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Original article**K-wire pullout strength in hand surgery: impact of diameter, threading length and drilling speed**

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Abstract**Introduction**

The aim of the present study was to assess the impact, combined and in interaction, of diameter, threading length and drilling speed on K-wire pullout strength in a synthetic model of a hand bone.

Material & methods

The material comprised Sawbones® (20 x20 x50 mm), K-wires (diameter 1.2 mm, 1.5 mm, 1.8 mm; threading 0 mm, 5 mm, 10 mm, 15 mm), a universal chuck with T handle and a drill (speed 0, 320, 500, 830, 1,290 rpm), and tensile testing machine and a digital decision aid. The Sawbones® were drilled, varying diameter, threading and speed. The Statistical Design Of Experiments (SDOE)

methodology enabled the number of trials to be reduced from 300 to 70. Tensile tests at 1 mm/sec was imposed on the K-wire up to pullout (pullout strength).

Results

There was no interaction between threading length and diameter effects or between drilling speed and diameter effects, but a strong interaction between drilling speed and threading length effects.

Conclusion

Before using K-wires for internal fixation in wrist or hand fracture, the surgeon has to select their characteristics, optimal holding power being theoretically ensured by large diameter wires with long threading inserted by a high-speed drill.

Level of evidence: I, experimental study

Key-words: pullout strength; K-wires; diameter; threading length; drilling speed

Introduction

Among the many internal fixation techniques for phalangeal and metacarpal fracture, K-wires are still very widely used, being easy to manipulate, relatively non-invasive, inexpensive and adaptable to all types of fracture, including comminuted fracture [1].

Clinical results for K-wire fixation vary between reports. Some studies found good results in radial [2] and metacarpal fracture [3], and others reported the contrary, finding specific complications [4, 5]. One reason for these discrepancies may lie in wire holding power within the bone.

Biomechanical studies in synthetic or animal or human cadaver bone have sought to identify parameters affecting holding power. Some authors showed that pullout strength increased with K-wire diameter [6, 7], threading length [8, 9] or drilling speed [10]. To our knowledge, none analyzed

the combination of and interaction between these three parameters, although this information would be helpful in selecting the set-up that would optimize holding power.

The present study therefore aimed to analyze the effect on pullout strength of the combination of and interaction between K-wire diameter, threading length and drilling speed in a synthetic hand bone model.

Material and methods

The material comprised a parallelepiped synthetic bone model in homogeneous polyurethane foam, 20 mm long, 20 mm high and 50 mm deep (Sawbones®, Vashon, WA, USA); stainless steel 316-L K-wires, 60 mm long and 1.2, 1.5 or 1.8 mm in diameter and with threading lengths of 0 (“smooth” wire), 5, 10 or 15 mm; a universal chuck with T handle (drilling speed averaging 30 rpm) (CF39/16®, Surgiway, Paris, France) and a calibrated pillar drill (DP3300AL®, Rexon™, Paris, France) with 4 speeds: 320, 500, 830 and 1,290 rpm. A tensile testing machine (3345®, Instron™, Norwood, MA, USA) with 1 kN load cell, pullout control and command and acquisition software (Bluehill3®, Instron™, Norwood, MA, USA) was used for wire pullout. Test design and analysis used the NemrodW® digital decision tool (<http://www.nemrodw.com/fr>, Marseille, France).

K-wires were introduced by drilling a parallelepiped of synthetic bone, held in a vise, through the whole height, without crossing. Several types of wiring were implemented, varying diameter, threading length and drilling speed. Each type was reiterated 5 times to assess reproducibility [11]. In theory, to assess the effect on pullout strength of combination and interaction for these 3 factors, trials would be needed for 3 diameters, 4 threading lengths and 5 speeds, for a total 60 configurations reiterated 5 times each; this would mean 300 trials, which was not feasible in a

reasonable time on a limited budget. In practice, on the other hand, the SDOE (Statistical Design Of Experiments) methodology [12] optimized solutions by determining a representative sample of the 300 trials so as to minimize the number while still highlighting the effect of the parameters and their interactions and minimizing the impact of experimental variance on the results of the predictive model, by using mathematical tools. The 60 possible configurations were thus represented by a 3-dimensional matrix based on an efficiency coefficient representing the number of required tests according to the complexity of the predictive model and the analysis of the matrix mathematical properties (especially the determinant). SDOE matrices are mathematical expressions of the experimental designs. These properties influence the confidence region of the results. For maximal efficiency and adequate matrix quality, the number of configurations could be reduced to 14, repeated 5 times each, for a total of 70 experiments (Fig. 1).

The wire pullout method consisted in first positioning and gripping the wired Sawbone® in the lower grip of the test machine. The free end of the wire was then positioned and gripped in the upper grip. The lower grip was immobile and 1 mm/sec tensile force was exerted by the upper vise until complete pullout (Fig. 2).

In each of the 70 tests, the load was recorded as a function of the increase in gauge length, the maximal force representing the pullout strength.

This method, identifying the configuration with the greatest holding power, was based on identifying the optimal solution on SDOE methodology [13]. This comprised 4 stages, identifying relevant factors and their most significant interactions; the first stage consisted in producing the 14 above configurations in the laboratory. The second consisted in obtaining a predictive equation from the 14 configurations by means of the Nemrod® digital decision tool. The third consisted in simulation to obtain a graphic representation of all possible configuration. And the fourth used a mathematical optimization method to obtain the configuration with the best holding power.

Results

Figure 3 and Table I show change in pullout strength according to threading length and wire diameter at the 3 drill speeds. There was no interaction between the effects of varying threading length and of varying diameter.

Figure 4 and Table II show change in pullout strength according to drilling speed and wire diameter with the 3 threading lengths. There was no interaction between the effects of varying drilling speed and of varying diameter.

Figure 5 and Table III show change in pullout strength according to drilling speed and threading length with the 3 diameters. There was a strong interaction between the effects of varying drilling speed and of varying threading length.

Discussion

The present study showed that the configuration with greatest pullout strength was a large diameter K-wire with long threading length, inserted at high speed.

This configuration is not always clinically transposable. For example, using a motor for K-wire insertion weakens the bone in contact, due both mechanical to damage and to the high temperature around the bit [10, 14]. Some authors even notch the end of the wire to circumvent this, although benefit has not been demonstrated [15].

