increasing IR speed from 5 to 50 rpm ($p = 0.024$) and an increase from 5 to 25 rpm that was not statistically significant ($p = 0.055$). Increasing IR speed from 25 to 50 rpm did not have a significant effect on push-in ultimate load ($p = 0.122$). Finally, for implants inserted in natural bone, PIE increased significantly from 5 to 25 rpm ($p = 0.001$) and from 5 to 50 rpm ($p < 0.001$), but it did not show a significant change from 25 to 50 rpm ($p = 0.89$).

Table 2

Summarized results of averaged maximum insertion torque (MIT), implant stability quotient (ISQ), push-in stiffness, push-in ultimate load, push-in energy (PIE), and insertion energy (IE) for different insertion rotational (IR) speeds in synthetic bone (PU-foam), along with statistical analyses data including mean differences, 95% confidence intervals (95% CI), effect sizes (Hedges' g), and Holm adjusted p-values (Holm p)

Stability indicator	5 rpm	25 rpm	50 rpm	Welch ANOVA p	Comparison	Mean difference	(95% CI)	Hedges' g	Holm p
MIT (N·cm)	11.11 ± 3.83	15.10 ± 1.94	13.75 ± 1.21	0.0466	5→25	3.99	(0.66, 7.31)	1.30	0.070
					5→50	2.64	(- 0.60, 5.88)	0.93	0.163
					25→50	-1.35	(- 2.89, 0.19)	-0.80	0.163
ISQ	57.20 ± 1.90	61.27 ± 2.35	61.73 ± 2.41	< 0.001	5→25	4.07	(2.05, 6.08)	1.82	0.001
					5→50	4.53	(2.49, 6.58)	2.00	< 0.001
					25→50	0.47	(- 1.77, 2.70)	0.19	0.666
Stiffness (N/mm)	900.18 ± 83.91	1028.60 ± 140.81	924.09 ± 132.46	0.0782	5→25	128.42	(17.72, 239.11)	1.06	0.078
					5→50	23.91	(- 81.64, 129.47)	0.21	0.636
					25→50	-104.51	(- 232.98, 23.97)	-0.73	0.209
Ultimate load (N)	316.83 ± 37.81	429.03 ± 29.18	435.33 ± 42.84	< 0.001	5→25	112.20	(80.32, 144.08)	3.18	< 0.001
					5→50	118.50	(80.50, 156.50)	2.81	< 0.001
					25→50	6.30	(- 28.47, 41.07)	0.16	0.706
PIE (N·mm)	80.44 ± 19.69	161.45 ± 16.62	175.49 ± 35.78	< 0.001	5→25	81.01	(63.85, 98.16)	4.26	< 0.001
					5→50	95.04	(67.34, 122.75)	3.15	< 0.001
					25→50	14.04	(- 12.98, 41.05)	0.48	0.281
IE (N·cm)	222.26 ± 111.51	372.04 ± 57.09	355.53 ± 37.83	0.0152	5→25	149.77	(53.03, 246.52)	1.67	0.019
					5→50	133.27	(38.85, 227.70)	1.61	0.023
					25→50	-16.50	(- 62.50, 29.50)	-0.33	0.457

Table 3

Summarized results of averaged maximum insertion torque (MIT), implant stability quotient (ISQ), push-in stiffness, push-in ultimate load, push-in energy (PIE), and insertion energy (IE) for different insertion rotational (IR) speeds in natural bone (bovine rib), along with statistical analyses data including mean differences, 95% confidence intervals (95% CI), effect sizes (Hedges' g), and Holm adjusted p-values (Holm p)