In clinical practice, it is important to be aware of the most significant interactions between diameter, threading length and drill speed. The present results showed that the longer the threaded part, the greater the pullout strength, except at low drilling speed, where threading length had no effect. Thus, if the wire is inserted manually, threading is not necessary, whereas long threading is preferable if a motor is used. The results also showed that the greater the diameter, the greater the

pullout strength, although to a lesser extent: diameter did not greatly affect pullout strength. Lastly, if the K-wire was smooth, pullout strength was greater for high drilling speeds. Thus, if a motor is used, it is better to have a threaded wire; but if a smooth wire is inserted by drill, it is better to use a low speed.

The present study had certain limitations. Theoretically, 300 tests should have been made, whereas only 70 actually were. To overcome this drawback, we extrapolated the results of the 70 tests by the SDOE simulation method [12], which is regularly used in general mechanics [16]. Another weakness is that the gradient of mechanical resistance in cortical versus cancellous bone is far from the mechanical properties of Sawbones®. Sawbones®, however, are always identical, avoiding an interaction factor that could not be controlled using biological bone, and improving reproducibility.

The present results showed that pullout strength depended on K-wire diameter, threading length and insertion speed, in agreement with the literature (Table IV). Smooth wires showed less holding power, as reported in [8,9,17]. One reason may lie in heating due to wire rotation within the bone. Some authors found that drilling holes with smooth wires induced higher temperatures than drilling with threaded wires of the same diameter [18, 19]; this is attributed to geometry, with efficient evacuation of bone debris and lower friction and heating. We also showed that, with threaded K-wires, pullout strength was better at higher speeds. Some authors explained this by the shorter exposure of the bone to thermal damage induced by drilling [10]. Poorer holding power may result from thermal necrosis associated with the heat generated during wire insertion [20, 21]. We further showed that, with smooth wires, higher drilling speeds reduced pullout strength.

Overall, the present results also showed that the longer the threaded part, the greater the pullout strength. This was also reported in [22] that drilling with longer threading induced a lower rise in temperature in the bone, as the threading allows better debris evacuation. Concerning wire diameter, we found that greater diameters were associated with better pullout strengths, as

reported in [6,7,23]. In contrast, when speeds were low (using a handle with Jacobs chuck), neither threading length nor diameter significantly affected pullout strength.

In conclusion, before using K-wires for internal fixation in wrist or hand fracture, the surgeon has to select the wire's characteristics, in the light of the fact that optimal holding power is theoretically ensured by wide diameter K-wires with long threading and high-speed motorized insertion.

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No other authors have conflicts of interest to disclose in relation to the present article.

Elsewhere, Philippe Liverneaux has interests with Newclip Technics™, Argomedical™ and CareSyntax™

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Author contributions: Louisa Tamiti: data collection

Sandrine Braymand: figures

Nadia Bahlouli: tables

Sybille Facca: re-editing

Philippe Liverneaux: writing

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Figure legends

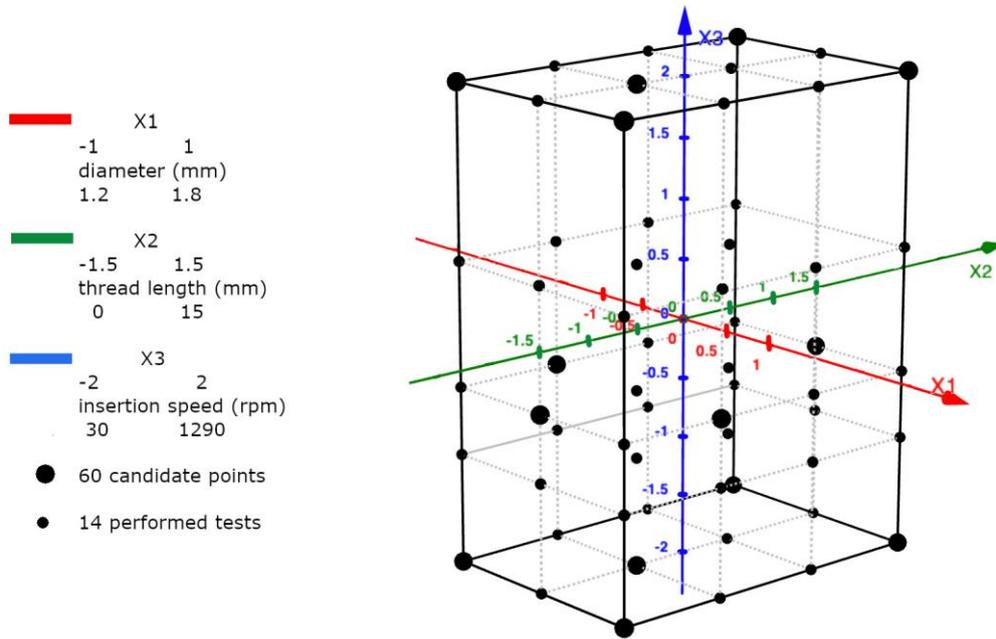


Figure 1 3D representation of the 14 configurations tested, out of the 60 possible configurations determined by the 3 factors: 3 wire diameters (red axis), 4 threading lengths (green axis), and 5 drilling speeds (blue axis). As the SDOE methodology requires a constant step between two values, a correspondence between steps and values of the 3 factors was defined.