Stability indicator	5 rpm	25 rpm	50 rpm	Welch ANOVA p	Comparison	Mean difference	(95% CI)	Hedges' g	Holm p
MIT (N·cm)	38.50 ± 7.19	44.19 ± 13.08	44.58 ± 8.96	0.2458	5→25	5.69	(- 4.54, 15.92)	0.51	0.506
					5→50	6.08	(- 1.75, 13.91)	0.71	0.359
					25→50	0.39	(- 10.24, 11.02)	0.03	0.939
ISQ	65.07 ± 4.47	71.23 ± 3.28	69.13 ± 4.77	0.0144	5→25	6.16	(2.28, 10.03)	1.52	0.012
					5→50	4.06	(- 0.41, 8.53)	0.84	0.145
					25→50	-2.10	(- 5.98, 1.78)	-0.49	0.268
Stiffness (N/mm)	1689.64 ± 702.73	1497.60 ± 435.09	2032.79 ± 616.76	0.1208	5→25	-192.04	(- 778.53, 394.45)	-0.32	0.554
					5→50	343.15	(- 302.78, 989.09)	0.50	0.554
					25→50	535.19	(29.66, 1040.72)	0.96	0.118
Ultimate load (N)	426.02 ± 76.92	532.69 ± 113.19	660.24 ± 216.84	0.0086	5→25	106.67	(13.29, 200.06)	1.04	0.055
					5→50	234.22	(73.85, 394.60)	1.34	0.024
					25→50	127.55	(- 38.85, 293.95)	0.71	0.122
PIE (N·mm)	137.13 ± 45.77	253.33 ± 68.58	257.31 ± 57.78	< 0.001	5→25	116.20	(59.92, 172.48)	1.88	0.001
					5→50	120.18	(69.91, 170.45)	2.19	< 0.001
					25→50	3.98	(- 55.72, 63.68)	0.06	0.890
IE (N·cm)	1107.76 ± 253.76	1162.55 ± 431.47	1118.05 ± 265.70	0.9493	5→25	54.79	(- 305.83, 415.42)	0.15	1.000
					5→50	10.29	(- 249.38, 269.96)	0.04	1.000
					25→50	-44.50	(- 408.55, 319.55)	-0.12	1.000

Discussion

Existing literature is inconclusive about the effect of insertion rotational (IR) speed on primary stability of dental implants. The main scope of this work was to determine if and how IR speed affects primary stability of dental implants in synthetic and natural bone. To this end, 60 dental implants were inserted in synthetic (PU-foam) and natural bone (bovine rib) at IR speeds of 5, 25, and 50 rpm. Primary stability indicators, including maximum insertion torque (MIT), implant stability quotient (ISQ), insertion energy (IE), push-in stiffness, push-in ultimate load, and push-in energy (PIE) were measured and reported.

The results of this study revealed that whether or not IR speed affects primary stability depends on the following factors: the insertion substrate the indicator used to gauge stability. Based on the results of this investigation, no significant sensitivity of push-in stiffness to IR speed was detected in either synthetic ($p = 0.078$) or natural bone ($p = 0.121$). Moreover, in natural bone, MIT did not change significantly with increasing IR speed ($p = 0.246$). Similar to the results of the present research in natural bone, an in-silico study by Dorogoy et al. [24] showed that increasing IR speed, up to 120 rpm, did not have a significant effect on MIT. Insertion torque is the result of frictional contact and the cutting action between implant threads and the substrate. The absence of a significant change in MIT based on IR speed suggests that within the range of the IR speeds tested here, the natural bone's overall resistance to implant insertion was relatively unchanged.

In synthetic bone, MIT showed a dependence on IR speed ($p = 0.0466$), increasing when comparing 5 to 25 rpm (Hedges' $g = 1.30$) and 5 to 50 rpm (effect size: 0.93); however, none of the pairwise comparisons were statistically significant after Holm adjustment (see Table 2). Interesting to note that Hsu et al. [25] showed that increasing IR speed reduced MIT, more pronouncedly in low-density PU-foam. The discrepancy between Hsu et al. [25] and the current study might be due to different implant designs and different mechanical properties of the PU-foam used. The elastic modulus of the low-density foam used by Hsu et al. was 12 MPa, which is comparable to the material properties of the foam used in the present study (Table 1); however, their foam samples included a 1 mm cortical layer with an elastic modulus of 16.7 GPa, while the PU-foam used here did not have a cortical layer. On the other hand, MIT in natural bone (bovine rib) did not change significantly with IR speed, which suggests a divergence between PU-foam and natural bone in their rate-dependent behavior. Based on this study's results, researchers need to apply special care when trying to extend their results, corresponding to dental implant stability measures, from synthetic- to natural bone.

Based on the outcomes of the present study, ISQ and push-in energy (PIE) showed similar trends in both substrates, as they increased when IR speed increased from 5 to 25 rpm, while there was not a significant increase when comparing them between 25 and 50 rpm (Tables 2 and 3). Push-in ultimate load also increased with increasing IR speed in both substrates, but the pairwise comparison differed between substrates. Previous studies suggest that ISQ measures the ability of the implant to resist bending loading conditions [33]. It is reasonable to say that increasing IR speed, within the conditions tested in this study, improves ISQ and subsequently the bending stability of the dental implants. This effect was consistent for both synthetic- and natural bone substrates. Hsu et al. [25] reported an increase in ISQ with increasing IR speed from 4 to 20 rpm, and not a significant change from 20 to 30 rpm. Bone density, implant design, surgical technique, and bone-implant interface are the main factors that affect ISQ [34] and mechanical test outcomes [35]. In this study, bone quality, implant design, and surgical technique, except for the insertion rotational speed, were controlled for all groups. Thus, in this study, the implant-substrate interface is likely to have been affected by the changes occurring in IR speed.

The results of the present work revealed that push-in stiffness did not change significantly based on IR speed in both substrates (synthetic bone: $p = 0.078$, natural bone: $p = 0.121$). Push-in stiffness is calculated as the slope of the initial linear section of the force-displacement curve of the push-in test. Thus, it measures the elastic stiffness of the contact between implant and the substrate, which is dependent on implant design, substrate mechanical properties, and the interface between implant and substrate. The synthetic substrates used here had the same mechanical properties, and the natural substrates were carefully selected by CT imaging to have the same bone quality based on their HU values.

Furthermore, drilling and insertion were both performed in a controlled manner by a CNC machine, which eliminated human-related error and variance between the samples. Therefore, since implant design was fixed and substrate mechanical properties in each category were kept constant, it could be suggested that no statistically significant effect of IR speed on push-in stiffness was detected in either substrate. Given the small sample sizes, which allowed only large effects to be detected in each substrate, the absence of a detected effect should not be read as evidence that no effect exists.

Increasing IR speed increases the rate at which the implant thread advances in the bone, compacting the surrounding bone while cutting it at the same time. Different studies have demonstrated rate-dependent behavior for PU-foam [36] and also in natural bone [37]. Therefore, increased rate of cutting and compaction coupled with strain rate-dependent behavior of PU-foam and natural bone may have led to their distinctive response to IR speed. Two features of the results may help explain the possible mechanisms behind this distinction. First, push-in stiffness, i.e., the elastic response of the bone-substrate construct, did not change significantly in either substrate. Second, the push-in test was performed after all the insertions were completed, so any difference in the push-in test outcomes based on IR speed was not due to instantaneous rate-dependent behavior of the substrate, as these differences persisted until the push-in test and indicated a permanent change in the substrate.

At 5 rpm, the insertion lasted 150 s, whereas at 25 rpm and 50 rpm, it lasted 30 s and 15 s, respectively. A longer insertion time likely allows more accumulated damage in the material adjacent to the thread flanks, resulting in a weaker anchorage, which is consistent with the lower push-in ultimate load and push-in energy measured at 5 rpm in both substrates. This is consistent with previous studies that have shown increased microcrack formation at lower strain rates [38].

That the push-in stiffness was not significantly affected fits the same picture. Previous studies have reported that yield behavior is strongly rate dependent while Young's modulus is unvarying over the biological loading limits [39]. For the case of the present study, the potential damage and microcrack development may have a lower effect on Young's modulus and stiffness, compared to their effect on yield properties of the substrate. Although microdamage does affect Young's modulus, its effect on yield strength may be more pronounced as reported by previous studies [40]. It must be emphasized that no direct measurement of microcrack or microdamage was performed for the present study and the justifications are literature-based speculations of the authors based on the present results.