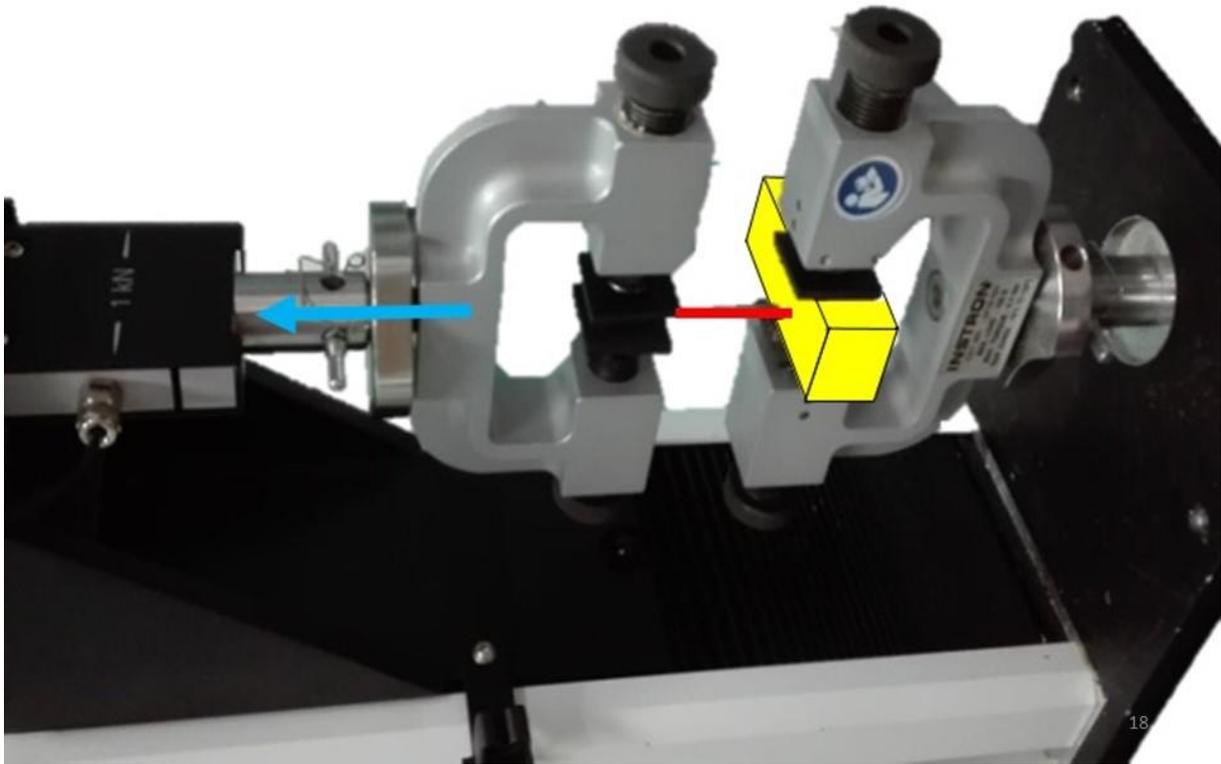
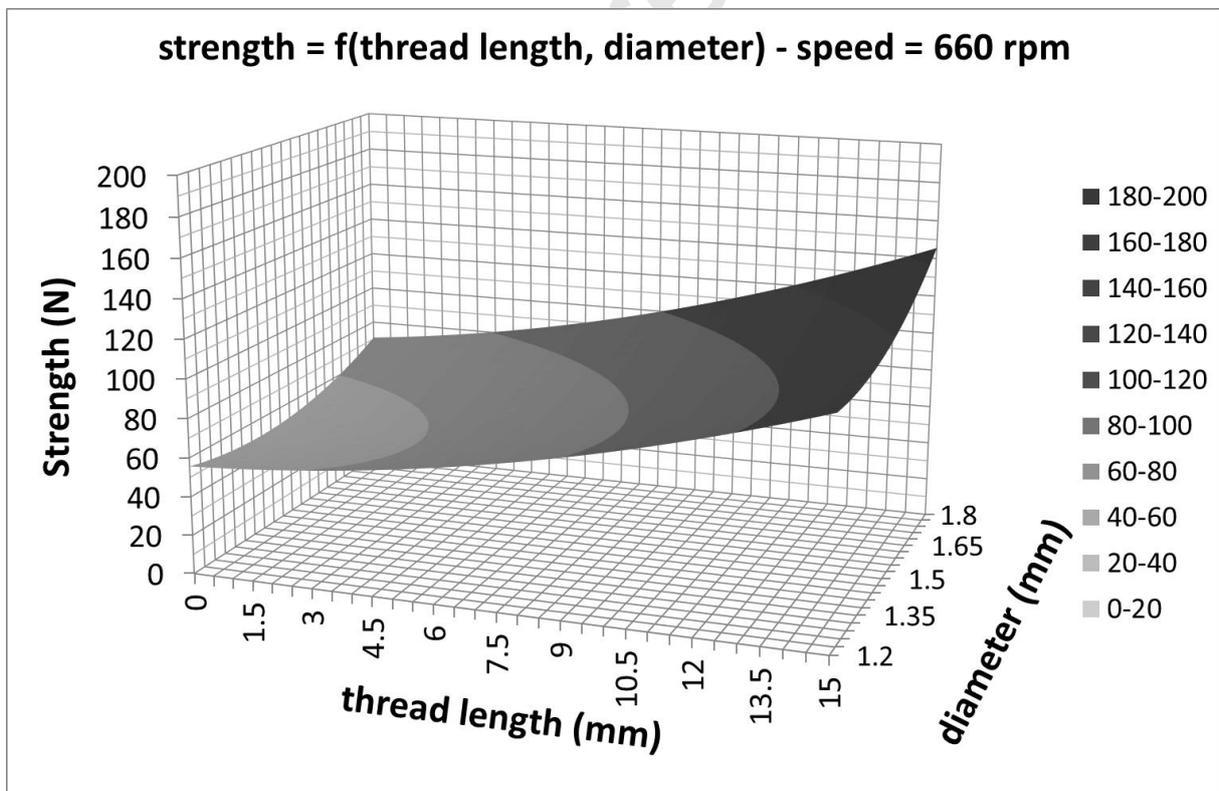
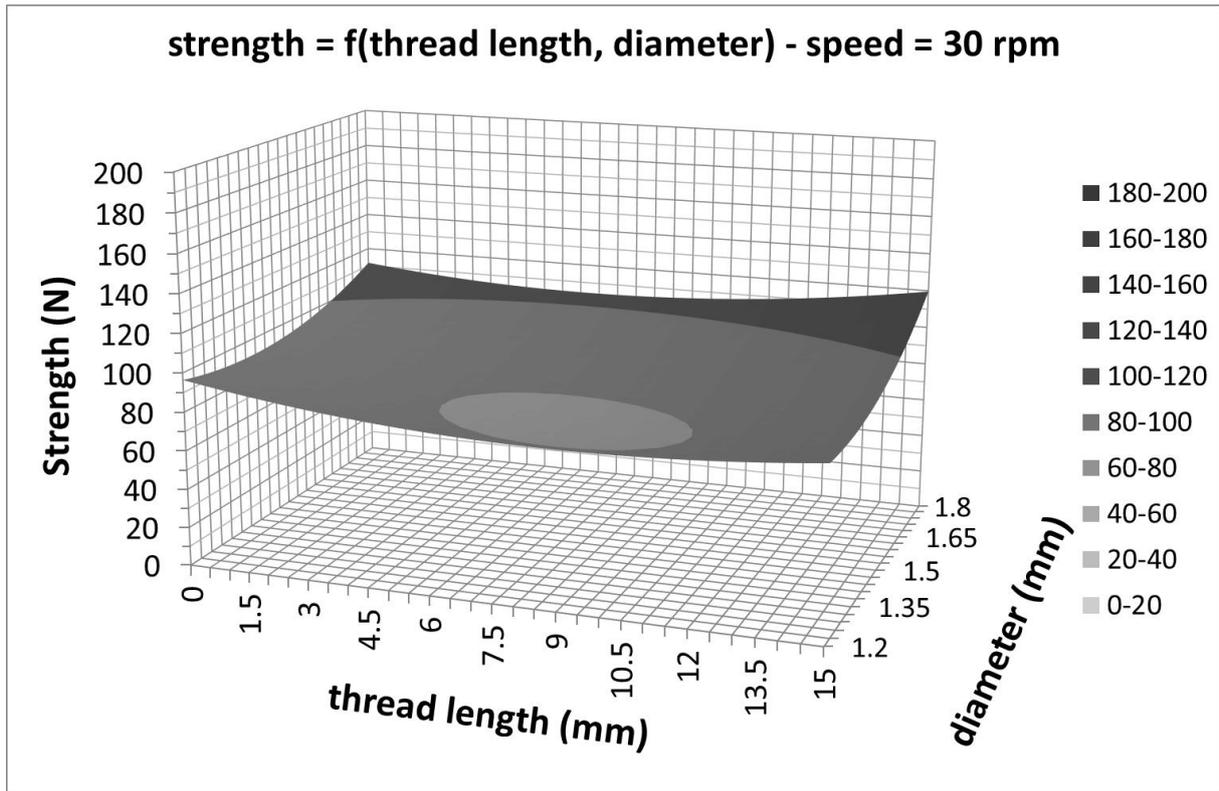