It was observed in this study that insertion energy (IE), which is the work associated with insertion torque (Eq. 1), differed between PU-foam and natural bone. In synthetic bone, IE showed dependence on IR speed ($p = 0.0152$), increasing with the rising IR speed from 5 to 50 rpm (5 to 25 rpm, $p = 0.019$ and 5 to 50 rpm, $p = 0.023$), but not changing significantly when IR speed rose from 25 to 50 rpm ($p = 0.457$). In contrast, in natural bone, IE showed no significant dependency on IR speed ($p = 0.949$). Insertion torque captures the instantaneous rate-dependent response of the substrate, and IE encompasses these variations of insertion torque over the whole insertion time. Therefore, it may be a potentially better indicator to differentiate rate-dependent behavior of the substrate compared to other indicators. This difference in the significance of IE between PU-foam and natural bone, which was not formally tested, may indicate that PU-foam cannot fully replicate the mechanical behavior of natural bone, for instance, its rate-dependent properties as well as non-homogeneity. Previous studies have shown that IE is mostly tied to substrate density [31]. Using IE as a stability indicator is not fully accepted yet [32]; however, it can be utilized as a substrate monitoring tool, as it is strongly sensitive to material property changes [41].

It is well-known that natural bone is non-homogeneous, anisotropic, and fluid-saturated, with its inelastic deformation followed by microdamage within a mineralized matrix that is accompanied by interstitial fluid redistribution. On the other hand, rigid polyurethane foam is a closed-cell polymer whose inelastic deformation proceeds by buckling and collapse of the cell walls, followed by local densification. It is expected that natural bone and PU-foam would show different trends based on IR speed. However, it is interesting to note that except for IE, and to a limited extent MIT, all other stability indicators exhibited similar trends in both substrates, which can be related to the range of IR speed employed in this study.

Thus, MIT and IE may be candidate indicators to differentiate between insertion substrates, although this study did not perform a substrate by speed interaction analysis and this suggestion therefore remains to be tested.

Both natural and synthetic bone dissipate energy irreversibly during implant insertion, but by different mechanisms and over different characteristic timescales. On that basis, a difference between the substrates in the insertion phase is expected. The direction of the change was the same in both substrates: mean MIT rose by 36% from 5 to 25 rpm in PU-foam and by 15% in bovine bone. What differed was the magnitude of the relative change and, more importantly, the distribution: at 25 and 50 rpm the coefficient of variation of MIT was 13% and 9% in PU-foam versus 30% and 20% in bovine bone (at 5 rpm it was 35% versus 19%, respectively). With ten specimens per group, a three-group one-way ANOVA ($\alpha = 0.05$, 80% power) could reliably detect only a large effect (Cohen's $f \approx 0.6$), and approximately forty specimens per group would have been required to resolve an effect of the size observed for MIT in bovine bone in this study ($f \approx 0.28$). The present data therefore do not establish that MIT and IE in bovine bone are insensitive to IR speed; they establish that the effect, if present, was below the resolution of this design in that substrate.

There were some limitations in this work. For instance, the bone samples utilized in this study lacked a cortical layer, which can affect the generalizability and clinical significance of the results. However, controlling the thickness of the cortical layer in natural bone is challenging, and even slight variations of it can lead to considerable changes in primary stability, thereby causing a significant increase in the number of samples required to achieve statistical significance. Furthermore, lack of a cortical layer would serve as the worst-case scenario for dental implant insertion, as implants inserted in low bone quality conditions have a lower chance of success. Thus, the results of this study could potentially be helpful for the riskier implantation sites. Additionally, because multiple implants were inserted within the same bovine bone blocks, some degree of block dependency cannot be avoided. The use of CT-derived HU values for site selection, harvesting the ribs from the same animal, and random allocation of insertion speeds was intended to minimize systematic differences among implantation sites.

Future studies could utilize more bone quality conditions that include a cortical layer, and also monitor heat generation based on insertion rotational speed. Quantifying the strain and stress fields generated within the substrate, using in-silico methods, such as finite element methods, can help discover new aspects of the problem tackled in this investigation, which can be executed in future studies.

Conclusions

In this investigation, it was found that increasing insertion rotational (IR) speed increases implant stability quotient (ISQ) and push-in energy (PIE) in both synthetic (PU-foam) and natural bone (bovine rib). These primary stability indicators first significantly increased with increasing IR speed from 5 to 25 rpm, but did not show a significant difference when the IR speed increased from 25 to 50 rpm. Push-in ultimate load also exhibited an overall increase with IR speed in both substrates, but pairwise comparisons differed between substrates. Thus, one may conclude that by increasing IR speed from 25 to 50 rpm, the insertion time decreases, but no significant additional improvement occurs for ISQ, PIE, and push-in ultimate load. Nonetheless, in PU-foam, MIT showed an overall dependence on IR speed while insertion energy (IE) showed an initial significant increase with increasing IR speed from 5 to 25 rpm, but no significant change when IR speed increased from 25 to 50 rpm. In natural bone, both IE and MIT showed no significant change with IR speed. These findings indicate that PU-foam may not fully replicate the non-homogeneous, anisotropic, and rate-dependent properties of natural bone, especially with regard to indicators such as IE and MIT; however, more testing is required for this to be confirmed. Moreover, MIT and IE were the only stability indicators whose significance differed between PU-foam and natural bone; however, their potential as substrate differentiating indicators requires further investigation. The results of this work suggest that, in low-density substrates, increasing the IR speed beyond approximately 25 rpm may confer limited additional benefit in regard to several stability indicators. More investigations are needed to discover new aspects of the multidisciplinary problem tackled in this study.

Declarations

Conflict of interest

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

Ethical Approval

No animals were sacrificed for the purpose of this paper. No human subjects or personal data was used in this paper.

Informed Consent

No informed consent was required for this study.

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Author Contribution

M.FK: Writing—original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. T.M: Writing—original draft, Visualization, Methodology, Formal analysis, Data curation. G.R: Supervision, Writing—review and editing.

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Data Availability

All data supporting the findings of this study are available within the paper and its Supplementary Information.