Figure 2 Traction test set-up (blue) to measure the pullout strength of the K-wire (red) in the Sawbone® (yellow).



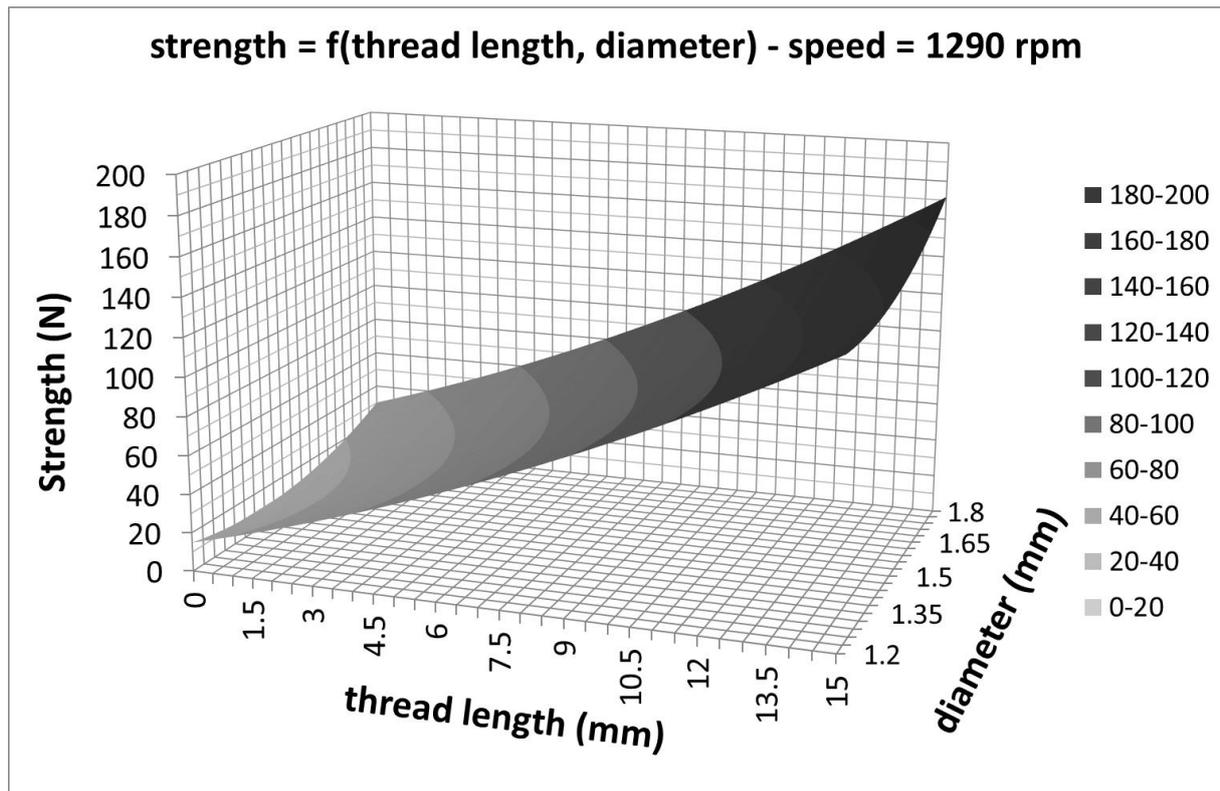
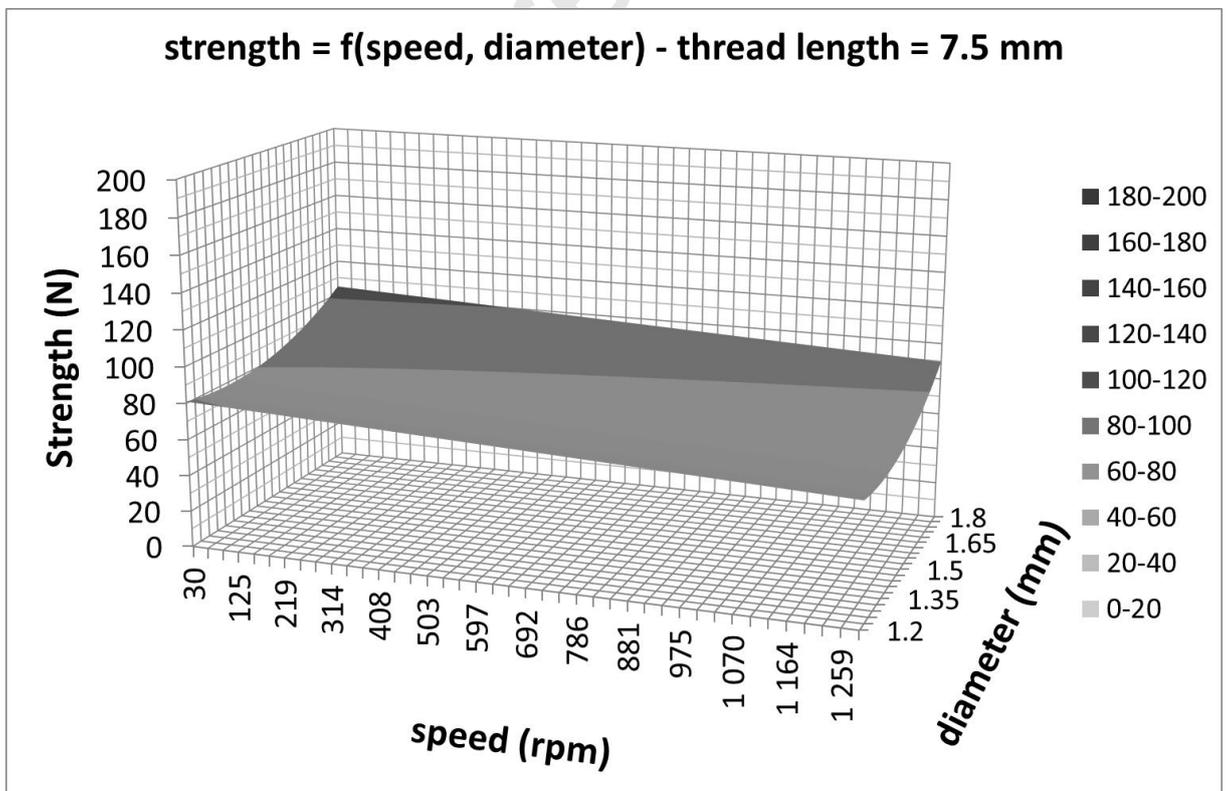
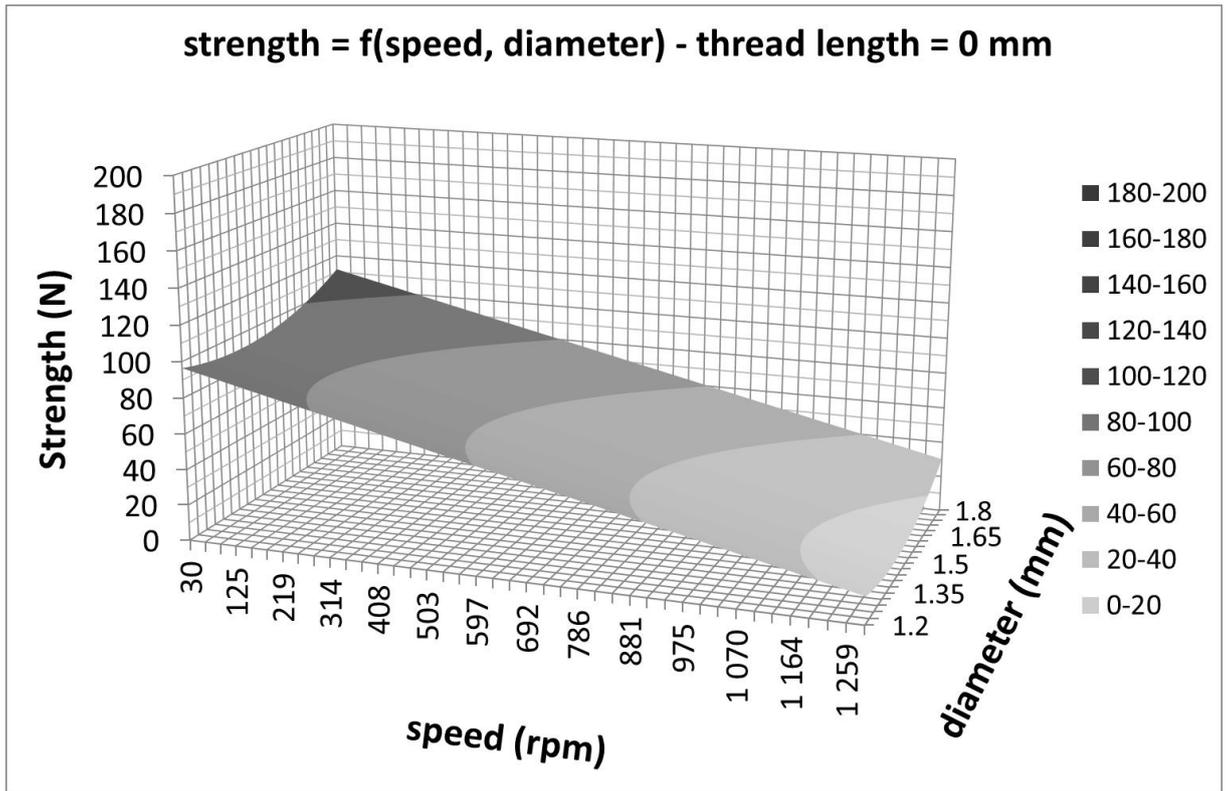


Figure 3 3D graph of change in pullout strength, using SDOE methodology, according to threading length and diameter for 3 drilling speeds.

A Impact of threading length and diameter on pullout strength at a constant speed of 30 rpm. Increasing threading length had little effect on pullout strength, whatever the diameter. Increasing the diameter increased pullout strength slightly, whatever the threading length.

B Impact of threading length and diameter on pullout strength at a constant speed of 660 rpm. Increasing threading length increased pullout strength moderately, whatever the diameter. Increasing the diameter increased pullout strength slightly, whatever the threading length.