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Figures

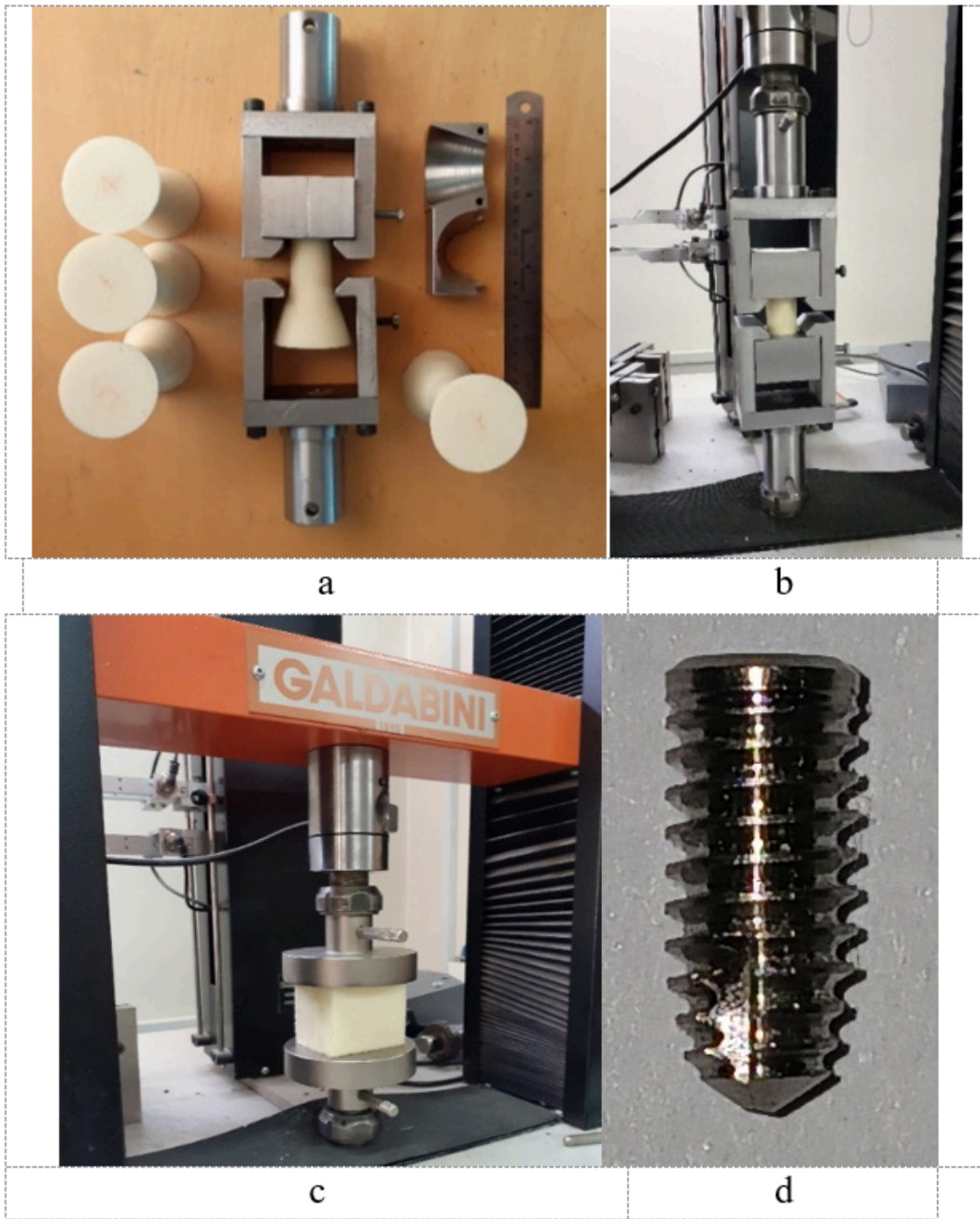


Figure 1

a) Fixture made for tensile test, b) tensile test set-up, c) compressive test set-up, d) dental implant

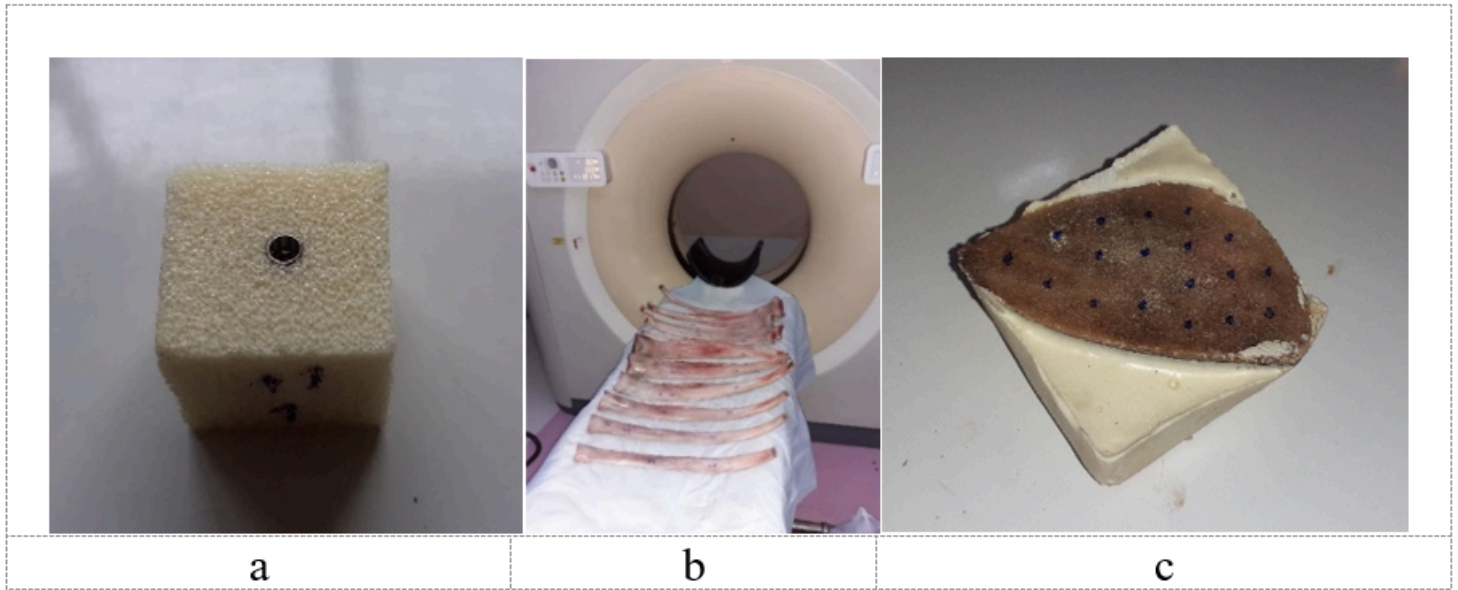


Figure 2

a) Synthetic bone sample (PU-foam), b) CT imaging of bovine ribs, and c) natural bone sample fixed in stone adhesive

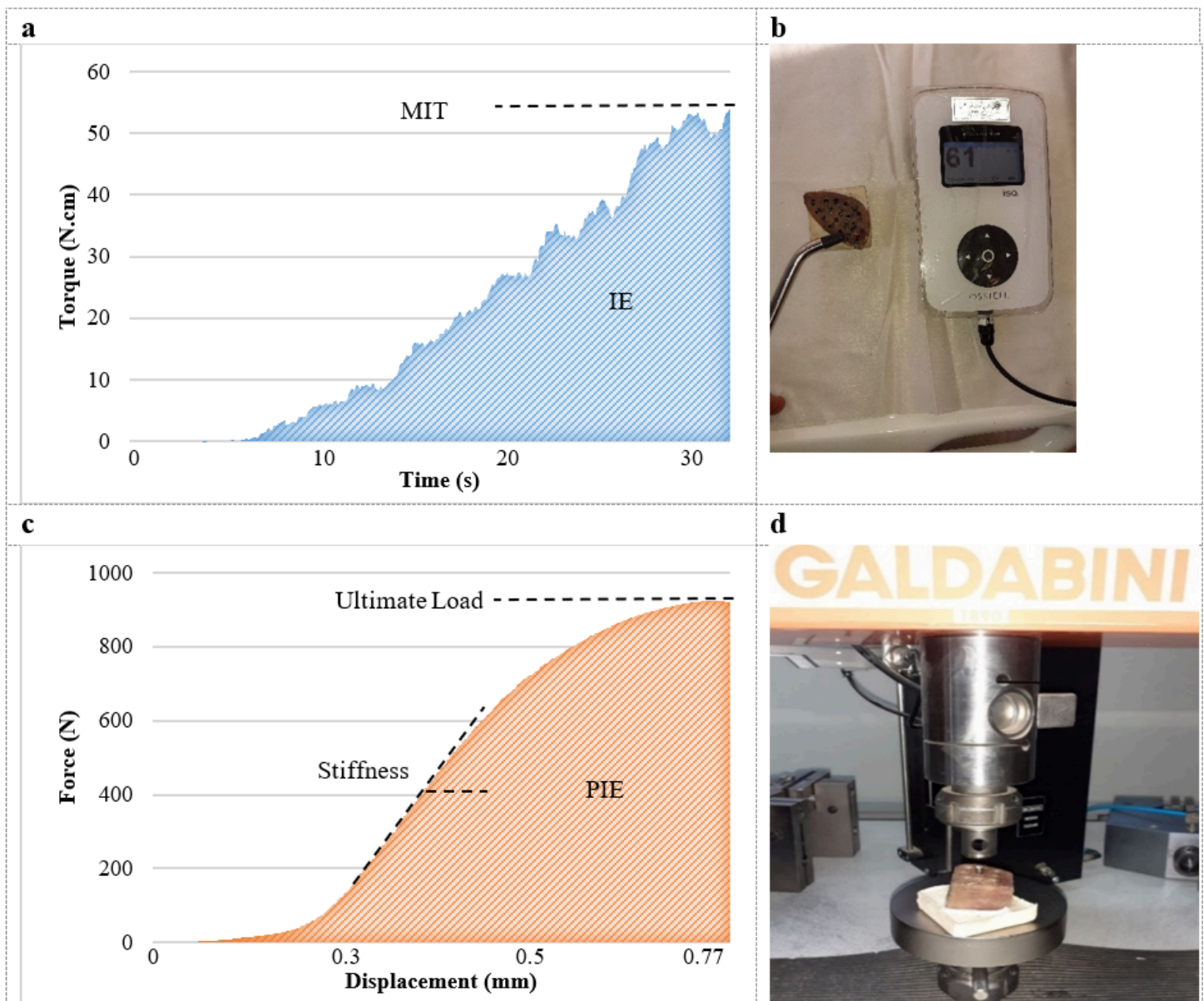


Figure 3

Different stability assessment methods used in this study, a) torque-time curve with maximum insertion torque (MIT) and insertion energy (IE) marked; b) ISQ measurement with an Osstell device; c) force-displacement curve of the push-in test, depicting push-in stiffness, push-in ultimate load, and push-in energy (PIE); and d) push-in test set-up