C Impact of threading length and diameter on pullout strength at a constant speed of 1,290 rpm. Increasing threading length strongly increased pullout strength, whatever the diameter. Increasing the diameter increased pullout strength slightly, whatever the threading length.



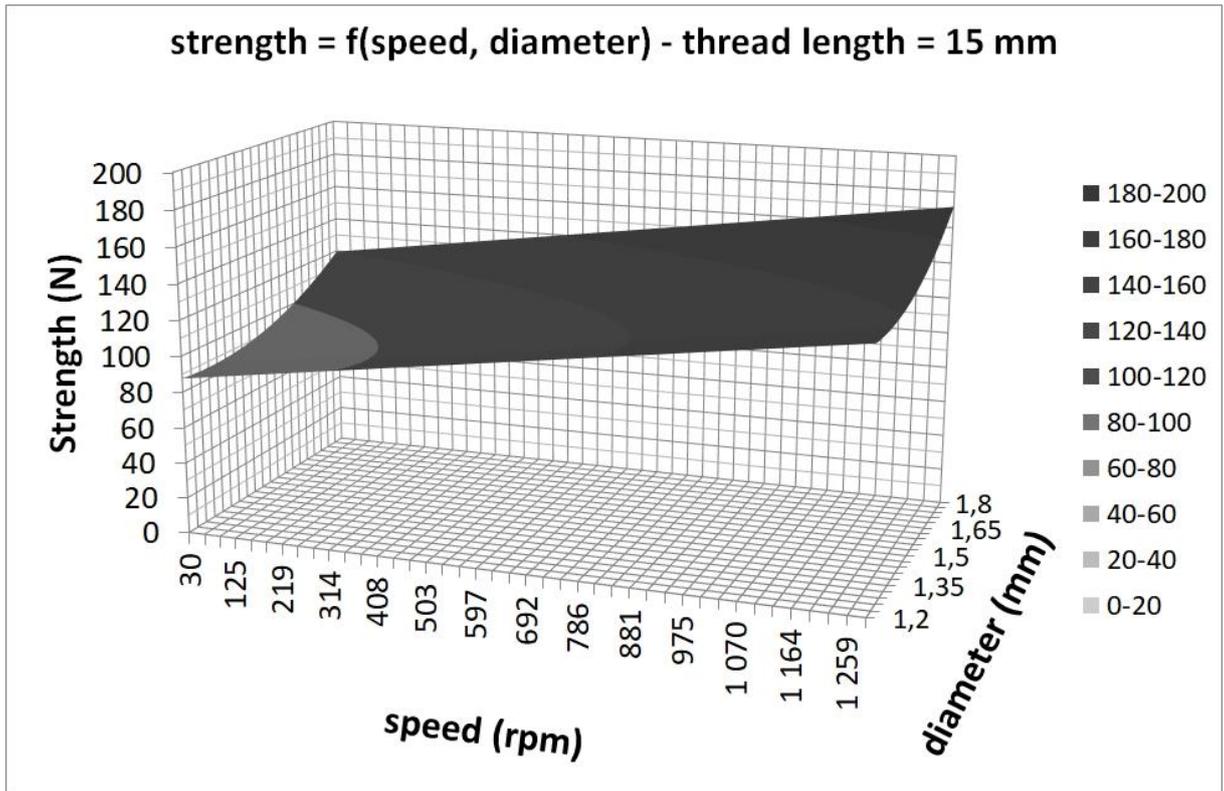
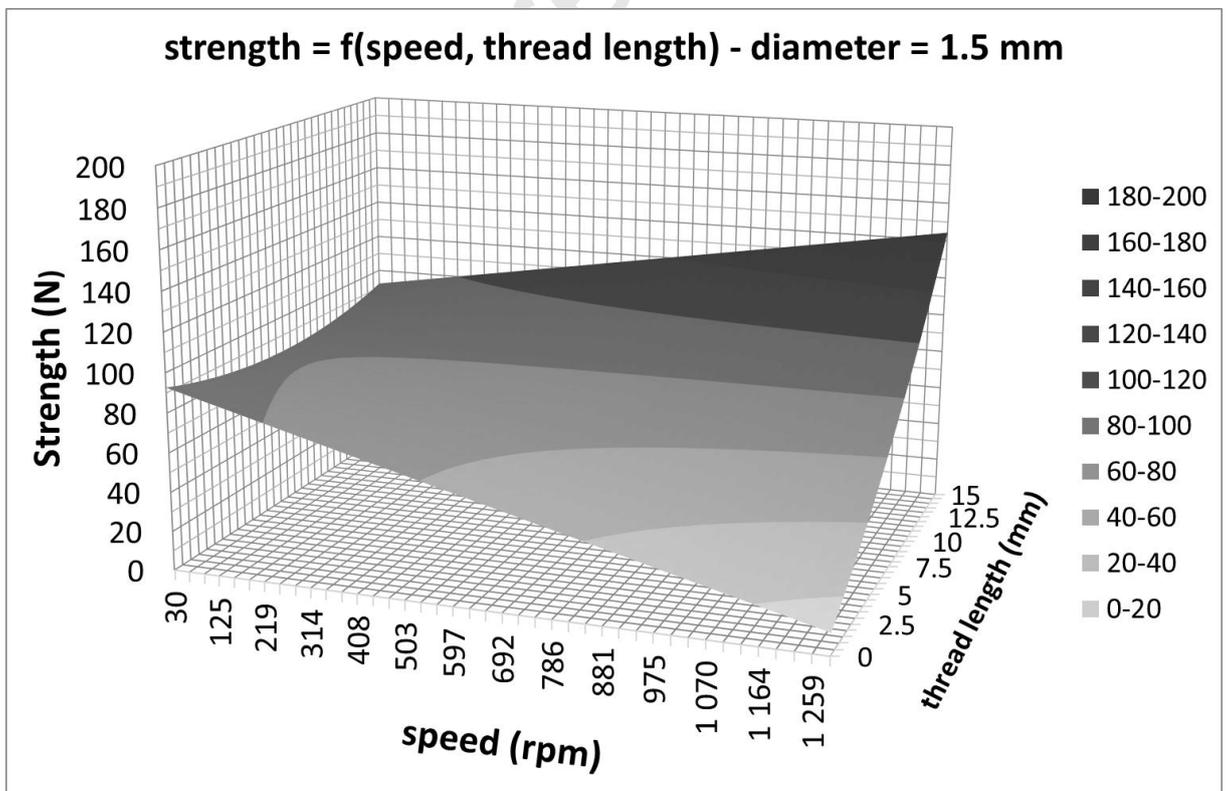
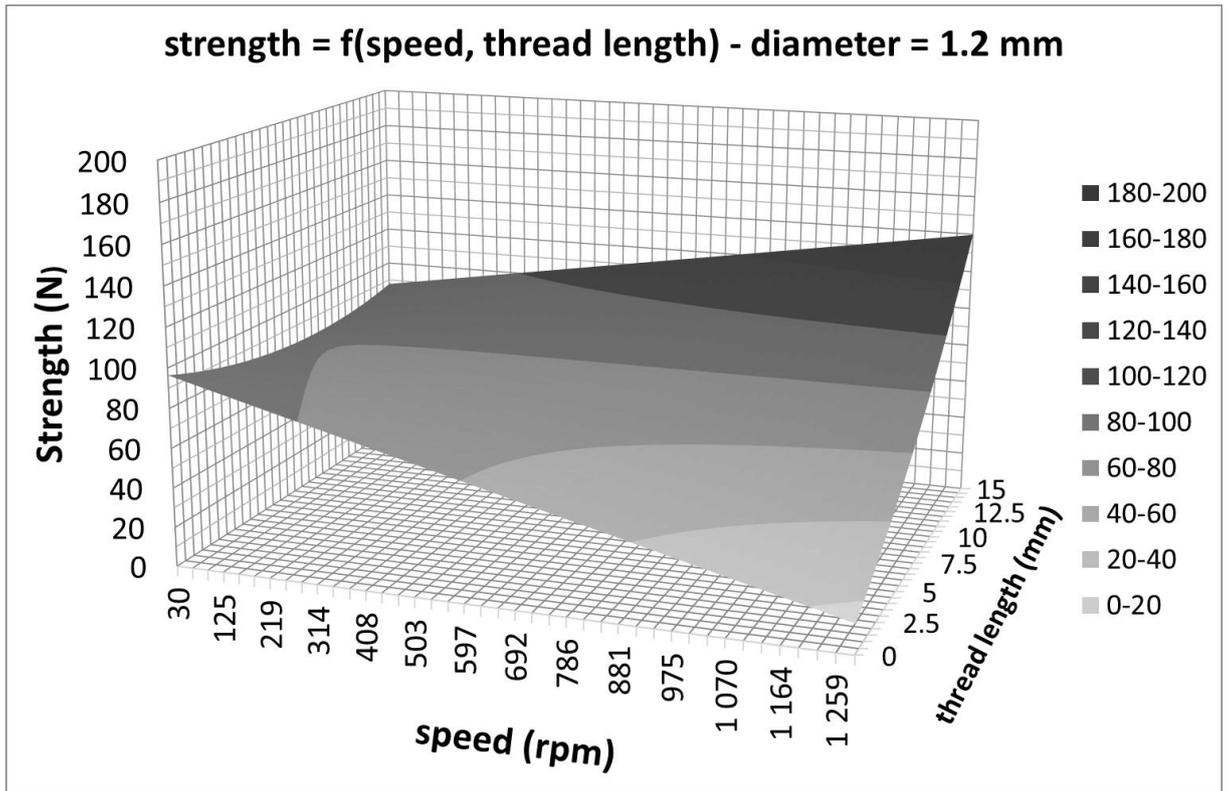


Figure 4 3D graph of change in pullout strength, using SDOE methodology, according to drilling speed and diameter for 3 threading lengths.

A Impact of insertion speed and diameter on pullout strength at constant threading length of 0 mm. Increasing speed strongly reduced pullout strength, whatever the diameter. Increasing diameter increased pullout strength slightly, whatever the drilling speed.

B Impact of insertion speed and diameter on pullout strength at constant threading length of 7.5 mm. Increasing speed reduced pullout strength very slightly, whatever the diameter. Increasing diameter increased pullout strength slightly, whatever the drilling speed.

C Impact of insertion speed and diameter on pullout strength at constant threading length of 15 mm. Increasing speed considerably increased pullout strength, whatever the diameter. Increasing diameter increased pullout strength slightly, whatever the drilling speed.



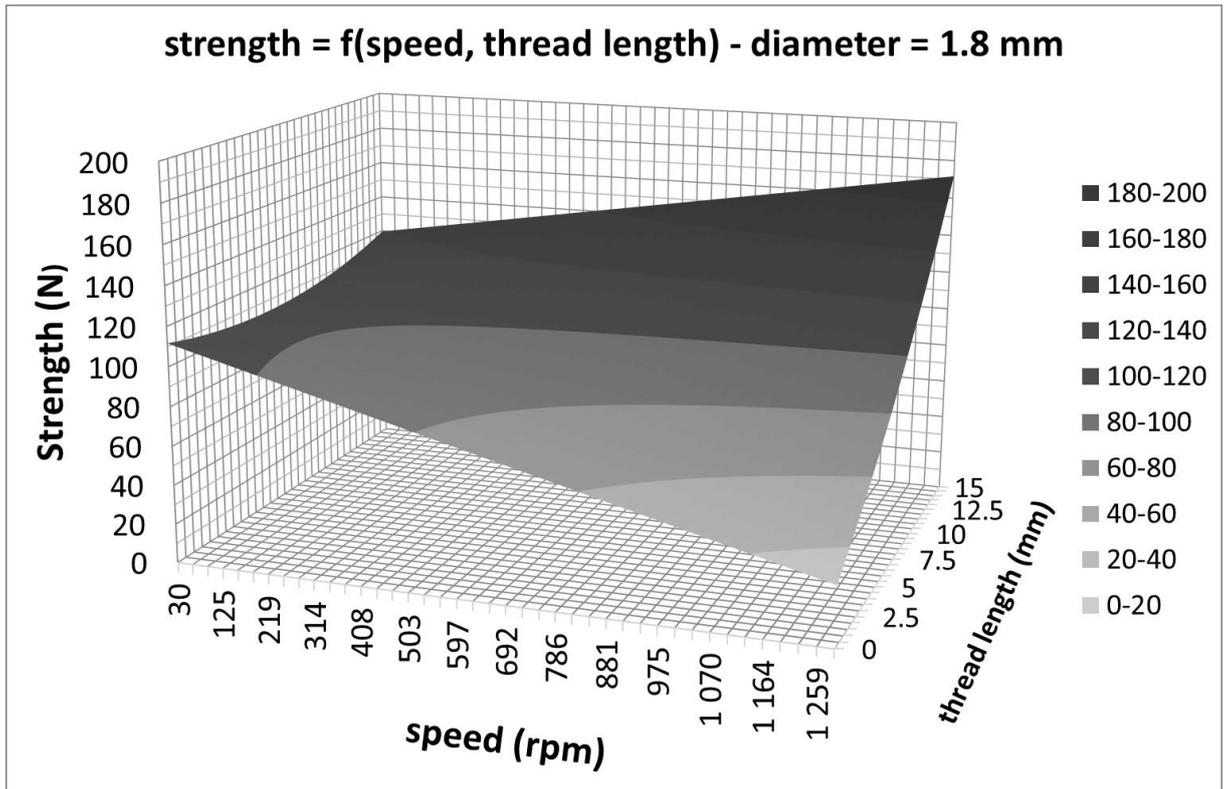


Figure 5 3D graph of change in pullout strength, using SDOE methodology, according to drilling speed and threading length for 3 diameters. Whatever the diameter, with short threading length increased speed reduced pullout strength, but increased pullout strength with long threading length. At low speed, increased threading length had little effect on pullout strength, but strongly increased pullout strength at high speed.

A Impact of insertion speed and threading length on pullout strength at a constant diameter of 1.2 mm.

B Impact of insertion speed and threading length on pullout strength at a constant diameter of 1.5 mm.

C Impact of insertion speed and threading length on pullout strength at a constant diameter of 1.8 mm.

Table I. Change in pullout strength according to threading length and diameter for 3 insertion speeds

S (rpm)	Change in P					
	Global impact		Curvature impact		Interaction impact	
30	When L ↗	When D ↗	When L varies	When D varies	When L varies	When D varies
	Little impact on P	slight ↗ in P	Slight concavity above	Slight concavity above	Same impact on P ☐ D (no interaction)	Same impact on P ☐ L (no interaction)
660	When L ↗	When D ↗	When L varies	When D varies	When L varies	When D varies
	Moderate ↗ in P	slight ↗ in P	No significant impact	Slight concavity above	Same impact on P ☐ D (no interaction)	Same impact on P ☐ L (no interaction)
1,290	When L ↗	When D ↗	When L varies	When D varies	When L varies	When D varies
	Strong ↗ P	slight ↗ in P	No significant impact	Slight concavity above	Same impact on P ☐ D (no interaction)	Same impact on P ☐ L (no interaction)

P pullout strength
L threading length
D diameter
S insertion speed
☐ whatever

Table II. Change in pullout strength according to insertion speed and diameter for 3threading lengths

L (mm)	Change in P					
	Global impact		Curvature impact		Interaction impact	
0	When S ↗	When D ↗	When S varies	When D varies	When S varies	When D varies
	Strong ↘ in P	slight ↗ in P	No impact	Slight concavity above	Same effect on P ⊗ D (no interaction)	Same effect on P ⊗ S (no interaction)
7.5	When S ↗	When D ↗	When S varies	When D varies	When S varies	When D varies
	Very slight ↘ in P	slight ↗ in P	No impact	Slight concavity above	Same effect on P ⊗ D (no interaction)	Same effect on P ⊗ S (no interaction)
15	When S ↗	When D ↗	When S varies	When D varies	When S varies	When D varies
	Sharp ↗ in P	slight ↗ in P	No impact	concavity above	Same effect on P ⊗ D (no interaction)	Same effect on P ⊗ D (no interaction)

P pullout strength
L threading length
D diameter
S insertion speed
⊗ whatever

Table III. Change in pullout strength according to insertion speed and threading length for 3 diameters

D (mm)	Change in P					
	Global impact		Curvature impact		Interaction impact	
1.2	When S ↗:	When L ↗:	When S varies:	When L varies:	When S varies:	When L varies:
	P varies differently according to L (globally heterogeneous effect)	P varies differently according to S (globally heterogeneous effect)	No effect	Slight concavity above when S ↘	P varies according to L: P ↘ when L ↘ P ↗ when L ↗	P varies according to S: P constant when S ↘ P ↗ when S ↗
1.5	When S ↗	When L ↗	When S varies	When L varies	When S varies	When D varies
	P varies differently according to L (globally heterogeneous effect)	P varies differently according to S (globally heterogeneous effect)	No effect	Slight concavity above when S ↘	P varies according to L: P ↘ when L short P ↗ when L ↗	P varies according to S: P constant when S ↘ P ↗ when S ↗
1.8	When S ↗	When L ↗	When S varies	When L varies	When S varies	When D varies
	P varies differently according to L (globally heterogeneous effect)	P varies differently according to S (globally heterogeneous effect)	No effect	Slight concavity above when S ↘	P varies according to L: P ↘ when L short P ↗ when L ↗	P varies according to S: P constant when S ↘ P ↗ when S ↗

P pullout strength
L threading length
D diameter
S insertion speed

Table IV. Literature results

Smooth wires show poorer holding power						
	Study species	P	L (mm)	D (mm)	S_{in}	S_{ext}
Degernes et al.	Bird bone	60 N	15	1.6	< 150 rpm	100mm/min
Abouzia et al.	Bovine femur	–	Fully threaded	2.5	20,000-100,000 rpm	–
The greater the diameter, the better the pullout strength						
Yovich et al.	Horse bone (metacarpal and metatarsal bones)	849.2 -1,116.0 kg	Fully threaded	4.5 – 5.5	manual	19 mm/s
Clary & Roe	Canine tibia	4,028 N	0	2.7	100 rpm	50 mm/min
Liu et al.	Bovine femur	122 N	0	2	1,000 rpm	1mm/s

P pullout strength
 L threading length
 D diameter
 S_{in} insertion speed
 S_{ext} extraction speed
 Rpm revolutions per minute